Voltage Stability Analysis of Electric Power Distribution System

THESIS

Submitted in partial fulfilment
of the requirements for the degree of
DOCTOR OF PHILOSOPHY

By

Hari Om Bansal

Under the Supervision of
Dr. Smarajit Ghosh

BIRLA INSTITUTE OF TECHNOLOGY AND SCIENCE
PILANI (RAJASTHAN)

2005

BIRLA INSTITUTE OF TECHNOLOGY AND SCIENCE
PILANI (RAJASTHAN)

CERTIFICATE

This to certify that the thesis entitled 'Voltage Stability Analysis of Electric Power Distribution System' and submitted by Hari Om Bansal ID.No. 2001PHXF029 for award of Ph.D. Degree of the Institute embodies original work done by him under my supervision.

Signature in full of
The Supervisor Smarajit Ghosh
Name in capital
block letters : Dr. SMARAJIT GHOSH
Designation : ASSISTANT PROFESSOR

Date: 13/05/05

ACKNOWLEDGEMENTS

I wish to express deep sense of gratitude and sincere thanks to my thesis supervisor Dr. Smarajit Ghosh for his guidance, encouragement, and constructive spontaneous suggestions throughout the period of this research work. It has been a privilege for me to work under him.

Much appreciations is expressed to Prof. G Raghurama, Chief Admissions and Placement Unit & Dean FD II, Prof. Sanjoy Roy and Prof. Vimal Bhanot who are the members of Doctoral Advisory Committee, for their valuable suggestions and moral support.

I am also thankful to my previous Doctoral Advisory Committee member Prof. H.V. Manjunath for his kind co-operation.

Gratitude is also accorded to BITS, Pilani, for providing all the necessary facilities to complete the research work. My special thanks go to Prof. S. Venkateswaran, Vice Chancellor, BITS, Pilani, for giving me an opportunity to do research at the institute.

I also thank Prof. L.K. Maheshwari, Director and Pro Vice Chancellor, BITS, Pilani, Prof K.E. Raman, Deputy Director (Administration), BITS, Pilani, Prof. V.S. Rao, Deputy director (Off Campus),BITS, Pilani, Prof. A.K. Sarkar, Dean ID and Faculty Division I and Prof. R.N. Saha, Dean EDD and Faculty Division III for providing the necessary infrastructure and other facilities to complete this research work.

I also express my heartfelt gratitude to Prof. Ravi Prakash, Dean, Research and Consultancy Division for his kind and affectionate enquiries about the work and continuous encouragement for making this work as a success.

I also thank to Dr. S.D. Pohekar for his kind assistance during this Ph.D. Work.

I also thank to Prof. Ved Prakash for his kind encouragement for preparing this thesis work.

Special thanks are also extended to all of my colleagues for their kind inspiration.

It is my privilege to thank my brother Mr. Mukesh Bansal, Bhabhi Mrs. Anju Bansal, father-in-law Shri G.L. Gupta and mother-in-law Smt. Saroj Gupta for their moral support in completing this work.

I would like to record my special affection and thanks to my wife Neelam whose encouragement and moral support has been a source of inspiration to me. I also thank my son, master Aryan for having cheerfully sacrificing the time that rightfully belonged to him.

Finally a very much appreciation is extended to my parents, Shri Prahlad Bansal and Smt. Dulari Bansal, without their encouragement, patience and understanding this endeavour would not have been possible.

Date: 13|05|05

(Hari Om Bansal)

Dedicated to My Parents

ABSTRACT

In this thesis work an attempt has been made for voltage stability analysis of electric power distribution system. A new expression for voltage stability index (VSI) is derived to be computed for all nodes of the distribution networks. The node having the minimum value of VSI is the most sensitive node that is more prone to voltage collapse. The proposed method has also been compared with two methods available in literature. The proposed expression for VSI ensures that the most sensitive node is always the end node having the minimum voltage; a feature that is lacking in the other reported methods. The critical values of total real power load (TPL) and total reactive power load (TQL) are also computed by the proposed method and by the other two methods. The system will actually collapse beyond the computed values of TPL and TQL because the load flow based methods have a tendency to collapse before the exact critical values of TPL and TQL. The computed critical values of TPL and TQL by the proposed method are less compared to that of computed by the other two methods.

Next planning of power distribution system is proposed with the help of Genetic Algorithm (GA) using the proposed expression for VSI in fitness function to identify the optimum location for the substation. The load points are connected to substation in optimum route. The optimal branch conductors have been selected taking the proposed expression for VSI as one of the constraints. The proposed method has also been compared with classical techniques available in literature, to show its superiority. The critical values of TPL and TQL are computed for the network selected by utility, beyond which voltage collapse will occur.

Again planning of power distribution system is proposed with the help of Differential Evolution (DE) using the proposed expression for VSI in cost function to identify the optimum location for the substation. The load

points are connected to substation in optimum route. The optimal branch conductors have been selected taking the proposed expression for VSI as one of the constraints. The results computed by this method are compared with the results computed by using Genetic Algorithm (GA) to show its superiority. The critical values of TPL and TQL are computed for the network selected by utility, beyond which voltage collapse will occur.

Further planning of distribution system is proposed to identify the near optimum location for the substation when the exact optimum location for the substation cannot be taken due to social causes or due to geographical reasons and also to identify the location for the substation corresponding to minimum cost from given multiple locations for the substation. In both cases the load points are connected to substation in optimum route and the optimal branch conductors have been selected taking the proposed expression for VSI as one of the constraints. The critical values of TPL and TQL are also computed in both cases for the networks selected by utility, beyond which voltage collapse will occur.

Finally, the overall conclusions and future scope of further research work have also been discussed.

TABLE OF CONTENTS

Chapter Number **Title** **Page Number**

Chapter 1 **Introduction**

Chapter 2 **Literature Survey**

Chapter 3 **Voltage Stability Analysis**

Chapter 4 **Planning of Distribution System Using Genetic Algorithm with the Help of Voltage Stability Index (VSI)**

Chapter 5 **Planning of Distribution System Using Differential Evolution with the Help of Voltage Stability Index (VSI)**

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

bl1(jj) : Active Part of I(jj)

bl2(jj) : Reactive Part of I(jj)

C1 : Composite Cost of Losses (Rs per kW)

CC : Carrying Charge Rate (Feeders)

C(i,k) : Cost of Capital

cl1(m2) : Active Part of IL(m2)

cl2(m2) : Reactive Part of IL(m2)

D : Levelized Annual Demand Cost of Losses per kW

DVMAX : Difference of Maximum Voltages

E : Energy Cost of Losses (Rs/ kWh)

I(jj) : Current Through the Branch-jj

ic : The Node Count (Identifies the Number of Nodes beyond a Particular Branch)

IE(jj, ic + 1) : Receiving-end Node

IK(ic) : Node Identifier (helping to Identify Nodes beyond All the Branches)

IL(m2) : Load Current at Node m2

jj : Branch Number i.e., jj = 1,2,3,..........,LN1

L(i) : Length of Feeder Segment i

L(i,k) : Cost of Losses

L(m2) : Voltage Stability Index of Node m2

LN1 : Number of Branches i.e., LN1 = NB – 1

LP(jj) : Real Power Loss of Branch-jj

LQ(jj) : Reactive Power Loss of Branch-jj

LSF : Loss Factor

m1= IS(jj) : Sending-end Node of Branch-jj

m2 = IR(jj) : Receiving-end Node of Branch-jj

NB : Number of Nodes i.e., i = 1,2,3,.........,NB

NTYPE : Total Number of Conductors

P (i) : Power Flow Through Segment i (kVA)

PL(m2) : Active Power Load at Node m2

PP(k) : Purchase Price of Conductor k (Rs/ Unit length)

QL(m2) : Reactive Power Load at Node m2

R(jj) : Resistance of the Branch-jj

R(k) : Per Unit Resistances

TPL : Total Real Power Load

TQL : Total Reactive Power Load

V(m1) : Voltage of Sending-end Node of Branch-jj

V(m2) : Voltage of Receiving-end Node of Branch-jj

VV(m2) : Magnitude of Voltage at Node m2

VSI : Voltage Stability Index

X(jj) : Reactance of the Branch-jj

Z(jj) : Impedance of the Branch-jj

CHAPTER 1

INTRODUCTION

1.1 Introduction

Energy is the basic necessity for the economic development of a country. There is a close relationship between the energy used per person and his standard of living. The greater the per capita consumption of energy in a country, the higher is the standard of living of her people. Energy may be needed as heat, as light, as native power etc. Electrical energy is superior to all other forms of energy in respect of its (i) convenient form, (ii) easy control, (iii) greater flexibility, (iv) cheapness, (v) cleanliness and (vi) high transmission efficiency.

Electric utilities in India are facing the pressure to reduce costs against a requirement of better quality and reliability of supply. Though generation and transmission systems have seen considerable technical development and capital investment, distribution systems have generally been neglected.

Although power generation, transmission and distribution are in the process of being unbundled, there still exists common interest for the concerned companies. After satisfactory generation and transmission of power to substation, distribution of power to consumer should be carried out satisfactorily. Therefore, distribution networks need to be utilized more efficiently. In general, these constitute the part of power system that distributes power to the consumers for utilization.

The transmission and distribution systems are similar to circulatory system of a human body. The transmission system may be compared with arteries in the human body and distribution system with its capillaries. They serve the same purpose of supplying the ultimate consumer in the city with the life-giving blood of civilization called electricity. More precisely, distribution system is the electrical system between the substation fed by the transmission system and the consumer meters. Broadly, it consists of feeders, distributors and the service mains. Figure 1.1 shows the typical components of a distribution system.

Electrical energy is generated, transmitted and distributed in the form of alternating current. One important reason for the widespread use of alternating current in preference to direct current is the fact that alternating voltage can be conveniently changed in magnitude by means of a transformer. Transformer has made it possible to transmit ac power at high voltage and utilize it at a safe potential. High transmission and distribution voltages have greatly reduced the current in the conductors and hence line losses.

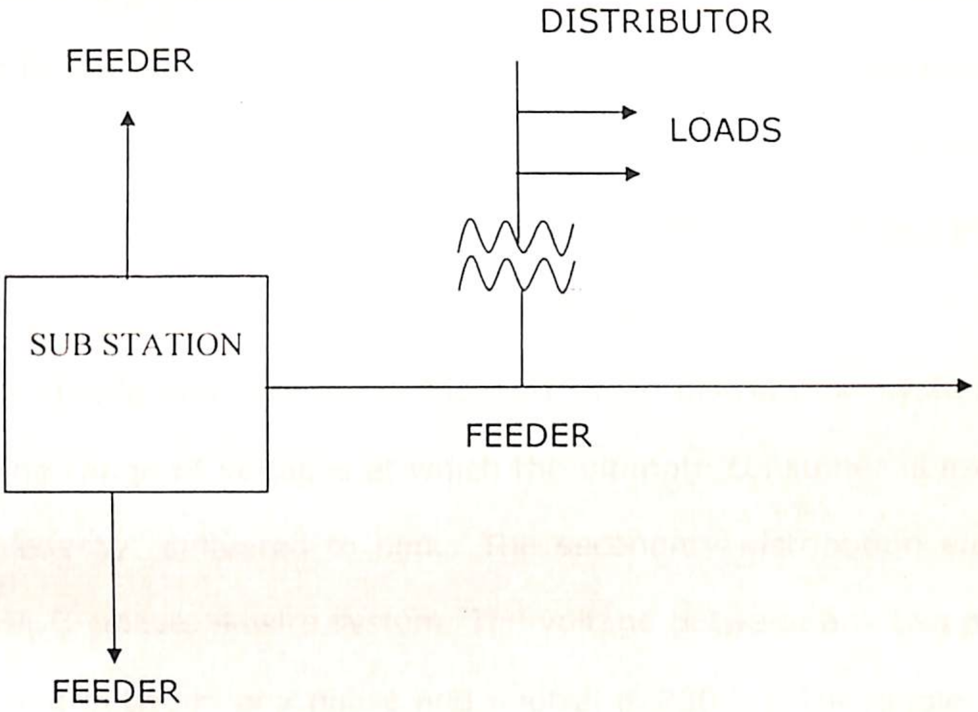


Figure 1.1 Typical Components of a Distribution System

The ac distribution system is classified into (i) primary distribution system and (ii) secondary distribution system.

Primary distribution system is part of ac distribution system that operates at voltages somewhat higher than general utilization, and handles larger blocks of electrical energy than what the average low-voltage consumer uses. The voltage used for primary distribution depends upon the amount of power to be conveyed and the required distance of the sub-station to be fed. In India, the most commonly used primary distribution voltages are 11 kV, 6.6 kV and 2.2 kV. Due to economic reasons, primary distribution is carried out by 3-phase, 3-wire system.

Secondary distribution system is the part of ac distribution system that includes the range of voltages at which the ultimate consumer utilizes the electrical energy, delivered to him. The secondary distribution employs 400/230 V, 3-phase, 4-wire system. The voltage between any two phases is 400 V and between any phase and neutral is 230 V. The single-phase domestic loads are connected between any one phase and the neutral whereas 3-phase 400 V motor loads are connected across 3-phase lines directly. All distribution of electrical energy is done by constant voltage system. In practice, the distribution circuits are radial in nature.

The following are the main requirements of a distribution system:

(i) **Proper Voltage:** One important requirement of a distribution system is that voltage variations at consumer terminals should be as low as possible. The changes in voltage are generally caused due to the variation of load on the system. Low voltage occurs due to the variation of load on the system that causes loss of revenue, inefficient lighting and possible burn out of motors. High voltage causes lamps to burn out permanently and may cause failure of other appliances. Therefore, a good distribution system must ensure that the voltage variations at consumer terminals are within permissible limits. The acceptable limit of voltage variations is ±6% of the rated value at the consumer terminals. Thus if the rated voltage is 230 V, then the highest voltage to the consumers should not exceed 244 V while the lowest voltage should not be less than 216 V.

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

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

Good voltage regulation is probably the most important factor and responsible for delivering good service to the consumers. For this purpose, design of feeders and distributors requires careful consideration.

(i) **Feeders:** A feeder is designed from the point of view of its current carrying capacity while the voltage drop consideration is relatively unimportant. It is because voltage drop in a feeder can be compensated by means of voltage regulation equipment at the sub-station.

(ii) **Distributors:** A distributor is designed from the point of view of the voltage drop in it. It is because a distributor supplies power to the consumers and there is an acceptable limit of voltage variation at the consumer terminals that is $\pm 6\%$ of rated value. The size and length of the distributor should be such that voltage at the consumer terminals must be within the permissible limits.

Generated electricity first goes to a transformer at the power plant that boosts high voltage up to 400 kV for transmission through extra-high voltage (EHV) lines. When electricity travels long distances, it is better to have it at higher voltages since the electricity can be transferred more efficiently at high voltages. High voltage transmission lines carry electricity long distances to a substation. At transmission substations a reduction in voltage occurs for distribution to other points in the system through high voltage (HV) transmission lines. Further voltage reductions for commercial and residential customers take place at distribution substations that connect to the primary distribution network.

Utility transmission and distribution systems link electric generators with end users through a network of power lines and associated components. In India, typically the transmission system is designed for 33 kV and above, while the distribution portion operates between 11 kV and 400 V. Industrial and commercial customers with large power demands often receive service directly from the primary distribution system.

Transformers are crucial components of the electric power distribution system. Utility transformers are high voltage distribution transformers typically used by utilities to step down the voltage of electricity going into their customer buildings. Distribution transformers are one of the most widely used elements in the electric distribution system. They convert electricity from the high voltage levels in utility transmission systems to voltages that can safely be used in businesses and homes. Distribution transformers are either mounted on overhead poles or on concrete pads.

The power distribution systems must provide supply to the consumers without interruption. The modern power distribution network is constantly being faced with an ever-growing load demand. Distribution networks experience distinct change of load from a lower to higher level everyday, and may experience voltage collapse above certain critical loading conditions.

1.2 Voltage Collapse

Voltage collapse problems have become a point of concern for many researchers. Voltage collapse is a local phenomenon that may have consequent serious fallouts. Future increase in the demand for electric power has been projected to far exceed the planned generation of existing power system in the coming decades. This has led to increasingly complex interconnected systems that are forced to operate ever closer to the limits of stability. This operation has necessitated close examination of dynamic stability assessment capabilities of power systems. Many new types of instabilities are beginning to afflict the operating status of critically balanced system. The instability may be manifested in different ways, depending upon the character and configuration of the system and upon its operating mode. Of these, voltage instability has been responsible for collapse of several major networks. Voltage stability studies of a power distribution system are consequently essential.

A blackout is a condition where a major portion or all of an electrical network is de-energized with much of the system tied together through closed breakers. Any sub network whose tie-lines to the high voltage grid cannot support reasonable contingencies is the possible candidate for a blackout. System separations are possible at all load levels and all times in the year. Changing generation patterns, scheduled transmission outages, and rapid weather changes among other reasons can lead to blackouts. Separations due to dynamic instability are typically initiated by multiple contingencies such as loss of corridors, transmission circuits, generating units, or delayed fault clearing. The system just prior to a blackout may not be dynamically unstable, though overloaded condition may initiate collapse. When an overloaded facility trips, other facilities will increase their loadings and may approach their thermal capabilities or relay trip settings. On August 14, 2003, parts of the Northeastern United States and Southeastern Canada experienced widespread power blackouts. The provinces of United States New York, New Jersey, Vermont, Michigan, Ohio, Pennsylvania, Connecticut, and Massachusetts were affected.

Among the major urban agglomerations touched by the electrical power outage in the United States were the cities of New York, Albany, Buffalo in New York, Cleveland and Columbus in Ohio, and Detroit. Ottawa and Toronto in Canada were also affected.

Previous incidents include the November 9, 1965 outage caused by a faulty relay at a power plant in Ontario, and which affected a large portion of land stretching from Toronto to New York. Another one followed on July 14, 1977, as a result of a lightning strike that affected New York City. The power supply in nine western US states were also affected in August 1996 as a result of a high demand for electricity, a heat wave and sagging electrical power lines.

Improving the performance of distribution systems to meet required target is a matter of selecting the most cost-effective technologies and operating practices. The distribution systems tend to be very extensive with a long life span for conductors and plant. It is not sufficient to analyze how a particular portion of the network may be modified to improve its performance on date. It is a matter of determining the expected optimum solution when allowance is made for the uncertainties in the prediction of the future scenario of customer demand. It is valuable to investigate long-term solutions especially so when the implementation of the solutions may require large-scale investments. Arising from these issues, the realization by the utilities and the increasing reliance on having accurate up-to-date information for decisions on increasing revenues, improving customer service must be set up. No doubt, the vast field and organizational experience of the power utilities will continue to provide the required inputs into the total process.

Since the distribution network of a power utility has a geographical reference, it will be beneficial to create the network also on the computer in a geographical context. This will provide useful reference for setting up of new facilities, provide necessary information on land use pattern for planning optimum expansion of network and enable more systematic network operation and maintenance.

However, monitoring of the distribution system in real time, and also introduction of a certain measure of automation into the distribution system will mean investments Supervisory Control and Data Acquisition system (SCADA). Integration of the network mapping and the network analysis software with SCADA will prove to be a tool of immense benefit to the power distribution system utility in improving the operating efficiency and consequent customer satisfaction.

Medium and long-term plans would introduce higher levels of automation and remote-monitoring systems, as by then the utility could have started to benefit from the short-term plans in controlling the energy losses and increasing revenues. Gradual introduction of electronic energy meters to replace the outdated electro-mechanical energy meters will be inevitable, as then it would permit monitoring. Installation of computerized customer billing, payment collection, customer complaint registering system and continuous loss monitoring are the key to efficient and financially strong utility.

The above approach is by no means sufficient to eliminate the commercial losses totally. As long as the energy consumed is not being charged to the consumer in accordance with the actual cost of energy being delivered, the losses will remain. Issues of tariff cross-subsidization and rationalization of the tariff, legislative and legal issues and issues relating to the surveillance and vigilance for revenue protection still remain inadequately addressed.

Voltage stability can be a major factor in planning and operations of power distribution systems. It is well known that voltage collapse has led to major system failures. With the development of power markets, more and more electric utilities are facing voltage stability-imposed limits. The most sensitive node of any distribution network must be identified and the critical loading of the network must be computed, beyond which voltage collapse will occur.

1.3 Objectives of the Research

The research endeavours to derive a new expression of voltage stability index (VSI) and its applications in planning of power distribution system. The objectives are divided into the following:

- To derive a new expression of VSI to be computed for all nodes of the distribution networks.
- To identify the most sensitive nodes of the distribution networks.
- To compute the critical values of total real power load (TPL) and total reactive power load (TQL) of the system.
- To identify the optimum location for the substation using Genetic Algorithm (GA) with the help of the proposed expression for VSI and to develop the planning and to compute the critical values of TPL and TQL of the system selected by utility.
- To identify the optimum location for the substation using Differential Evolution (DE) with the help of the proposed expression for VSI and to develop the planning and to compute the critical values of TPL and TQL of the system selected by utility.
- To identify the near optimum location for the substation and also to select the location for the substation from given multiple locations for the substation corresponding to minimum cost and to compute the critical values of TPL and TQL of the system selected by utility.

1.4 Scope of the Research

Jasmon and Lee (1991a) while deriving the expression for VSI had reduced the whole network into its single line equivalent that is valid at the operating point and put the voltage magnitude 1.0 p.u. for all nodes that led wrong results. Ranjan *et al.* (2004a) while deriving the expression for VSI had reduced the whole network into its single line equivalent indirectly at the operating point and assumed the magnitude of sending-end voltage of each branch is equal to that of the magnitude of receiving-end voltage that led wrong results.

Ranjan *et al.* (2002) used the classical technique by incorporating R and X in the method proposed by Hsu and Chen (1990) to identify the optimum location for the substation. Since they did not provide the co-ordinate of the substation, the author has recalculated their work. Since exact location of the substation can only reduce the planning cost and loss, the Genetic Algorithm and Differential Evolution can be used to identify the optimum location for the substation. Till date no attempt has been made to identify the optimum location for the substation with the help of VSI using evolutionary computing like Genetic Algorithm and Differential Evolution. Identification of the optimum location for the substation is carried out by the Genetic Algorithm and Differential Evolution with the help of the proposed VSI. The following are the scope of research:

A new expression for VSI is derived for electric power distribution networks to be computed for all nodes. With the help of derived expression for VSI the most sensitive nodes of the networks are identified. The critical values of TPL and TQL are also computed. Planning of distribution system is proposed using Genetic Algorithm with the help of the proposed expression for VSI to identify the optimum location for the substation. The load points are connected in optimum route and optimal branch conductors are selected taking the proposed expression for VSI as one of the constraints. The critical values of TPL and TQL of the network selected by utility have also been computed, beyond which voltage collapse will occur. Planning of distribution system is again proposed using Differential Evolution with the help of the proposed expression for VSI to identify the optimum location for the substation. Once again, the load points are connected in optimum route and the optimal branch conductors are selected taking the proposed expression for VSI as one of the constraints. The critical values of TPL and TQL of the network selected by utility have also been computed, beyond which voltage collapse will occur. Planning of distribution systems is also proposed to identify the near optimum location for the substation and to select the location for the substation corresponding to minimum cost from given multiple locations for substation. The load points are connected in optimum route and the optimal branch conductors are selected taking the proposed expression for

VSI as one of the constraints. The critical values of TPL and TQL of the network selected by utility have also been computed, beyond which voltage collapse will occur.

1.5 Organization of the Research

Chapter 1 has presented the introduction of distribution system, voltage collapse, objectives of the research, scope of the research and organization of the research.

Chapter 2 presents the comprehensive literature survey on load flow, voltage stability and planning of power distribution system.

Chapter 3 presents a new expression of VSI to be computed for all nodes of the distribution networks. The node having minimum value of voltage stability index is the most sensitive node that is more prone to voltage collapse compared to other nodes due to change of its load. Three different types of radial distribution networks have been selected. The most sensitive node and its value of VSI obtained by the proposed method and by the methods of Jasmon and Lee (1991a) and Ranjan *et al.* (2004a) have been compared. The most sensitive node is the end node having the minimum voltage in all the three cases using the proposed method only whereas other two methods are unable to assure it. The critical values of TPL and TQL have been computed by the proposed method and by the methods of Jasmon and Lee (1991a) and Ranjan *et al.* (2004a) and these values have been compared. The comparison shows that the critical values of TPL and TQL computed by the proposed method are less compared to the other two methods.

Chapter 4 presents a method for planning of power distribution system using Genetic Algorithm with the help of the expression of VSI proposed in Chapter 3. In the present chapter the following have been carried out:

(i) Identification of the optimum location for the substation using Genetic Algorithm with the help of the proposed expression for VSI as one of the constraints,

(ii) connection of load points in optimum route using knowledge-based expert systems proposed by Chen and Hsu (1989) and Hsu and Chen (1990),

(iii) selection of optimal branch conductors using the method proposed by Tram and Wall (1988) incorporating the proposed expression of VSI as one of the constraints and

(iv) identification of the most sensitive node of the network using the proposed expression for VSI.

The effectiveness of the proposed method is demonstrated by comparing it with the method developed by Ranjan *et al.* (2002). The critical values of TPL and TQL of the network selected by utility have also been computed. The cost and loss depends on location of the substation and selection of optimal branch conductors. If alternate algorithms are used for connection of load points in optimum route and selection of optimal branch conductors, the results may be different.

Chapter 5 presents a method for planning of power distribution system using Differential Evolution with the help of the expression of VSI proposed in Chapter 3. In the present chapter the following have been carried out:

(i) Identification of the optimum location for the substation using Differential Evolution with the help of the proposed expression for VSI as one of the constraints,

(ii) connection of load points in optimum route using knowledge-based expert systems proposed by Chen and Hsu (1989) and Hsu and Chen (1990),

(iii) selection of optimal branch conductors using the method proposed by Tram and Wall (1988) incorporating the proposed expression for VSI as one of the constraints and

(iv) identification of the most sensitive node of the network using the proposed expression for VSI.

The effectiveness of the proposed method is demonstrated by comparing it with the method proposed in Chapter 4 using Genetic Algorithm. The critical values of TPL and TQL of the network selected by utility have also been computed. The cost and loss depends on location of the substation and selection of optimal branch conductors. If alternate algorithms are used for connection of load points in optimum route and selection of optimal branch conductors, the results may be different.

Chapter 6 deals with two cases. The first one is to identify the near optimum location for the substation when the exact optimum location is inaccessible due to geographical and social causes. The second one is to select the location for the substation from the given multiple locations for the substation. In both cases, the load points are connected to substation in optimum route and optimal branch conductors have been selected incorporating the proposed expression for VSI as one of the constraints. The most sensitive nodes in both cases are identified. The critical values of TPL and TQL of the network selected by utility have also been computed. The cost and loss depends on the substation location and selection of optimal branch conductors. If alternate algorithms are used for connection of load points in optimum route and selection of optimal branch conductors, the results may be different.

Chapter 7 discusses the overall conclusions and future scope of further research work in electric power distribution systems.

References present the list of previous papers published by researchers in load flow, voltage stability analysis 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 17 node radial distribution network.

Appendix – B shows the line data and load data of 29 node radial distribution network.

Appendix – C shows the line data and load data of 33 node radial distribution network available in Baran and Wu (1989a).

Appendix – D shows the data for conductors available in Ranjan *et al.* (2003).

Appendix – E shows the co-ordinate and load kVA of each of 53 load points available in Ranjan *et al.* (2002).

Appendix – F shows the co-ordinate and load kVA of each of 16 load points.

Appendix – G shows the co-ordinate and load kVA of each of 28 load points.

CHAPTER 2

LITERATURE SURVEY

2.1 Literature Survey of Electric Power Distribution System

Literature survey of electric power distribution system shows progressive work in the following areas:

(i) Load flow of power distribution system,

(ii) Network reconfiguration of power distribution system,

(iii) Optimal planning of power distribution system,

(iv) Reactive power compensation of power distribution system,

(v) Calculation of feeder losses and transformer capacity of power distribution system and

(vi) Voltage stability analysis of power distribution system.

Exhaustive literature survey on load flow, voltage stability analysis and planning of power distribution system is presented below.

2.2 Survey on Load Flow of Power Distribution System

A suitable load flow is required for all the selected works in this thesis. The load flow of distribution system is different from that of transmission system because it is radial in nature and has high R/X ratio. Convergence of load flow is utmost important. Literature survey shows that the following works have been carried out on load flow studies of electric power distribution systems.

Using ladder network theory, Kersting and Mendive (1976) and Kersting (1984) developed a load flow technique for solving radial distribution networks that updates voltages and currents during the backward and forward sweeps. Stevens *et al.* (1986) had shown that the technique developed by Kersting and Mendive (1976) and Kersting (1984) was found to be fastest but did not converge in five out of twelve cases studied. Shirmohammadi *et al.* (1988) presented a method for solving radial distribution networks based on the direct voltage application of Kirchhoff's laws. They also proposed a branch-numbering scheme to enhance the numerical performance of the solution method and also extended their method for solving the weakly meshed distribution networks. Baran and Wu (1989) obtained the load flow solution of radial distribution networks by iterative solution of three fundamental equations representing the real power, reactive power and voltage magnitude. Chiang (1991) proposed three different algorithms for solving radial distribution networks based on the method of Baran and Wu (1989). Renato (1990) proposed one method for obtaining load flow solution of radial distribution networks. He calculated 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, receiving - end voltage of each the node was computed. Goswami and Basu (1991) presented an approximate method for solving radial and meshed distribution networks. The prime limitation of their method was that any node in the network was not the junction of more than three branches i.e., one incoming and two outgoing. Jasmon and Lee (1991) proposed a new load flow method for obtaining the load flow solution of radial distribution networks. They used the three fundamental equations representing the real power, reactive power and voltage magnitude that had been proposed, by Baran and Wu (1989). Das *et al.* (1995) proposed a load flow method using power convergence. Ghosh and Das (1999) proposed a load flow method for solving radial distribution networks based on the technique nodes beyond branches. They used voltage convergence and provided the proof of convergence and proposed an algorithm to identify the nodes beyond each branch that is very efficient. Ranjan *et al.* (2004) proposed a new load flow technique using power convergence characteristic. They claimed that their algorithm can easily accommodate the composite load modelling if the composition of load is known. They also claimed that this algorithm has good convergence property for practical radial distribution networks without giving any proof in support of the power convergence.

2.3 Survey on Voltage Stability Analysis of Power Distribution System

Engineers have long been struggling with developing voltage stability criteria for their systems shown by Taylor (1994). Sole reliance on either P–V or V–Q analysis is not sufficient to assess voltage stability and proximity to voltage collapse. Each analysis is needed to confirm the results of the other (i.e., P–V analysis is needed to confirm the results of V–Q analysis and vice versa). Member systems may use either method for general voltage stability evaluation, contingency screening etc. But voltage stability margins must be demonstrated by both P–V and V–Q analysis.

In addition to P–V and V–Q analysis, full long–term dynamic simulation, fast dynamic simulation by Custem *et al.* (1997), nodal analysis by Gao *et al.* (1992), Kundur (1994) and security-constrained optimal power flow analysis by Merrit *et al.* (1988) are valuable tools for providing insights into the voltage instability and collapse phenomenon.

Literature survey shows that a few works have been done on voltage stability analysis of power distribution system. Ajjarapu *et al.* (1992) presented the earlier works on voltage stability analysis of transmission system. Brownell *et al.* (1989) provided the recordings of increased load demand of a system and showed its voltage collapse. They also proposed urgent compensation of reactive power. Jasmon and Lee (1991a) proposed a voltage stability analysis of radial distribution networks. They reduced the whole network by its single line diagram that is valid only at the derived operating point. They had put voltages of all nodes equal to 1.0 p.u. to simplify the derivation of voltage stability index. This method is unable to handle changing load pattern. Using Thevenin's theorem, Chebbo *et al.* (1992) suggested a method to study the voltage collapse. Rahman *et al.* (1995) proposed a method to study the voltage collapse using Thevenin's theorem. They suggested a voltage stability index. Gubina *et al.* (1997) proposed a method to study voltage stability analysis of radial distribution networks reducing the system model to its single line equivalent. Chakravorty *et al.* (2001) proposed a voltage stability index to identify the most sensitive node of the network. They handled the composite load using power convergence and used the load flow technique proposed by Das *et al.* (1995). The stability index proposed by them is similar to the index proposed by Rahman *et al.* (1995). Ranjan *et al.* (2004a) suggested a new voltage stability index to identify the most sensitive node of the network. They used the load flow proposed by Das *et al.* (1995) for satisfactory convergence of composite load modelling and considered the voltage convergence in load flow. They assumed the equality of magnitude of voltage for sending-end node and receiving-end node of each branch while deriving voltage stability index. They had also assumed that the load at any node was the sum of the loads of all nodes following it. Ranjan *et al.* (2004a) did not use the load flow proposed by Ranjan *et al.* (2004). Ranjan *et al.* (2004) had claimed that power convergence gave the satisfactory convergence for composite load modelling. Ranjan *et al.* (2004a) had shown that the constant power load model system collapsed for less load compared to the constant current and constant voltage load model.

2.4 Survey on Planning of Power Distribution System

Power distribution planning is a complex task in which planners must ensure that there is adequate substation capacity (transformer capacity) and feeder capacity (distribution capacity) to meet the load demands. Decisions such as allocation of power flow, installation of feeders and substations, and procurement of transformers are expensive and should be evaluated carefully.

The cost of power distribution constitutes a significant portion of the overall cost. Gonen (1986) proposed a systematic approach to distribution planning to substantially decrease the amount of cost incurred.

Ponnavaikko and Rao (1981) optimized the configuration of each individual feeder by deciding on the length, conductor size, and gradation, and by addressing the economic, tradeoff between capital and operating costs. Mikic (1986) provided further details of the cost tradeoff.

Adams and Laughton (1974) was one of the earlier works and developed the above formulation. There were two cost components; the fixed cost and the variable cost of power flow for a particular connection.

Using the transportations model framework, Crawford and Holt (1975) provided a procedure, based on analysis of loads and feeders on a grid basis, to determine the optimal substation service boundary.

Masud (1974) proposed a two-phase method for power distribution planning. The first phase determined the substation decisions, with consideration on re-distribution of load. The second phase used a transportation model, with substation capacity from the first phase, to determine the optimal power flow for the feeders.

Fawzi *et al.* (1983) adopted a similar model while incorporating non-linear variable power cost and voltage drop. A branch and bound algorithm was used to first decide on the substations (with approximate feeders' considerations). This solution then became part of an iterative procedure to determine the optimal feeders' configuration.

Hindi and Brameller (1977) also provided detailed discussions on the dynamics of the power flow along with some computational experience.

Thompson and Wall (1981) presented a branch-and-bound algorithm for this problem. Two major bounding criteria of the algorithm were: (i) minimum incremental cost bound, and (ii) shortest path customer assignment. The former assumed the fixed costs of all potential substations to be zeros and the power flow problem was solved thus giving the lowest incremental cost of power flow. This incremental cost plus the actual fixed cost of the potential substation provided a lower bound cost.

Willis and Northcote-Green (1985) tested the efficiency of some of the above models based on their (i) overall benefit to planning, (ii) capacity to handle large program analysis, (iii) sensitivity to load forecasting error, and (iv) actual level of improvement. Four sets of simulated tests were used. For overall benefit and error sensitivity, the substation feeder models were found to be more superior.

Gonen and Foote (1981) obtained substation locations, substation transformer sizes, additions of incremental capacity, load transfers, and feeder routes and sizes. Detailed procedure on the linearization of the variable concave cost function, using continuous variables, was also included. There were a large number of logical constraints.

Sun *et al.* (1982) utilized the fixed-charge-transshipment framework of earlier single-period models to develop a procedure to solve the multi-period distribution problem. Their procedure consisted of two phases. The first phase was essentially a static base problem where decisions for substations and flows were first determined. Based on this initial configuration, new inputs (growth and new demand locations) for the next period were incorporated to determine the optimal installation and flow of that period. In turn, the base configuration plus the added configuration then became the basis for the following year's decision and so on until the end of the planning horizon. This procedure would not guarantee on overall optimal solution since current decisions were not related to future ones.

El-Kady (1984) explicitly included time-dependent fixed and variable charges as well as time-dependent cost of losses. Relationships of future-installations were modeled using variables of fixed installation costs incurred only once, while variable costs would be accounted for throughout the equipment's life. Additionally, voltage drop in feeders were characterized as a stepwise functions of power flow. The overall problem was partitioned into smaller problems where the problem size became more manageable.

Gonen and Ramirez-Rosado (1986) pursued the model framework of Gonen and Foote (1981) and provided more explicit considerations. Notable additions such as value of fixed and variable costs and the explicit modelling of voltage drop and radiality constraints were present.

Ramirez-Rosado and Gonen (1991) adopted the two-phase approach of Sun *et al.* (1982) while incorporating more planning details.

The two-phase approach of Sun *et al.* (1982) and the pseudodynamic planning approach of Ramirez-Rosado and Gonen (1991) are both simplifying approaches to reduce the dynamic problem into a static one, thus allowing the problems to be solved more efficiently at the expense of getting an optimal solution.

Aoki *et al.* (1990) proposed "branch-exchange" algorithm for an approximate optimal solution for single-period distribution planning. It worked as follows:

- Start with a feasible configuration; add a route to form a loop.
- Then, to gain feasibility, a route (with either high installation cost or constraint violation) is an improvement, retain the exchange; otherwise, abandon the exchange.
- Repeat this procedure iteratively until the objective function cannot be improved any further.

The determination of the most sensitive exchange was selected from the information provided by the simplex tableau.

Nara *et al.* (1991) extended the single-period branch-exchange approximation algorithm of Aoki *et al.* (1990) to a multi period approximation algorithm. The algorithm worked as follows:

- **Forward Path:** At period t, using the branch-exchange method, the approximate optimal expansion plan for t = t + 1 was determined. This one-period expansion plan determination was termed the "Forward Path".
- **Backward Path:** Unlike the two-phase method that proceeds period-by-period into the future, the proposed algorithm would do a

"Backward path" after each "Forward Path". The "Backward Path" was to return to the proceeding period to see if the expansion plan P_0, found up to that period, was indeed the best that could be achieved via branch-exchange. This was done by removing, one preceding period at a time, the period's facility that were not utilized and by performing branch-exchange on the resulting configuration.

- **Backward/ Forward Path:** If at any period, the plan forming "Backward Path" was not an improvement, the backward process would stop and the forward process would resume with the previous "Forward Path" plan starting period (resulting in a plan P_1), then the algorithm would restart at $t = 1$ with the new period-1 plan as the basis for the next "Forward Path" , the subsequently, developed plan P_2 would be compared to the previously determined backward plan P_1, with the better plan to replace P_0 for the next "Forward Path" at $t = t + 2$.

Further extending on their previous work, Nara *et al.* (1992) provided a "multi-stage" branch-exchange algorithm. Basically, the proposed algorithm attempted to move away from the local optimum found by the single-stage model by forcing further branch-exchanges with more refined branch selection criteria. Although termed "multi-stage" the algorithm did not address any time-dynamic issues; it was multi-stage in the sense that several series of branch-exchange were pursued.

Quintana *et al.* (1993) divided the planning problem into two stages such as clustering and forecasting, and planning. In stage 1, the problem of load growth was solved in two phases. The first phase divided the service area into smaller sub areas with the demand points in each sub area summed to form a single demand node, the second phase assessed the demand forecast per demand node. In stage 2, the planning problem was to determine the overall installations required (without knowing when to install) by solving the problem of meeting projected demand at the horizon year. In the second phase, for each intermediate year between the base and the horizon year, was to determine an optimal intermediate system using only the equipment set from the static optimum problem. This optimization model of the sub-problem was constrained non-linear formulation and was solved using non-linear optimization software.

Development of expert systems for distribution planning had been reported based on PROLOG, an artificial-intelligent programming language. Wong and Cheung (1987) listed several AI/expert systems for various power-system applications. They presented a set theory based formulation for load allocation in distribution substation. The system first generates all hypothetical solutions.

Chen and Hsu (1989) developed a rule-based system for the load re-allocation in the case of distribution expansion planning. The authors proposed two algorithms, one to minimize power loss and the other to minimize investment cost. These algorithms formed the basis for the inference engine. The system was implemented on a PC using PROLOG language. The heuristic rules used by the planners were also incorporated in the expert system. The software was also able to compute the system reliability of developed plan. The system was used to assist the planners in the expansion of a three station, twenty-eight feeder networks.

Hsu and Chen (1990) later designed an expert system for determining substation locations and feeder configuration of a distribution system. The substation locations were determined using an operations research based "location-allocation method". The method was used to minimize the feeder losses and support the inference engine.

Braunder and Zobel (1994) divided computer based engineering methods developed over the last three decades in three phases. They characterized the knowledge-based methods as the beginning of the third phase. These methods complement the pure algorithmic methods without being part of the algorithm. The knowledge-based systems provide the flexibility needed for analyzing today's complex distribution networks. They also discussed architecture and components of a knowledge-based programming system. The above model would be repeated for each substation in the service area for existing of unsatisfied load. Leung and Khator (1995) also provided a load reallocation model (additionally expressing the substation-load assignment as transportations type demand-supply constraints set) that sought to re-allocate unsatisfied load under the single-contingency environment.

Under the single-contingency scenario, Sarada *et al.* (1995) proposed a method that could prescribe the least cost feeder expansion plan. The model determined the installation schedule as well as sites of new feeders, while concurrently determined the optional load reallocation to meet load demand.

An approximate algorithm for loss minimum load allocation was developed by Aoki *et al.* (1987) that was extended by Aoki *et al.* (1988), further refining their work, proposed the following algorithm that quickly restored the emergency load in a distribution system.

Aoki *et al.* (1989) proposed a procedure of deciding the open locations of switches in order to achieve load balancing of transformers and feeders while subject to their capacity limits. The procedure identified rules to systematically balance two transformers at a time until approximate balance was achieved to all transformers.

Civanlar *et al.* (1988) presented a scheme, with a simple formula, for determining the open/ closed states of the tie and sectionalizing switches to reduce power losses in distribution feeders via feeder reconfiguration.

Extending the work of Civanlar *et al.* (1988), Baran and Wu (1989) developed two different methods to assess power flow after a load transfer was made. The two methods were based on a set of recursive equations that described power flow. Both loss reduction and load balance were estimated.

Hsu and Jwo-Hwu (1993) incorporated the issue of the protective device-coordination in a feeder reconfiguration algorithm. The algorithm first identified a set of regions in which switch operations were allowed. The protective devices were designed such that proper co-ordination could be attained during load balancing and load reduction where switches were assessed on/off states.

Nara *et al.* (1994) provided a multi-year expansion having similar with the models as Nara *et al.* (1991).

Glamocanin (1990) proposed a method for obtaining optimal location and sizing of substations and network routing for an urban distribution system. The algorithm that they had developed was based on the requirement that each load point should be supplied by at least two feeding points either from the same substation or from other substation. The main limitation of their work was that they had considered the uniform cable size of the feeder segments.

Yeh *et al.* (1996) proposed a new problem solving environment utilizing different form of resources to approach better substations in the distribution planning domain. They used algorithm for the optimal solutions and this had been demonstrated through an example of street lighting design.

Hongewi *et al.* (1997) described a method to solve the optimal planning problem of distribution substations automatically selecting the location, size and service area of the distribution substation.

Nahman *et al.* (1996) suggested a method for selection of main initial parameters and timing of reconstructions of rural distribution networks in long term planning to meet the increasing load demands with minimum total worth cost. Their model incorporated capital and exploitation costs as well as the costs due to undelivered energy and load curtailments.

Goswami (1997) proposed an algorithm for planning of radial system based on the branch exchange technique. He applied the branch exchange between the elements of the networks under adjacent substations. A complete power flow was required after each branch exchange. This model is suitable for small systems.

Singh *et al.* (1998) proposed a model for optimal sizing and locating distribution substations and feeders in a time dynamic power distribution systems. Their model captured the non--linear costs due to power flow and the effects of harmonics. They used the Bender's decomposition technique as a solution methodology.

Ranjan *et al.* (2002) suggested three new techniques for radial distribution system planning that they claimed their own contributions. They proposed (i) optimum location of substation, (ii) connection of load points to substation in optimum route and (iii) optimal branch conductor selection. Ranjan *et al.* (2002) modified the method proposed by Hsu and Chen (1990) by incorporating R and X of each branch to obtain the optimum location of substation that did not give any appreciable improvement. The second and third methods proposed by Ranjan *et al.* (2002) were already proposed by Chen and Hsu (1989), Hsu and Chen (1990) and Tran and Wall (1988) respectively. Moreover, Ranjan *et al.* (2002) did not provide the co-ordinate of substation. They modified the convergence criteria of load flow algorithm proposed by Das *et al.* (1995) using voltage convergence instead of power convergence to incorporate composite load model. Ranjan *et al.* (2002) claimed that only voltage convergence gave the convergence for composite load model.

The following contradictory statements exist in literature:

Chakravorty and Das (2001) used power convergence to incorporate composite load models. They also claimed that power convergence gave the satisfactory convergence for composite load model. Ranjan *et al.* (2004) and Chakraborty and Das (2001) claimed that power convergence gave the satisfactory convergence of load flow for composite load model. Das *et al.* (1995) claimed that power convergence gave satisfactory convergence for load flow. Ghosh and Das (1999) proved that voltage convergence only gave the satisfactory convergence of load flow for any type of load modeling with proof of convergence. Ranjan *et al.* (2002, 2004a) admitted that voltage convergence gave the convergence of load flow for composite load model.

2.5 Previous Published Method/ Data Used

In the present thesis work, author has used the following data/methods from the previous research work:

(a) Load flow algorithm and IDENT software proposed by Ghosh and Das (1999),

(b) Heuristic rules for planning of substation proposed by Hsu and Chen (1990),

(c) Method for selection of optimal branch conductor proposed by Tram and Wall (1988),

(d) Connection of load points in optimum route proposed by Chan and Hsu (1989),

(e) Line data and load data of 33 node radial distribution network proposed by Baran and Wu (1989a),

(f) Data of conductors proposed by Ranjan *et al.* (2003) and

(g) Co-ordinate and load kVA of each of 53 load points proposed by Ranjan *et al.* (2002).

CHAPTER 3

VOLTAGE STABILITY ANALYSIS

3.1 Introduction

Voltage stability is a property of power distribution system that enables it to stay in a state of equilibrium voltage under normal operating condition and the system also returns to an acceptable state of equilibrium voltage after a disturbance. If the power consumption from the system goes beyond its capability, a sequence of events accompanying voltage instability results in a low acceptable voltage profile of the distribution networks. Unlike a transmission system, the distribution system is radial in nature. The distribution networks have high R/X ratio compared to the transmission networks, and hence are ill-conditioned in nature. The voltage stability index of distribution systems is usually different from that of transmission systems because the latter have $X>>R$. During derivation of voltage stability index of distribution systems, X and R are equally significant and are generally both taken into account.

The modern power distribution networks are constantly being faced with an ever-growing load demand. Distribution networks experience distinct change of load from a lower to higher level everyday. The distribution system experiences voltage collapse beyond certain critical loading conditions. The system voltage stability is system's capability to keep acceptable voltages in all buses in normal conditions after disturbances.

Voltage stability is a major concern in planning and operations of power systems. It is well known that voltage instability and collapse have led to major system failures. With the development of power markets, more and more electric utilities are facing voltage stability-imposed limits.

Literature survey shows that a few works have been done on voltage stability analysis of power distribution systems. Ajjarapu *et al.* (1992) presented the earlier works on voltage stability analysis of transmission systems. Brownell *et al.* (1989) provided the recordings of increased load demand of a system and showed its voltage collapse and also proposed urgent compensation of reactive power. Jasmon and Lee (1991a) proposed a method for voltage stability analysis of radial distribution networks. They reduced the whole network by its single line diagram that is valid only at the derived operating point. They had put voltages of all nodes equal to 1.0 p.u. to simplify the derivation of voltage stability index. This method is unable to handle changing load patterns. Using Theremin's theorem, Chebbo *et al.* (1992) suggested a method to study voltage collapse. Rahman *et al.* (1995) proposed a method to study voltage collapse using Thevenin's theorem. They also suggested a voltage stability index. Gubina *et al.* (1997) proposed a method to study voltage stability analysis of radial distribution networks reducing the system model to its single line equivalent. Chakravorty *et al.* (2001) proposed a voltage stability index to identify the most sensitive nodes of the networks. They handled the composite load using power convergence and used the load flow algorithm proposed by Das *et al.* (1995). The stability index proposed by them is similar to the index proposed by Rahman *et al.* (1995). Ranjan *et al.* (2004a) suggested a new voltage stability index to identify the most sensitive node of the network. They assumed the equality of magnitude of voltage for sending-end node and receiving-end node of each branch while deriving voltage stability index. They have also assumed that the load at any node is the sum of the loads of all nodes following it. They used the load flow proposed by Das *et al.* (1995) for satisfactory convergence of composite load modelling and considered the voltage convergence in load flow.

In this chapter a new expression for voltage stability index (VSI) of power distribution network is proposed to be computed for all nodes of distribution networks. While deriving the expression for voltage stability index, the author has not reduced the distribution network into its single line equivalent and has neither put voltages 1.0 p.u. for all nodes nor maintained the equality of the voltage magnitude of sending-end node and receiving-end node. Therefore, the proposed expression for VSI is more general in comparison to the expressions of VSI proposed by Jasmon and Lee (1991a) and Ranjan *et al.* (2004a). The node having minimum value of VSI is more prone to voltage collapse. The critical values of the total real power load (TPL) and total reactive power load (TQL) of the distribution network have also been computed by the proposed method and by the methods of Jasmon and Lee (1991a) and Ranjan *et al.* (2004a). The network will remain stable upto the critical values of TPL and TQL, beyond which the voltage collapse will occur. The effectiveness of the proposed method is demonstrated by three examples. The proposed method has also been compared with the methods of Jasmon and Lee (1991a) and Ranjan *et al.* (2004a). Since the voltage magnitude at all nodes of the distribution network must be computed before computation of VSI at all nodes, the load flow is run at first. The load flow algorithm proposed by Ghosh and Das (1999) is used to compute voltage at all nodes of the distribution network.

3 .2 Assumptions

It is assumed that the three-phase radial distribution networks are balanced and can be represented by their single line diagrams. The charging current has also been neglected in the present thesis work, and the constant power model is assumed for all loads.

3.3 Load Flow Method [Ghosh and Das (1999)]

Figure 3.1 shows the single line diagram of a distribution network. The load flow algorithm proposed by Ghosh and Das (1999) is explained in this section using this network as an example. Let

NB be the number of nodes i.e., i = 1,2,3,.....,NB

LN1 be the number of branches i.e., LN1 = NB - 1

jj be the branch number i.e., jj = 1,2,3,.......,LN1

m1= IS(jj) be the sending-end node of branch-jj

m2 = IR(jj) be the receiving-end node of branch-jj

V(m1) be the voltage of sending-end node of branch-jj

V(m2) be the voltage of receiving-end node of branch-jj

R(jj) be the resistance of the branch-jj

X(jj) be the reactance of the branch-jj

Z(jj) be the impedance of the branch-jj

I(jj) be the current through the branch-jj

PL(m2) be the active power load at node m2

QL(m2) be the reactive power load at node m2

IL(m2) be load current at node m2

LP(jj) be the real power loss of branch-jj

LQ(jj) be the reactive power loss of branch-jj

DVMAX be the maximum voltage difference

VV(m2) be the magnitude of voltage at node m2

TPL be the total real power load

TQL be the total reactive power load

Table 3.1 shows branch number (jj), sending-end node (m1) and receiving-end node (m2) of Figure 3.1.

The voltage at any receiving-end node (m2) of branch-jj is given by

$$V(m2) = V(m1) - I(jj)Z(jj) \tag{3.1}$$

i.e., $$V(m2) = V(m1) - I(jj)\,[R(jj) + j\,X(jj)] \tag{3.2}$$

where $$m1 = IS(jj) \tag{3.3}$$

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

The load current of any receiving-end node m2 = IR(jj) of branch-jj is

$$IL(m2) = \frac{PL(m2) - jQL(m2)}{V^{*}(m2)} \tag{3.5}$$

The real and reactive power losses of each branch are

$$LP = |I(jj)|^{2} R(jj) \tag{3.6}$$

and $$LQ = |I(jj)|^{2} X(jj) \tag{3.7}$$

respectively.

The current through branch-jj is the sum of all load currents of all nodes beyond branch-jj i.e.,

$$I(jj) = \sum_{i=1}^{N(jj)} IL\{IE(jj,i)\} \tag{3.8}$$

where N(jj) is the total number of nodes beyond branch jj and IE(jj, i) is the receiving-end node discussed in Art. 3.4.

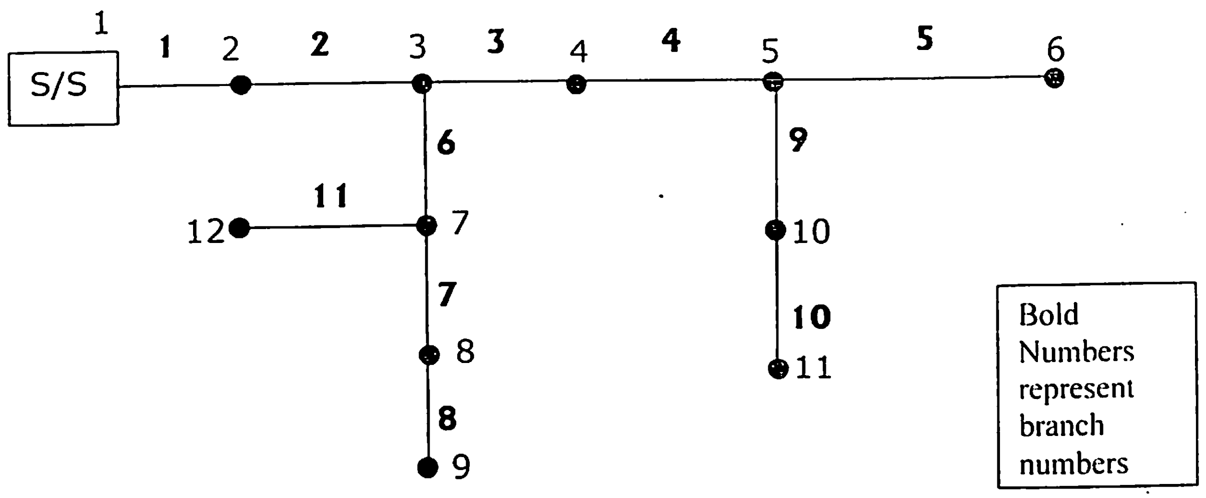


Figure 3.1 Single Line Diagram of Radial Distribution Network

Table 3.1 Branch Number, Sending-end Node and Receiving-end Node of Figure 3.1

Branch Number (jj)	Sending-end Node (m1) IS(jj)	Receiving-end Node (m2) IR(jj)
1	1	2
2	2	3
3	3	4
4	4	5
5	5	6
6	3	7
7	7	8
8	8	9
9	5	10
10	10	11
11	7	12

To determine the nodes beyond all the branches the IDENT software proposed by Ghosh and Das (1999) is used and it is explained in Art. 3.4.

3.4 Identification of Nodes beyond All the Branches (IDENT Software) [Ghosh and Das (1999)]

Before identifying the nodes beyond all the branches, the following variables are defined at first:

ic is the node count (identifies the number of nodes beyond a particular branch);

IK(ic) is the node identifier (helping to identify nodes beyond all the branches);

N(jj) is the total number of nodes beyond branch jj;

IE(jj, ic + 1) is the receiving-end node;

IE(jj, ic + 1) is explained below.

Let us consider the first branch in Figure 3.1 (Table 3.1), i.e. jj = 1; the receiving-end node of branch-1 is 2, i.e. IR(jj) = IR(1) = 2. Therefore, IE(jj, ic + 1) = IE(1, ic + 1) will help to identify all the nodes beyond branch-1. This will help to compute the exact current flowing through branch-1. Similarly , for branch-2, i.e. jj = 2; the receiving-end node of branch-2 is 3, i.e. IR(jj) = IR(2) = 3. Therefore, IE(jj, ic + 1)= IE(2, ic + 1) will identify all the nodes beyond branch-2 that will help to compute the exact current flowing through branch-2. Before identification of nodes beyond a particular branch, 'ic' has to be reset to zero. For identification of nodes beyond a particular branch, 'ic' will be incremented by 1. For jj = 1 (first branch of Figure 3.1), IR(jj) = IR(1)= 2; we check whether IR(1) = IS(i) or not for i = 2, 3, 4, ..., LN1. It is seen that IR(1) = IS(2) = 2, the corresponding receiving-end nodes are IR(2) = 3. Therefore, IE(1, 1) = 2, IE(1,2) = 3. There should not be any repetition of nodes while identifying nodes beyond a particular branch. From the above discussion, it is seen that node 2 is connected to node 3. First this IDENT software will check whether node 3 appears in the left-hand column of Table 3.1. It is seen that node 3 is connected to nodes 4 and 7. Therefore, IE(1,3) = 4 and IE(1,4) = 7. Next the algorithm will check whether nodes 4 and 7 appear in the left-hand column of Table 3.1. It is seen that the node 4 is connected to node 5 and node 7 is connected to node 8. Therefore, IE(1, 5) = 5 and IE(1,6) = 8. The proposed logic will thereafter again check whether nodes 5 and 8 are connected to any other nodes. This process will continue unless all nodes are identified beyond branch-1. The nodes beyond branch-1 are as shown in Table 3.2. The total current flowing through branch-1 is equal to the sum of the load currents of all nodes beyond branch-1. For jj = 2 (second branch of Figure 3.1; Table 3.1), IR(jj) = IR(2) = 3, we check whether IR(2) = IS(i) or not for i = 3, 4,..., LN1. It is seen that IR(2) = IS(3) = 3 and IR(2) = IS(6) = 3. The corresponding receiving-end nodes are IR(3) = 4 and IR(6)=7. Therefore, IE(2, 1) = 3 and IE(2, 2) = 7. Again node 3 is

Table 3.2 Nodes beyond Each Branch of Figure 3.1

Branch Number (jj)	Nodes beyond Branch-jj	Total Number of Nodes beyond Branch-jj
1	2,3,4,5,6,7,8,9,12,10,11	11
2	3,4,5,6,7,8,9,12,10,11	10
3	4,5,6, 10,11	5
4	5,6, 10,11	4
5	6	1
6	7,8,9,12	4
7	8,9	2
8	9	1
9	10,11	2
10	11	1
11	12	1

connected to nodes 4 and 7. The proposed logic will identify the nodes that are connected to nodes 4 and 7. It will check whether node 4 and node 7 appear in the left-hand column of Table 3.1 or not. It is seen that node 4 is connected to node 5 and node 7 is connected to node 8. Therefore, IE(2, 3) = 5 and IE(2, 4) = 8. The proposed logic will check whether nodes 5 and 8 are connected to any other nodes or not. This process will continue unless all nodes are identified beyond branch-2. The nodes beyond branch-2 are shown in Table 3.2. Similarly it is necessary to consider the receiving-end node of branch-3, branch-4,..., branch-LN1 (=11) in Figure 3.1 and, in a similar way to that discussed above, the nodes are to be identified beyond the rest of branches. The nodes beyond each branch of Figure 3.1 are shown in Table 3.2. If the receiving-end node of any branch in Figure 3.1 is an end node of a particular lateral, the total current of this branch is equal to the load current of this node. For example, consider node 6 in Figure 3.1 (branch-5, Table 3.1); this is an end node. Therefore, the branch current I(5) is equal to the load current of node 6 only. Similarly, 9, 11 and 12 are end nodes of Figure 3.1. The proposed computer logic will identify all the end nodes automatically. The algorithm of IDENT software is presented below.

```
Step -1    :    Start
Step -2    :    Read sending-end and receiving-end nodes and total
                number of nodes and branches.
```

```
Step -3    :  jj = 1
Step -4    :  k = jj +1
Step -5    :  Set ic = 0 and id = 0
Step -6    :  i = k
Step -7    :  nc = 0
Step -8    :  If IR(jj) ≠ IS(i) , go to  Step - 18 .
Step -9    :  If ic = 0 , go to Step - 16 .
Step -10   :  in = 1
Step -11   :  If IR(i) = IE(jj, ic+1), go to Step -13.
Step -12   :  nc = 1
Step -13   :  in = in + 1
Step -14   :  If in < ic, go to Step - 11
Step -15   :  If nc = 1, go to Step–18 else go to Step- 17
Step -16   :  IE(jj, ic+1) = IR(jj)
Step -17   :  ic = ic + 1, IK(ic) = i, IE(jj, ic+1 ) = IR(jj),
              N(jj) = ic+1
Step -18   :  i = i + 1
Step -19   :  If ic ≤ LN1, go to Step - 7
Step -20   :  If ic ≠ 0 , go to Step - 25
Step -21   :  id = id + 1
Step -22   :  If  id > ic , go to Step - 26
Step -23   :  IR(jj) = IE(jj, id) and K = IK(id) + 1.
```

```
Step -24  :  If $id \le ic$ , go to Step -6 else go to Step-26 .
Step -25  :  $IE(jj, ic+1) = IR(jj)$,
             $N(jj) = ic+1$.
Step -26  :  $jj = jj + 1$.
Step -27  :  If $jj \le LN1 - 1$, go to Step-4
Step -28  :  $IE(LN1) = IR(LN1)$.
Step -29  :  Stop
```

3.5 Derivation of Proposed Expression for Voltage Stability Index (VSI)

The voltage equation and load current at any node are given in equations (3.2) and (3.5) respectively. The current through any branch is the sum of the currents of all nodes beyond that branch.

Let $x = I(jj)/IL(m2)$.

Let $cl1(m2)$ be the active part of $IL(m2)$,

$cl2(m2)$ be the reactive part of $IL(m2)$,

$bl1(jj)$ be the active part of $I(jj)$ and

$bl2(jj)$ be the reactive part of $I(jj)$.

If $IL(m2) = cl1(m2)+j\,cl2(m2)$ and $I(jj) = bl1(jj) +j\,bl2(jj)$, then

$$x = \frac{I(jj)}{IL(m2)} = \frac{bl1(jj)+jbl2(jj)}{cl1(m2)+jcl2(m2)} = \frac{[bl1(jj)+jbl2(jj)][cl1(m2)-jcl2(m2)]}{[cl1(m2)]^2+[cl2(m2)]^2}$$

$$= \frac{[bl1(jj)cl1(m2) + bl2(jj)cl2(m2)] + j[bl2(jj)cl1(m2) - bl1(jj)cl2(m2)]}{[cl1(m2)]^2 + [cl2(m2)]^2}$$

$$= c + jd$$

where $c = \dfrac{bl1(jj)cl1(m2) + bl2(jj)cl2(m2)}{[cl1(m2)]^2 + [cl2(m2)]^2}$ and

$$d = \frac{bl2(jj)cl1(m2) - bl1(jj)cl2(m2)}{[cl1(m2)]^2 + [cl2(m2)]^2}$$

$$\therefore I(jj) = x\ IL(m2) = x\left[\frac{P(m2) - jQ(m2)}{V^*(m2)}\right]$$

$$= (c + jd)\left[\frac{P(m2) - jQ(m2)}{V^*(m2)}\right] \tag{3.9}$$

Using equation (3.9), equation (3.2) can be written as follows:

$$V(m1) = V(m2) + (c + jd)\left[\frac{P(m2) - jQ(m2)}{V^*(m2)}\right][R(jj) + jX(jj)] \tag{3.10}$$

$$\text{or, } V(m1)V^*(m2) = V(m2)V^*(m2) + (c + jd)\ [\{P(m2) - jQ(m2)\}\{R(jj) + jX(jj)\}] \tag{3.11}$$

$$\text{or, } V(m1)V^*(m2) = |V(m2)|^2 + (c + jd)\,[\{P(m2)R(jj) + Q(m2)X(jj)\} + j\{P(m2)X(jj) - Q(m2)R(jj)\}] \tag{3.12}$$

$$\text{or, } V(m1)V^*(m2) = |V(m2)|^2 + (a + jb)(c + jd)$$

where $a = [P(m2)R(jj) + Q(m2)X(jj)]$ and $b = [P(m2)X(jj) - Q(m2)R(jj)]$

$$\text{or, } V(m1)V^*(m2) = |V(m2)|^2 + (e + jf) \tag{3.13}$$

where e = ac - bd and f = ad + bc

$$e = [P(m2)R(jj) + Q(m2)X(jj)]\left[\frac{bl1(jj)cl1(m2) \ + bl2(jj)cl2(m2)}{\{cl1(m2)\}^2 + \{cl2(m2)\}^2}\right] - [P(m2)X(jj) - Q(m2)R(jj)]\left[\frac{bl2(jj)cl1(m2) - bl1(jj)cl2(m2)}{\{cl1(m2)\}^2 + \{cl2(m2)\}^2}\right] \qquad (3.14)$$

$$\text{and } f = [P(m2)R(jj) + Q(m2)X(jj)]\left[\frac{bl2(jj)cl1(m2) - bl1(jj)cl2(m2)}{\{cl1(m2)\}^2 + \{cl2(m2)\}^2}\right] + [P(m2)X(jj) - Q(m2)R(jj)]\left[\frac{bl1(jj)cl1(m2) \ + bl2(jj)cl2(m2)}{\{cl1(m2)\}^2 + \{cl2(m2)\}^2}\right] \qquad (3.15)$$

$$\therefore V(m1)V^*(m2) = \left[|V(m2)|^2 + e\right] + jf \qquad (3.16)$$

Complex conjugate of equation (3.16) is given by

$$\therefore V^*(m1)V(m2) = \left[|V(m2)|^2 + e\right] - jf \qquad (3.17)$$

Multiplying equation (3.16) by equation (3.17), it can be obtained

$$|V(m2)|^4 + \left(2e - |V(m1|^2\right)|V(m2)|^2 + \left(e^2 + f^2\right) = 0 \qquad (3.18)$$

To get feasible solution of $|V(m2)|^2$, the discriminant of equation (3.18) must be ≥ 0 i.e.,

$$\left(2e - |V(m1)|^2\right)^2 - 4(e^2 + f^2) \geq 0$$

$$\therefore |V(m1)|^4 - 4e|V(m1)|^2 - 4f^2 \geq 0 \qquad (3.19)$$

Let

$$L(m2) = |V(m1)|^4 - 4e|V(m1)|^2 - 4f^2 \qquad (3.20)$$

be the new expression for voltage stability index (VSI) of node m2 of the distribution networks.

For stable operation of radial distribution networks L(m2) ≥ 0 for m2=2,3,......,NB. The voltage at each node is computed using the load flow algorithm proposed by Ghosh and Das (1999). The VSI i.e., L(m2) at each node is computed using equation (3.20). Node having minimum value of VSI is more prone to voltage collapse. However, the network will remain stable as long as the value of VSI of all nodes is greater than or equal to zero. The algorithm for computation the value of VSI at all nodes and identification of most sensitive node is presented below.

Step -1 : Read the system data

Step -2 : Set v(i) =1.0 + j 0.0 for all i i.e., i =1,2,....,NB
Set VV(i) = v(i) for all i i.e., i = 1,2,.......,NB

Step -3 : Set ISS(jj) = IS(jj) and IRR(jj) = IR(jj) for jj = 1,2,3,.........,LN1

Step -4 : Set iteration count k =1

Step -5 : Set kMAX = 100(say)

Step -6 : Set DVMAX = 0.0 and ε = 0.00001

Step -7 : Identify the nodes beyond each branch using the IDENT software as discussed in Art 3.4

Step -8 : Compute load currents IL(m2) for all m2 i.e., for m2 =2,3,4,....,NB using equation (3.5)

Step-9 : Compute the current through each branch i.e., I(jj) for all jj i.e., jj = 1,2,3,.....,LN1 using equation (3.8)

Step -10 : Set jj =1

Step -11 : Set m1 = ISS(jj) and m2 = IRR(jj). Compute receiving-end voltage V(m2) for all m2 i.e., for m2 =2,3,4,....,NB using equation (3.2)

Step -12 : Compute the absolute change in voltage at node m2 i.e., DV(m2) = ABS(|V(m2)|- |VV(m2)|)

Step -13 : If DV(m2) > DVMAX go to Step-14. Otherwise go to Step-15

Step -14 : DVMAX = DV(m2)

Step -15 : jj = jj + 1

Step -16 : If jj < LN1, go to Step-11, otherwise go to Step-17

Step -17 : If DVMAX< ε go to Step-21

Step -18 : k = k+1

Step -19 : Set VV(m2) = V(m2) for m2 = 2,3,..........,NB

Step -20 : If k < kMAX, go to Step-6, otherwise go to Step-28

Step -21 : Print "Solution has converged"

Step-22 : Compute voltages of each node and line losses

Step-23 : Compute IL(m2) for all m2 i.e., for m2 =2,3, 4,...., NB for all nodes using equation (3.5) and I(jj) for all jj i.e., jj = 1,2,3,.....,LN1 using equation (3.8)

Step-24 : Compute x = I(jj)/IL(m2) using equation (3.9)

Step-25 : Compute the voltage stability index of all nodes using equation (3.20)

Step-26 : Identify the node of the network having minimum voltage

Step-27 : Identify the node of the network having minimum VSI and print the results and go to Step-29

Step-28 : Print "Solution has not converged"

Step-29 : Stop

3.6 Computation of the Critical Loading

To compute the critical values of TPL and TQL of the network, the most sensitive node of the network is identified at first. The real power load and reactive power load of this node are increased by 0.1 times of its previous value in each step and the load flow is run. Finally, VSI of the most sensitive node and V_{min} of the network are plotted along the Y-axis and its TPL is plotted along the X-axis. The value of TPL corresponding to VSI = 0 and $V_{min} = 0$ gives the critical value of TPL of the network. Again, VSI of the most sensitive node and V_{min} of the network are plotted along the Y-axis and its TQL are plotted along the X-axis. The value of TQL corresponding to VSI = 0 and $V_{min} = 0$ gives the critical value of TQL of the network. The algorithm for computation of critical values of TPL and TQL is presented below.

Step -1 : Set a1=1.0 and k =1
Step -2 : Read system data
Step -3 : Set kMAX = 100
Step -4 : PL(m2) = PL(m2)*a1 and QL(m2)=QL(m2)*a1
Step -5 : Identify the nodes beyond each branch using the IDENT software as discussed in Art. 3.4
Step -6 : Compute the voltage of each node using the load flow algorithm as discussed in Art. 3.5
Step-7 : Compute VSI at each node
Step-8 : Identify the most sensitive node
Step-9 : Print VSI i.e., L(m2) and kVA(m2) for m2 = 2,3,4,...,NB
Step-10 : a1 = a1+0.1 and k= k+1
Step-11 : If k < kMAX, go to Step - 4, otherwise go to Step-13
Step-12 : Print the result
Step-13 : Stop

During the computation of the critical values of TPL and TQL of the network, it has been found that the load flow fails to converge beyond a certain values of TPL and TQL that is the point of collapse for the load flow algorithm. Extrapolation is carried out from this point to compute the values of TPL and TQL theoretically at VSI = 0 and V_{min}= 0 that are the critical values of TPL and TQL respectively, beyond which the system will collapse. Ajjarapu *et al.* (1992) had shown that the exact point of collapse was near about the zone of voltage collapse.

3.7 Examples

To demonstrate the effectiveness of the proposed method three examples are selected. The first example is a 17 node radial distribution network (Base values are 11 kV and 100 MVA), the second example is a 29 node radial distribution network (Base values are 11kV and 100 MVA) and the third example is a 33 node radial distribution network (Base values are 12.66 kV and 100 MVA).

The schematic diagram of 17 node radial distribution network has been shown in Figure 3.2. Line data and load data for this 17 node radial distribution network have been shown in Appendix-A (Table A.1 and Table A.2 respectively). Table 3.3 and Table 3.4 show the load flow results and the computed value of VSI at all nodes for 17 node radial distribution network. The values of TPL and TQL of the system are 939 kW and 828.12 kVAr respectively. Real power and reactive power losses of this system are 17.03 kW and 12.80 kVAr respectively.

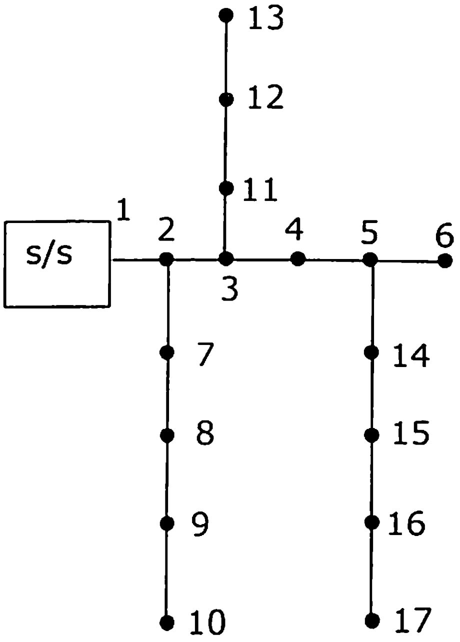


Figure 3.2 17 Node Radial Distribution Network

Table 3.3 Load Flow Results for 17 Node Radial Distribution Network

Node Number	Voltage Magnitude (p.u.)
1(S/S)	1.000000
2	0.994822
3	0.989366
4	0.986510
5	0.979880
6	0.978705
7	0.991196
8	0.990116
9	0.989817
10	0.989579
11	0.987749
12	0.986704
13	0.986452
14	0.976952
15	0.974909
16	0.973995
17	**0.972880**

Table 3.4 Values of VSI for All Nodes of 17 Node Radial Distribution Network

Node Number	VSI		
	Proposed Method	Jasmon and Lee (1991a)	Ranjan *et al.* (2004a)
2	0.979393	0.001627	0.494428
3	0.958077	0.001456	0.489058
4	0.947107	0.000910	0.486374
5	0.921822	0.002895	0.479359
6	0.917498	**0.004602**	0.477781
7	0.965214	0.004003	0.490234
8	0.961044	0.001653	0.489752
9	0.959885	0.000592	0.489720
10	0.958965	0.000939	0.489399
11	0.951884	0.002553	0.487186
12	0.947866	0.002749	0.486105
13	0.946900	0.000994	0.486295
14	0.910927	0.002854	0.476504
15	0.903343	0.002653	0.474561
16	0.899968	0.001779	0.473889
17	**0.895852**	0.004340	**0.472163**

The schematic diagram of 29 node radial distribution network has been shown in Figure 3.3. Line data and load data for this 29 node radial distribution network have been shown in Appendix-B (Table B.1 and Table B.2 respectively). Table 3.5 and Table 3.6 show the load flow results and the computed value of VSI at all nodes for 29 node radial distribution network. The values of TPL and TQL of the system are 876.75 kW and 773.14 kVAr respectively. Real power and reactive power losses of this system are 47.26 kW and 28.74 kVAr respectively.

The schematic diagram of 33 node radial distribution network has been shown in Figure 3.4. The nodes have been renumbered. Line data and load data for this 33 node radial distribution network are available in Baran and Wu (1989a) and have been shown in Appendix-C (Table C.1 and Table C.2 respectively). Table 3.7 and Table 3.8 show the load flow results and the computed value of VSI at all nodes for 33 node radial distribution network. The values of TPL and TQL are 3715 kW and 2300 kVAr respectively. Real power and reactive power losses of this system are 202.52 kW and 135.12 kVAr respectively.

Table 3.9 shows the comparison of the most sensitive nodes and the values of their VSI for 17 node, 29 node and 33 node radial distribution networks for normal load condition obtained by the proposed method and by methods of Jasmon and Lee (1991a) and Ranjan *et al.* (2004a) as well

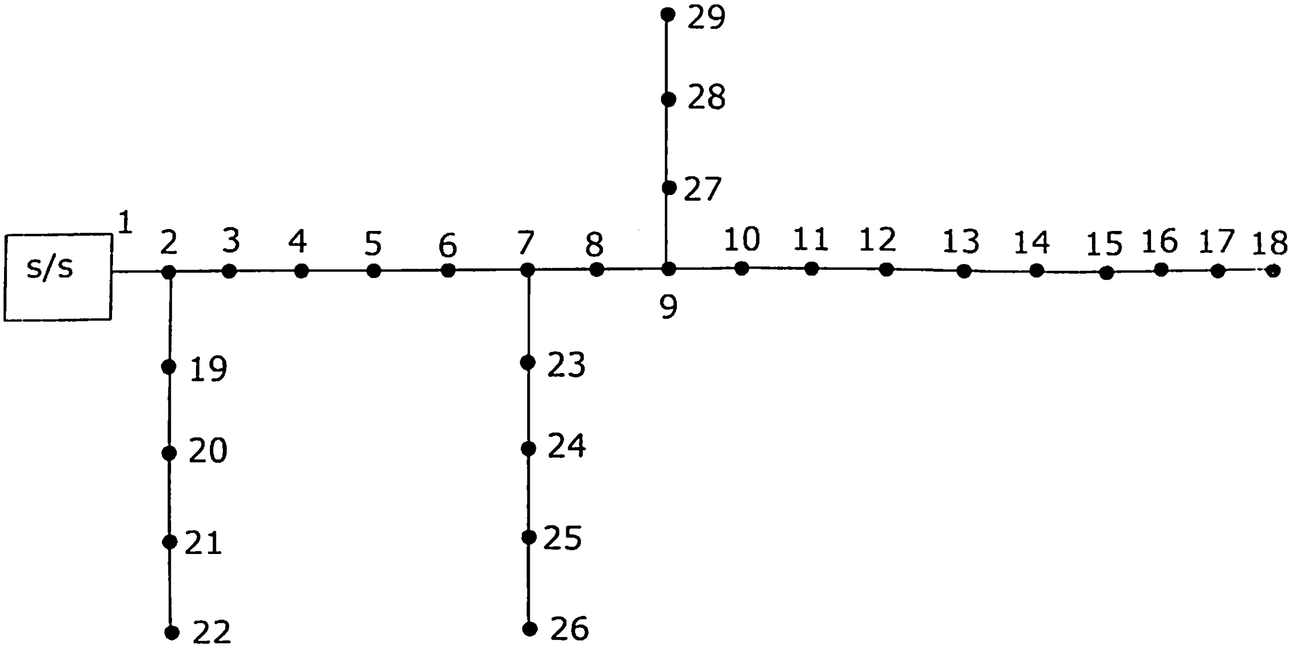


Figure 3.3 29 Node Radial Distribution Network

Table 3.5 Load Flow Results for 29 Node Radial Distribution Network

Node Number	Voltage Magnitude (p.u.)
1(S/S)	1.000000
2	0.997866
3	0.992946
4	0.987534
5	0.982819
6	0.968392
7	0.961816
8	0.958286
9	0.953803
10	0.948026
11	0.942455
12	0.936352
13	0.933339
14	0.928998
15	0.926777
16	0.924450
17	0.923428
18	**0.923145**
19	0.995412
20	0.993964
21	0.992764
22	0.992533
23	0.959569
24	0.957307
25	0.955809
26	0.955188
27	0.949635
28	0.945853
29	0.944921

Table 3.6 Values of VSI for All Nodes of 29 Node Radial Distribution Network

Node Number	VSI		
	Proposed Method	Jasmon and Lee (1991a)	Ranjan *et al.* (2004a)
2	0.991482	0.000349	0.497781
3	0.972033	0.000316	0.492892
4	0.951005	0.000552	0.487474
5	0.932985	0.000987	0.482720
6	0.878961	0.001016	0.468638
7	0.855710	0.000740	0.462360
8	0.843273	0.000353	0.459067
9	0.827592	0.001813	0.454417
10	0.807691	0.002553	0.448739
11	0.788871	0.002786	0.443415
12	0.768620	0.001128	0.438096
13	0.758837	0.000587	0.435414
14	0.744793	0.001393	0.431170
15	0.737728	0.001561	0.429068
16	0.730345	0.002543	0.426669
17	0.727129	0.002517	**0.425731**
18	**0.726238**	0.001047	0.425836
19	0.981759	0.002786	0.494726
20	0.976068	0.002301	0.493407
21	0.971364	0.003177	0.491996
22	0.970464	0.000917	0.492332
23	0.847811	0.001009	0.460134
24	0.839847	0.004602	0.457068
25	0.834607	0.004100	0.455761
26	0.832445	0.002372	0.455599
27	0.813217	0.003940	0.449919
28	0.800345	**0.004765**	0.446128
29	0.797224	0.003524	0.445557

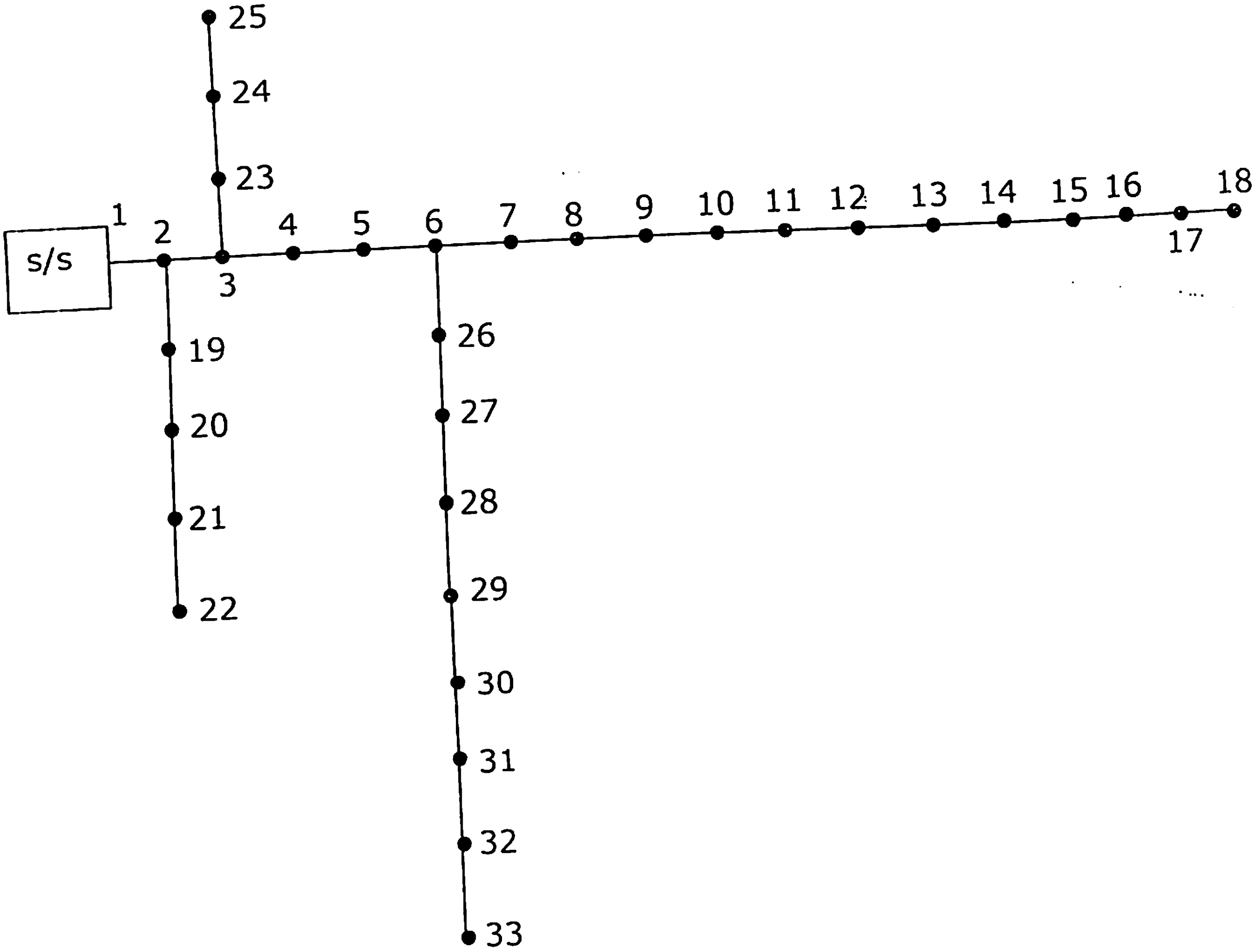


Figure 3.4 33 Node Radial Distribution Network [Baran and Wu(1989a)]

Table 3.7 Load Flow Results for 33 Node Radial Distribution Network

Node Number	Voltage Magnitude (p.u.)
1(S/S)	1.000000
2	0.997032
3	0.982939
4	0.975457
5	0.968061
6	0.949661
7	0.946175
8	0.941332
9	0.935064
10	0.929416
11	0.928557
12	0.927057
13	0.920945
14	0.918679
15	0.917267
16	0.915899
17	0.913873
18	**0.913266**
19	0.996504
20	0.992926
21	0.992222
22	0.991584
23	0.979353
24	0.972682
25	0.969357
26	0.947731
27	0.945167
28	0.933728
29	0.925510
30	0.921952
31	0.917791
32	0.916876
33	0.916592

Table 3.8 Values of VSI for All Nodes of 33 Node Radial Distribution Network

Node Number	VSI		
	Proposed Method	Jasmon and Lee (1991a)	Ranjan *et al.* (2004a)
2	0.988165	0.000300	0.496962
3	0.933094	0.001358	0.482745
4	0.905276	0.001468	0.475392
5	0.878129	0.000716	0.468392
6	0.812727	0.001579	0.450533
7	0.801420	0.002480	0.447004
8	0.785140	0.004138	0.442018
9	0.764406	0.001912	0.436694
10	0.746119	0.001873	0.431439
11	0.743418	0.000269	0.431041
12	0.738625	0.000669	0.429550
13	0.719275	0.003207	0.423268
14	0.712276	0.003046	0.421224
15	0.707914	0.001016	0.420435
16	0.703702	0.001390	0.419088
17	0.697488	0.002790	0.416884
18	**0.695646**	0.002217	**0.416473**
19	0.986089	0.000525	0.496379
20	0.971977	0.004732	0.491769
21	0.969248	0.001397	0.491903
22	0.966759	0.002528	0.490988
23	0.919909	0.001398	0.479217
24	0.895035	**0.012954**	0.469817
25	0.882925	0.012893	0.466603
26	0.806746	0.000368	0.449005
27	0.798046	0.000516	0.446542
28	0.759887	0.002052	0.435411
29	0.733591	0.003633	0.427376
30	0.722467	0.006414	0.423397
31	0.709506	0.005331	0.419838
32	0.706710	0.002531	0.419698
33	0.705837	0.001040	0.419811

Table 3.9 Comparison of Most Sensitive Nodes and their Voltage Stability Index by Computed by the Proposed Method, and the Methods Proposed by Jasmon and Lee (1991a) and Ranjan *et al.*(2004a) as well as Nodes having Minimum Voltage and Their Voltage Magnitudes for 17, 29, and 33 Radial Distribution Networks

Method	Example-1: 17 Node Radial Distribution Network		Example-2: 29 Node Radial Distribution Network		Example-3: 33 Node Radial Distribution Network	
	Node Number	VSI / V_{min}	Node(s) Number	VSI / V_{min}	Node Number	VSI / V_{min}
Proposed Method	MSN :17	0.895852	MSN :18	0.726238	MSN :18	0.695646
	NMV:17	0.972880	NVM :18	0.923145	NMV :18	0.913266
Jasmon and Lee (1991a)	MSN :6	0.004602	MSN :28	0.004765	MSN :24	0.012954
	NMV:17	0.972880	NMV:18	0.923145	NMV:18	0.913266
Ranjan *et al.* (2004a)	MSN :17	0.472163	MSN :17	0.425731	MSN :18	0.416473
	NMV:17	0.972880	NMV:18	0.923145	NMV:18	0.913266

MSN : MOST SENSITIVE NODE

NMV : NODE HAVING MINIMUM VOLTAGE

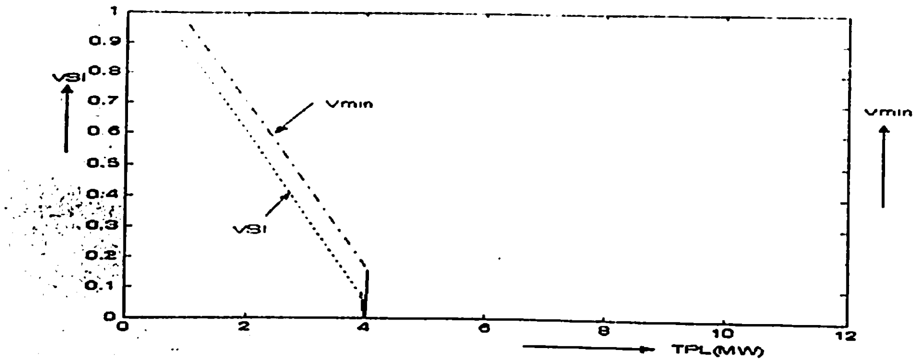
the nodes having minimum voltage and their voltage magnitudes for the above radial distribution networks.

From above discussion, we can conclude that the proposed method gives the assurance that the most sensitive node is the end node having the minimum voltage in all cases whereas the methods proposed by Jasmon and Lee (1991a) and Ranjan *et al.* (2004a) are unable to assure it.

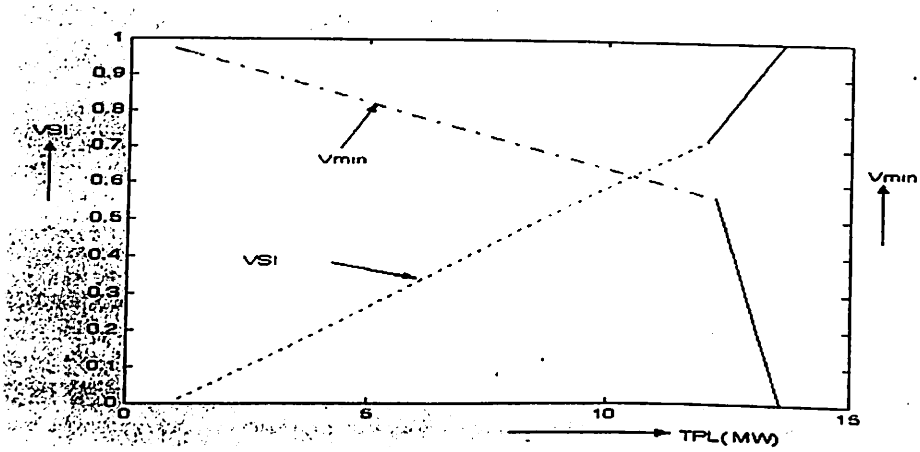
Figure 3.5 (a), (b) and (c) and Figure 3.6 (a), (b) and (c) show the respective plot of VSI of the most sensitive node and V_{min} vs TPL and VSI of the most sensitive node and V_{min} vs TQL computed by the proposed method and the methods proposed by Jasmon and Lee (1991a) and the method proposed by Ranjan *et al.*(2004a) respectively for 17 node radial distribution network.

Figure 3.7 (a), (b) and (c) and Figure 3.8 (a), (b) and (c) show the respective plot of VSI of the most sensitive node and V_{min} vs TPL and VSI of the most sensitive node and V_{min} vs TQL computed by the proposed method and the methods proposed by Jasmon and Lee (1991a) and the method proposed by Ranjan *et al.*(2004a) respectively for 29 node radial distribution network.

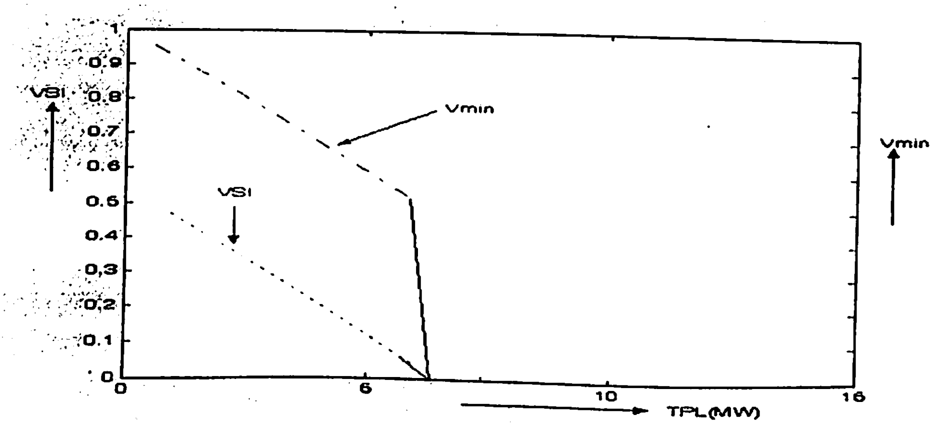
Figure 3.9 (a), (b) and (c) and Figure 3.10 (a), (b) and (c) show the respective plot of VSI of the most sensitive node and V_{min} vs TPL and VSI of the most sensitive node and V_{min} vs TQL computed by the proposed



(a) Using the Proposed Method

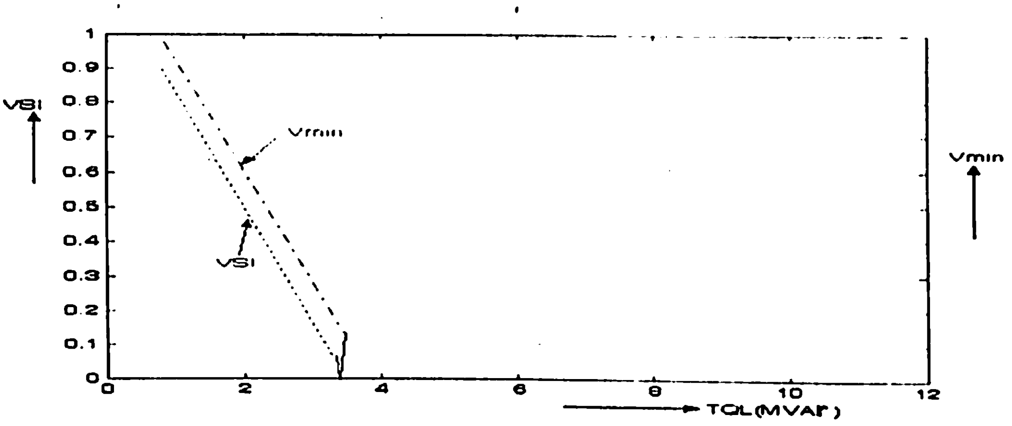


(b) Using the Method Proposed by Jasmon and Lee (1991a)

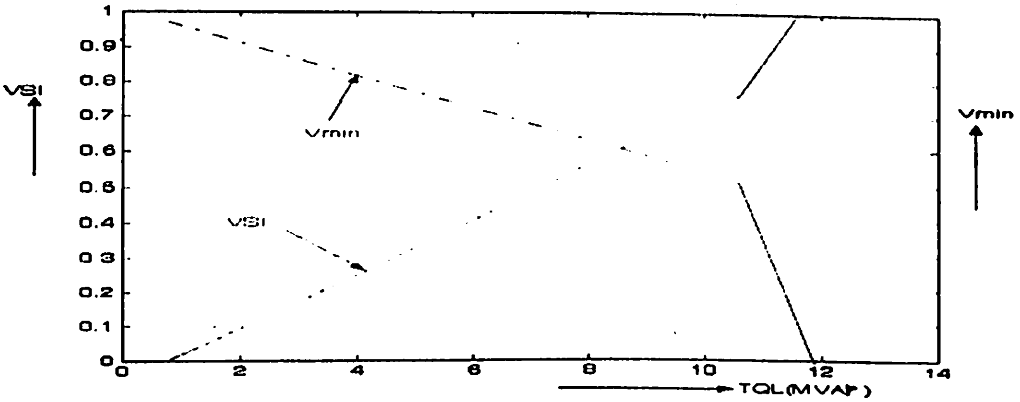


(c) Using the Method Proposed by Ranjan *et al.*(2004a)

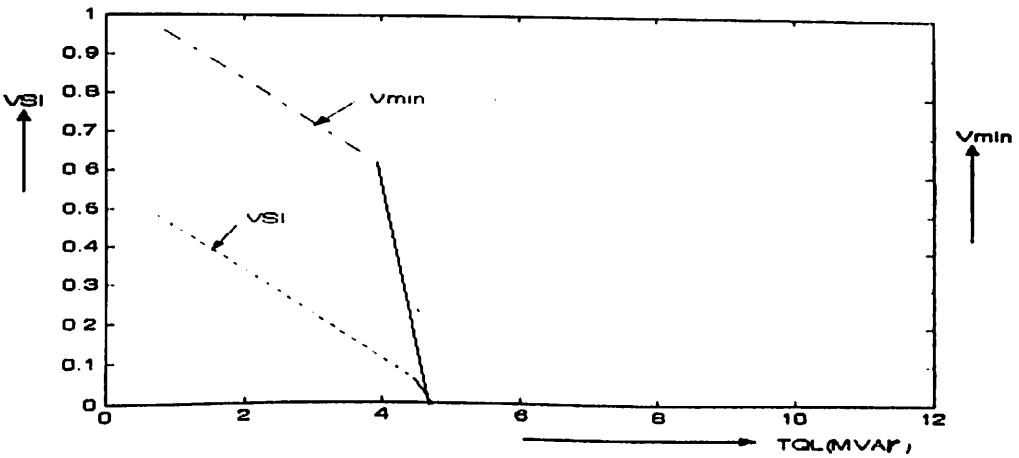
Figure 3.5 Plot of VSI of the Most Sensitive Node and V_{min} vs TPL of 17 Node Radial Distribution Network



(a) Using the Proposed Method

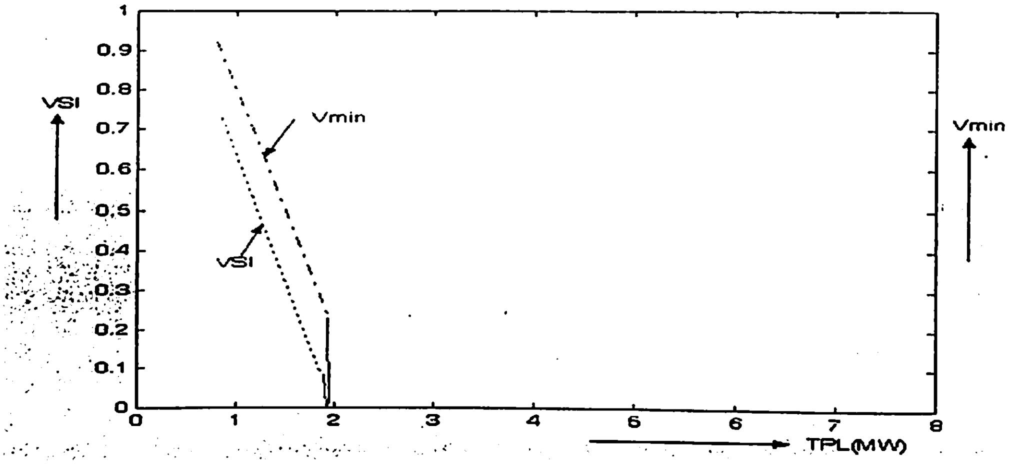


(b) Using the Method Proposed by Jasmon and Lee (1991a)

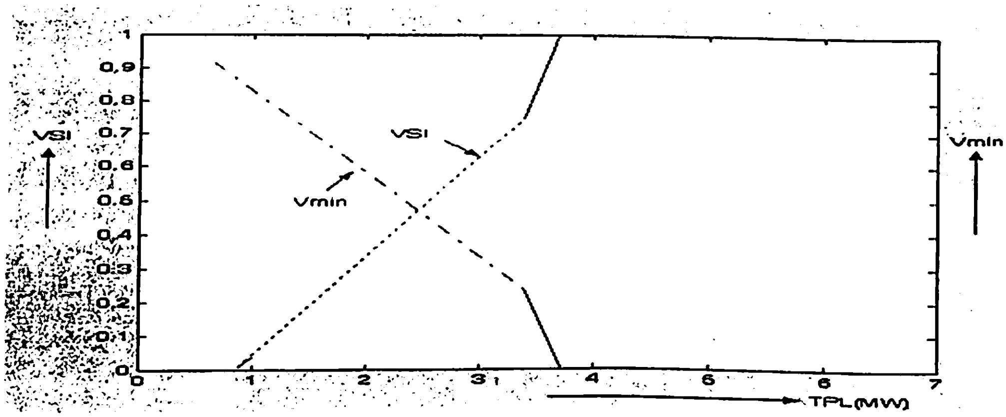


(c) Using the Method Proposed by Ranjan *et al.* (2004a)

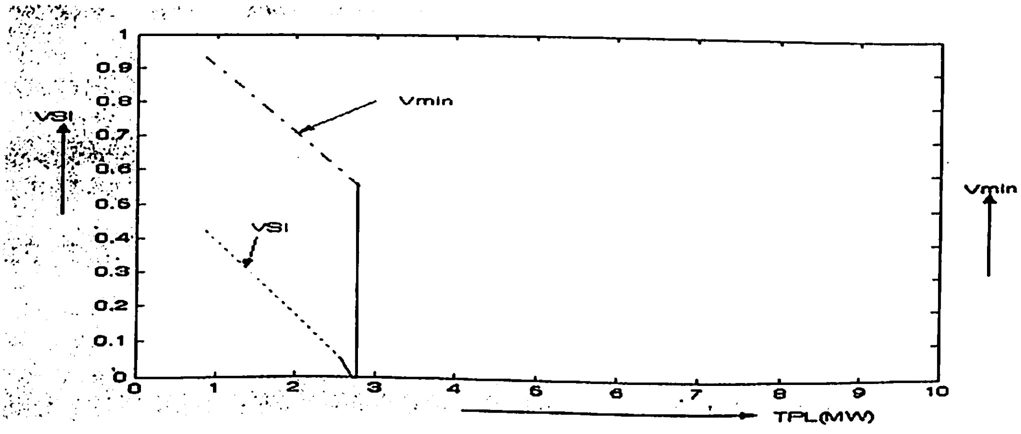
Figure 3.6 Plot of VSI of the Most Sensitive Node and V_{min} vs TQL of 17 Node Radial Distribution Network



(a) Using the Proposed Method

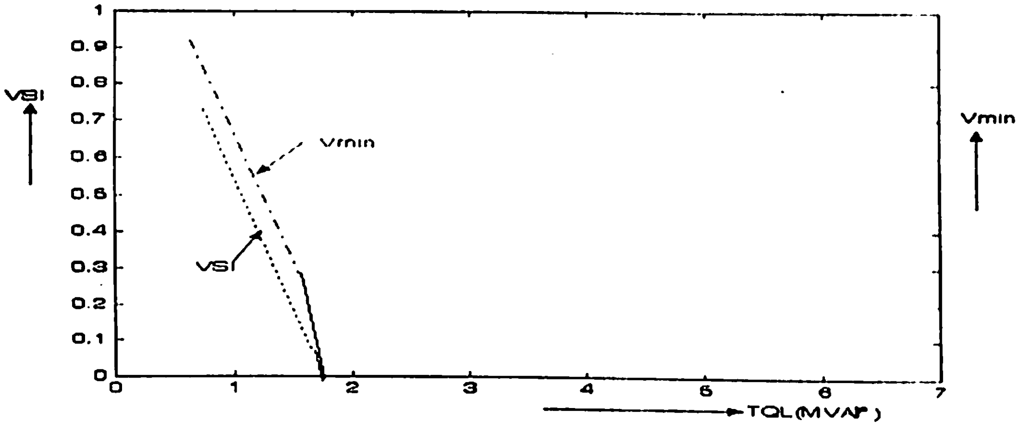


(b) Using the Method Proposed by Jasmon and Lee (1991a)

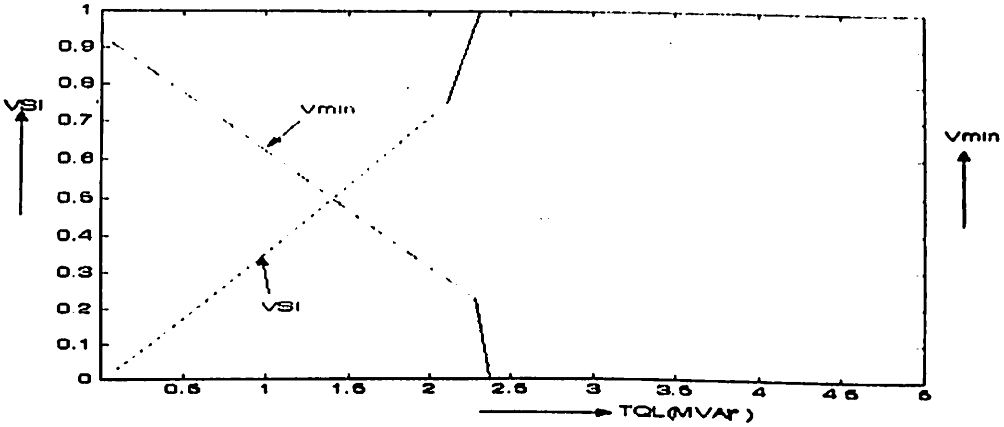


(c) Using the Method Proposed by Ranjan *et al.* (2004a)

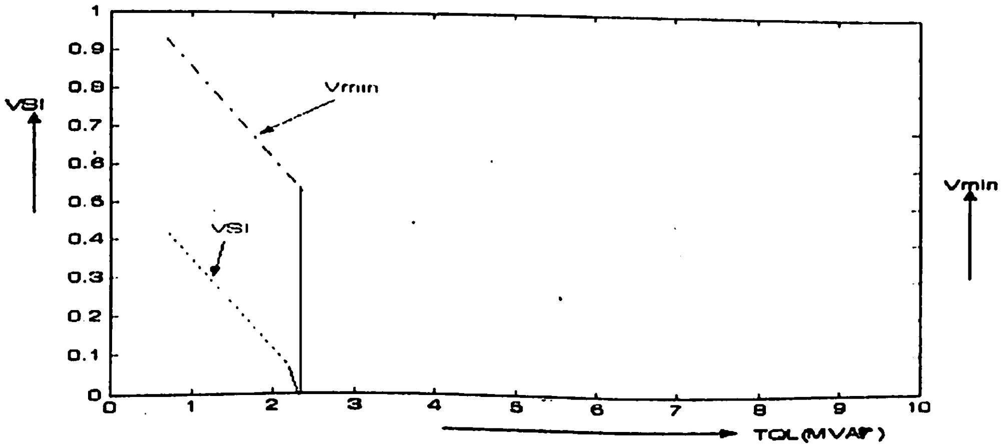
Figure 3.7 Plot of VSI of the Most Sensitive Node and V_{min} vs TPL of 29 Node Radial Distribution Network



(a) Using the Proposed Method

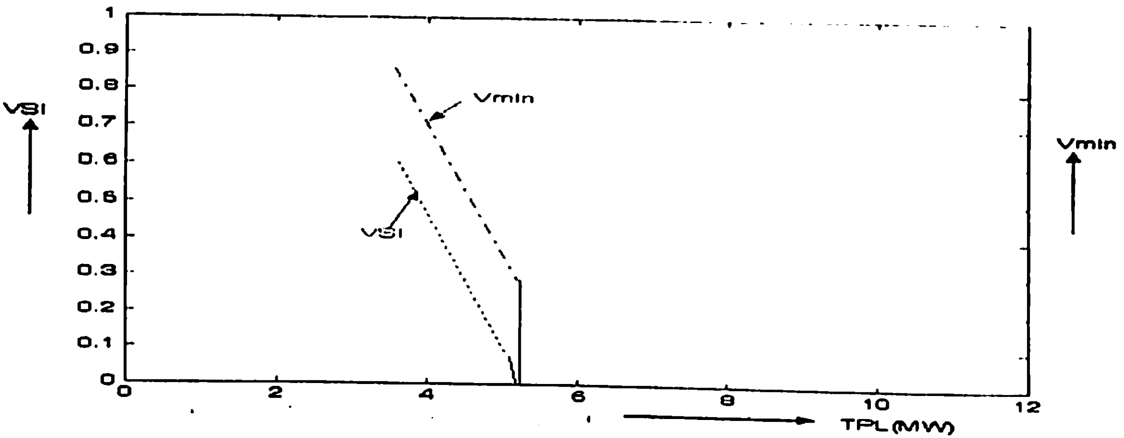


(b) Using the Method Proposed by Jasmon and Lee (1991a)

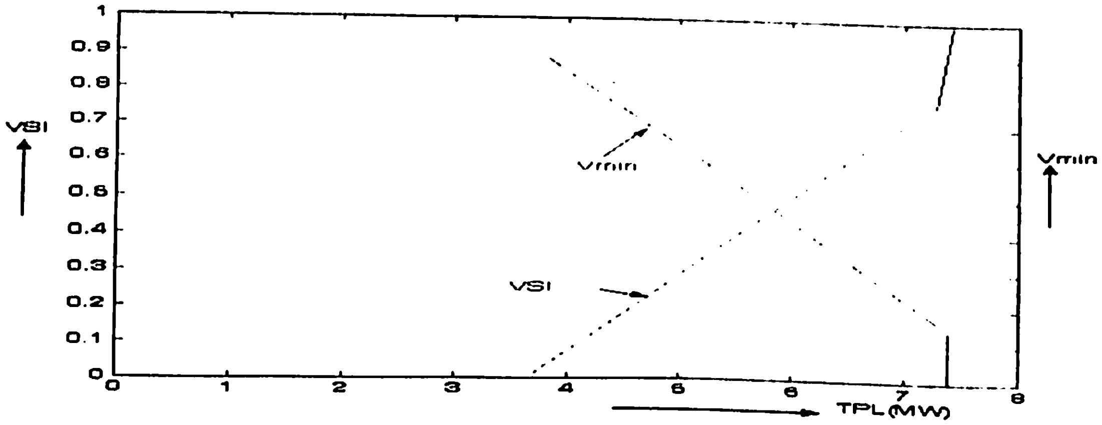


(c) Using the Method Proposed by Ranjan *et al.* (2004a)

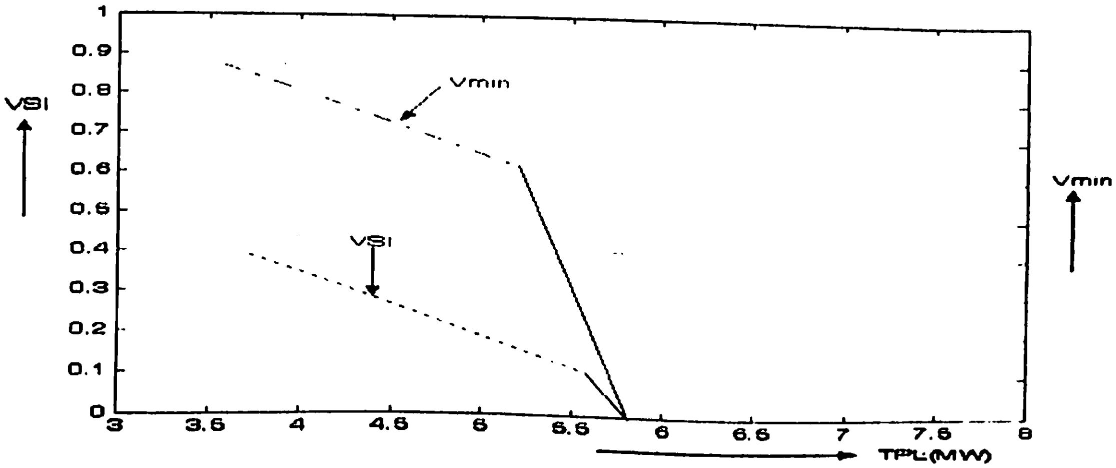
Figure 3.8 Plot of VSI of the Most Sensitive Node and V_{min} vs TQL of 29 Node Radial Distribution Network



(a) Using the Proposed Method

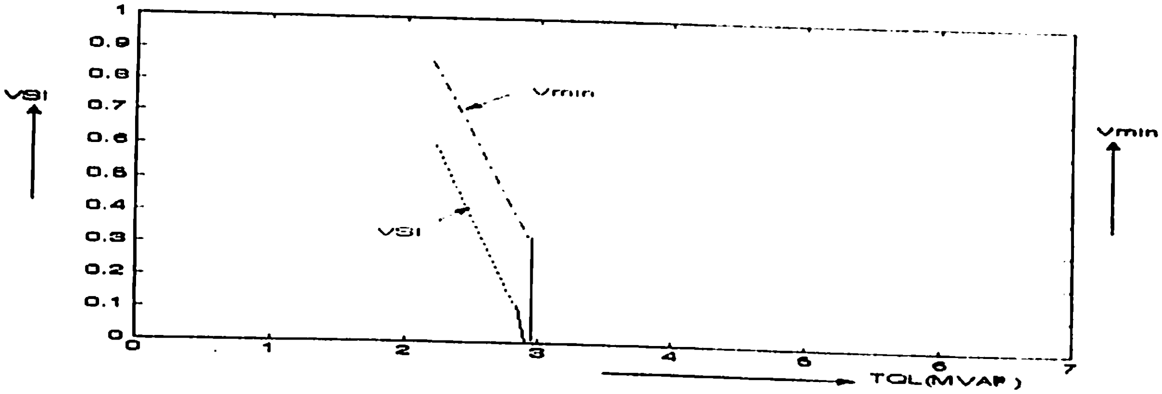


(b) Using the Method Proposed by Jasmon and Lee (1991a)

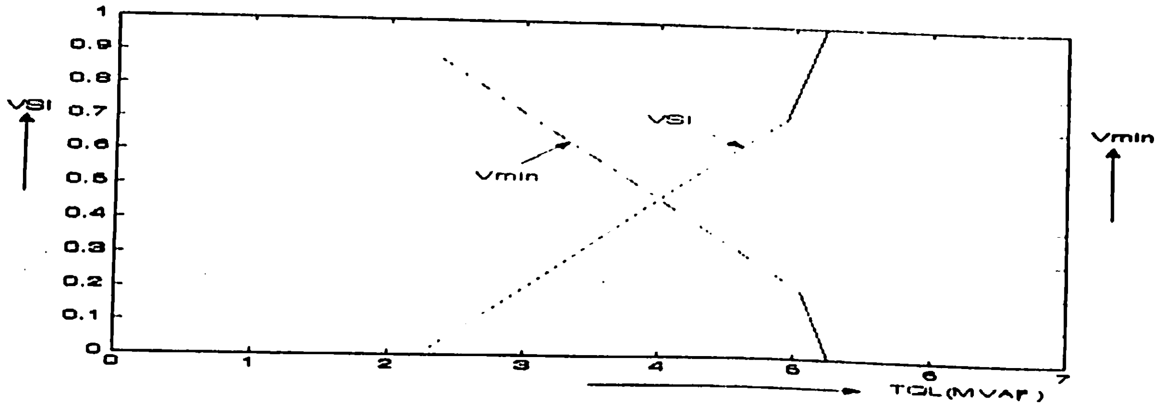


(c) Using the Method Proposed by Ranjan *et al.* (2004a)

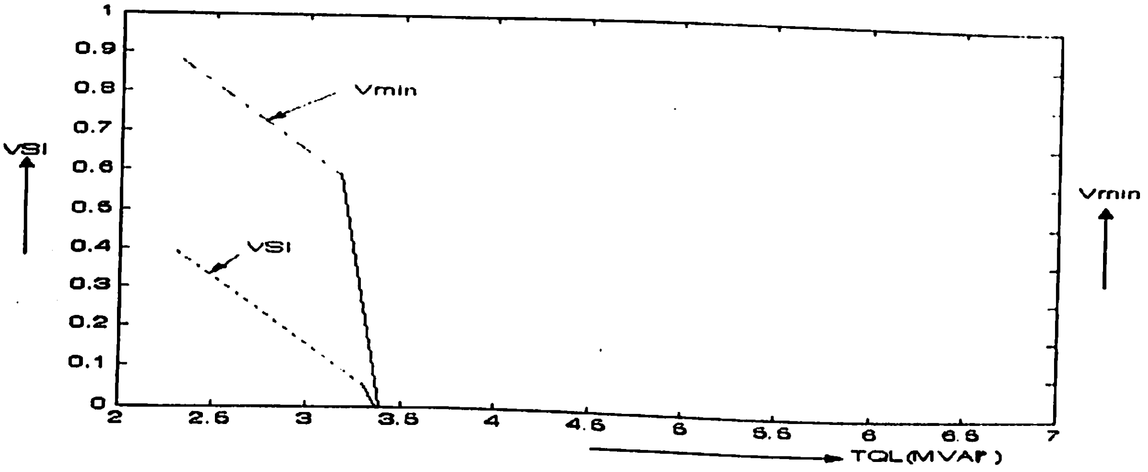
Figure 3.9 Plot of VSI of the Most Sensitive Node and V_{min} vs TPL of 33 Node Radial Distribution Network



(a) Using the Proposed Method



(b) Using the Method Proposed by Jasmon and Lee (1991a)



(c) Using the Method Proposed by Ranjan *et al.* (2004a)

Figure 3.10 Plot of VSI of the Most Sensitive Node and V_{min} vs TQL of 33 Node Radial Distribution Network

method and the methods proposed by Jasmon and Lee (1991a) and Ranjan *et al.* (2004a). Table 3.10 shows the comparison of the critical values of TPL and TQL computed by the proposed method and the methods proposed by Jasmon and Lee (1991a) and Ranjan *et al.* (2004a) for the above three examples. The critical values of TPL and TQL computed by the proposed method are less compared to that of computed by Jasmon and Lee (1991a) and Ranjan *et al.* (2004a). This is due to the fact that Jasmon and Lee (1991a) reduced the whole network into its single line equivalent network and put the voltage magnitude 1.0 p.u. for all nodes On the other hand, Ranjan *et al.* (2004a) indirectly reduced the whole network into its equivalent network and assumed that the voltage magnitude of sending-end node is equal to that of its receiving-end node for all branches.

3.8 Summary

In this chapter, a new expression for VSI is derived to be computed for all nodes of the balanced power distribution networks. The node of any distribution network having the minimum value of VSI becomes the most sensitive node of that network. To demonstrate the effectiveness of the proposed method three examples 17 node, 29 node and 33 node radial distribution networks have been selected. The most sensitive nodes and

Table 3.10 Comparison of Critical Values of TPL and TQL of 17 Node, 29 Node and 33 Node Radial Distribution Networks Computed by the Proposed Method and by the Methods of Jasmon and Lee (1991a) and Ranjan *et al.* (2004a)

Methods	Example 1: 17 Node Radial Distribution Network		Example 2: 29 Node Radial Distribution Network		Example 3: 33 Node Radial Distribution Network	
	TPL (MW)	TQL (MVAr)	TPL (MW)	TQL (MVAr)	TPL (MW)	TQL (MVAr)
Proposed Method	4.00	3.50	1.92	1.86	5.20	2.99
Jasmon and Lee (1991a)	13.80	11.80	3.80	2.40	7.30	5.20
Ranjan *et al.* (2004a)	6.25	4.80	2.87	2.32	5.80	3.40

their values of VSI in all three cases obtained by the proposed method and by the methods of Jasmon and Lee (1991) and Ranjan *et al.* (2004a) have been compared and also the nodes having the minimum value of voltage and their voltage magnitudes in all the three cases. This comparison shows that the most sensitive nodes identified by the proposed method are the end nodes and also the nodes having the minimum voltage for all the above three cases whereas the other two methods are unable to assure it. The critical values of TPL and TQL of 17 node, 29 node and 33 node radial distribution networks have also been computed by the proposed method and the methods of Jasmon and Lee (1991a) and Ranjan *et al.* (2004a) and the values have been compared. The proposed method gives the less critical values of TPL and TQL. This is due to the fact that Jasmon and Lee (1991a) while deriving the expression for VSI had reduced the whole network into its single line equivalent which is valid at the operating point and put the voltage magnitude 1.0 p.u. for all nodes whereas Ranjan *et al.* (2004a) while deriving the expression for VSI had reduced the whole network into its single line equivalent indirectly at the operating point and assumed that the voltage magnitude of sending-end node is equal to that of the receiving-end for all branches that led higher values and unable to identify the proper most sensitive node. The networks are stable at these computed critical values of TPL and TQL and will collapse, beyond which voltage collapse will occur.

CHAPTER 4

PLANNING OF DISTRIBUTION SYSTEM USING GENETIC ALGORITHM WITH THE HELP OF VOLTAGE STABILITY INDEX (VSI)

4.1 Introduction

The planning, design and operation of power distribution system require continuous and comprehensive analysis in order to evaluate the system performance and to determine the effectiveness of alternative plans for system expansion. These studies play a vital role in providing a high standard of power system reliability, security and quality and in ensuring the maximum utilization of optimal investment.

Exhaustive literature survey of planning of electric power distribution system has already been presented in Chapter-2.

Chen and Hsu (1989) developed a rule-based system for the load re-allocation in the case of distribution expansion planning. They proposed two algorithms, one to minimize power loss and the other to minimize investment cost. These algorithms formed the basis for the inference engine. The system was implemented on a PC using PROLOG language. The heuristic rules used by the planners were also incorporated in the expert system. The software was also able to compute the system reliability of developed plan. The system was used to assist the planners in the expansion of a three station, twenty eight feeder networks.

Hsu and Chen (1990) later on designed an expert system for determining substation locations and feeder configuration of a distribution system. The substation locations were determined using an operation research based "location–allocation method". The method was used to minimize the feeder losses and support the inference engine.

Goswami (1997) proposed an algorithm for planning of radial distribution system based on the branch exchange technique. He applied the branch exchange between the elements of the networks under adjacent substations. A complete power flow was required after each branch exchange. This model is suitable for small systems.

Singh *et al.* (1998) proposed a model for optimal sizing and locating distribution substations and feeders in a time dynamic power distribution systems. Their model captured the non linear costs due to power flow and the effects of harmonics. They used the Bender's decomposition technique as a solution methodology.

Ranjan *et al.* (2002) suggested three new techniques for radial distribution system planning that they claimed their own contributions. They proposed (i) optimum location of the substation, (ii) connection of load points to substation in optimum route and (iii) selection of optimal branch conductor selection. Ranjan *et al.* (2002) modified the method proposed by Hsu and Chen (1990) by incorporating R and X of each branch to identify the optimum location of substation that did not give any appreciable improvement. The second and third methods proposed by Ranjan *et al.* (2002) were already proposed by Chen and Hsu (1989), Hsu and Chen (1990) and Tram and Wall (1988) respectively. Moreover, Ranjan *et al.* (2002) did not provide the co-ordinate of the substation.

Planning of power distribution system must be carried out properly because the exact optimum location of the substation can only ensure minimum cost. The selection of optimal branch conductor once again reduces the cost. In the present chapter the following have been carried out:

(i) Identification of the optimum location for the substation using Genetic Algorithm (GA) using the expression of VSI proposed in Chapter 3 in fitness function,

(ii) connection of load points in optimum route using knowledge-based expert systems proposed by Chen and Hsu (1989) and Hsu and Chen (1990),

(iii) selection of optimal branch conductors using the method proposed by Tram and Wall (1988) using the proposed expression for VSI as one of the constraints and

(iv) identification of the most sensitive node of the network using the proposed expression of VSI.

The critical values of TPL and TQL of the system selected by utility have been computed, beyond which the system will collapse.

4.2 Genetic Algorithm (GA)

Genetic Algorithm is an efficient technique that searches for the optimum value. Genetic Algorithm is a computerized search and optimization algorithm based on the mechanics of natural genetics and natural selection. Holland of University of Michigan, Ann Arbor, envisaged the concept of these algorithms in the mid-sixties and published his seminal work [Holland (1975)]. The Genetic Algorithm is discussed below.

4.2.1Terminology of Genetic Algorithm (GA)

- Population – It is a subset of the solution space of the problem. An initial randomized population is assumed in our case. A population is a collection of organisms.
- Generation – It is the term for the collection of organisms (population) at some particular point of time in the run.
- Gene – A gene is a means by which a trait in an organism is expressed. A gene will decide the fitness of an organism and it is an atomic unit.
- Chromosome – It is a collection of genes that gives an organism some meaning.

- Organism – It may contain a single chromosome or multiple chromosomes. An organism is a particular solution of the problem under consideration.
- Encoding – Encoding is a means of transforming the solution set into a form that is apt to solve by employing GA. Binary encoding is the most common method and this will be used here. This is a method where chromosomes are binary strings and genes are bits. An example "000111" would normally correspond to an integer solution of 7 if the LSB is weighted as 1. Each and every bit location is treated as a gene. The above organism could also have a different phenotype (external view or actual meaning of the chromosome) by assigning a weight of 0.5 to the LSB. In that case the organism would correspond to a solution of 3.5 (floating point).
- Fitness – In maximization problem an organism that corresponds to a greater value is considered to be fitter than an organism that corresponds to a smaller value. In minimization problem an organism that corresponds to a smaller value is considered to be fitter than an organism that corresponds to a smaller value.
- Fitness function – This is a function that evaluates how fit an organism is. The fitness function decides the efficiency of the Genetic Algorithm and hence should be chosen meticulously. In a minimization problem with binary encoding a string of 1's

correspond to least fitness and a string of 0's will mean an optimized organism with maximum fitness.

- Reproduction – This is the process of producing the next set of organisms or the next generation. The techniques used for reproduction and cross over and mutation are described below. As in the case of natural evolution, a fitter organism will obviously have more chances to reproduce than its weaker counterpart. This will hence tend to propel organisms of future generations towards achieving better fitness that ultimately will result in achieving optimum.
- Cross over – Considering a binary encoding, cross over is a process that produces new organisms by extracting one half of the genes (bits) from one organism and other set of genes (bits) from another organism. Crossing over will occur at some randomly chosen point in the chromosome.
- Mutation – It will lead to different organisms by randomly altering one of the genes of the organisms. Mutation will occur at a rate called Mutation Rate that is generally very low.

4.2.2 Organization of Genetic Algorithm (GA)

The organization Genetic Algorithm is presented below.

- **Initialization of Organisms** – Initialization of organisms is usually done on a random basis. This initial set of organisms is the starting point of any Genetic Algorithm. When binary encoding is employed initialization would involve producing a set of random strings.

- **Evaluation of Organisms** - Organisms need to be evaluated in order to decide how fit they are. A fitness function does this job in a Genetic Algorithm. The efficiency of a Genetic Algorithm will depend upon the quality of the fitness function. In maximization problem the fitness function should essentially return the decimal value of the encoded binary string, while in a minimization problem an organism that has a number of genes as 1's should map to a very low fitness value.
- **Production of next generation** – In order to move towards an optimized set of organisms (the solution of the problem) reproduction needs to be carried out. Cross over and Mutation is two basic methods by which this is achieved. Survival of the fitness needs to be explained in this context. An organism with a better fitness value will have a better chance of reproduction and transferring its traits to the next generation than its weaker counterpart. The new generation of organisms is evaluated again and again asked to be reproduced. This mimics the natural process of evolution. Organisms will get

better through the generations and at some point of time the difference between the fitness levels of successive generations reach an extremely small value.

The algorithm will be terminated after achieving this state.

The algorithm is presented below.

Step -1 : Start

Step -2 : Population Initialization

Step -3 : Organism fitness Evaluation

Step -4 : Produce next generation

Step -5 : If Optimality is achieved then go to step-6. Otherwise go to step - 4.

Step -6 : Stop

Figure 4.1 shows the flow diagram of Genetic Algorithm to identify the optimum location for the substation.

4.2.3 Roulette Wheel Selection Method

In order to produce the next generation we need to select organisms so that they can be reproduced. The roulette wheel selection method is one of the most common methods that are used to accomplish this process.

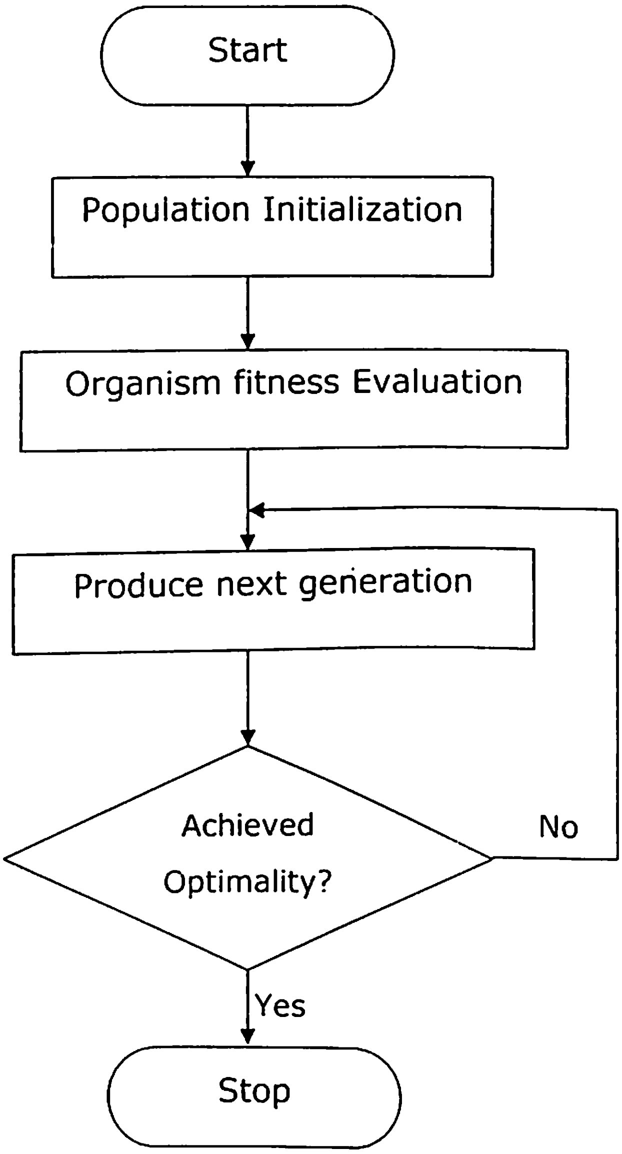


Figure 4.1 Flow Diagram of Genetic Algorithm (GA) for Optimum Location of Substation

- Selection should be based on the fitness levels of organisms, meaning that a fitter organism should be given more chance to mate.
- There should be some element of chance involved as in the natural evolution process

The Roulette wheel method satisfies both these criteria.

Organisms are allocated space (sectors) on a wheel depending on their level of fitness. An organism with better fitness is allocated more space than its weaker counterpart.

Next, the wheel is spun and the organism corresponding to that space which is pointed to the pointer of the wheel is chosen for mating.

From the above explanation it is obvious that both the element of the chance and the fitness of organism are taken into consideration in this process.

4.2.4 Producing the Next Generation

Crossover

Once the organisms that are to be mated are decided, cross over at random point is employed to accomplish the process of reproduction. In this case, single point cross over has been employed. This means that the offspring string is a copy of parent 1 up to a randomly chosen point, and a copy of parent 2 from that point onwards.

For example:

Parent 1	1 0 0 / 1 1 0
Parent 2	0 1 1 / 1 0 0
Offspring	1 0 0 / 1 0 0

Here we can see the random crossover point is gene position 3 in the chromosomes.

Crossover is carried out for both X and Y chromosomes (coordinates) of the organisms (sub-station).

Mutation

Mutation is another genetic operator that ensures that the vital bit of information is introduced into the generation.

Mutation is a random alternation of some gene in a chromosome

Gene before mutation: 1 1 1 1 1

Gene after mutation : 1 1 1 1 0

As we can see gene at position 0 has been changed from1 to 0.

4.3 Identification of the Optimum Location for the Substation Using Genetic Algorithm (GA)

A brief description of the elements in the process of using Genetic Algorithm to solve the problem is given below.

An organism in the present case will mean a possible location of the sub-station. An organism will comprise of two chromosomes – the X and Y co-ordinates. The X and Y co-ordinates will be encoded as binary strings. A generation is hence a set for pairs of co-ordinates of possible sub-station locations on the map. A good fitness function in this case will be one that will assign maximum fitness to a minimum VSI. For each and every organism in a generation, the VSI of all the load points from the sub-station (S/S) will be computed and the organisms are ranked in the ascending order of this VSI. The fitness function is the max of this min VSI.

In any generation,

$$Fi = Max\{Min(VSI)\} \tag{4.1}$$

Fi is the fitness of organism i

where VSI is the voltage stability index of most sensitive node.

Reproduction of organisms is carried out using crossing over and mutation as the Genetic Operations.

4.4 Knowledge Based Expert System

The most common form of architecture used in the present planning work is the rule based system. Each rule represents a small chunk of knowledge relating to the given domain of expertise. A number of related rules collectively may correspond to a chain of inferences that lead from some initially known facts to some useful conclusions. When the known facts support the conditions in the rule's left side, the conclusion or action part of the rule is then accepted as known or at least known with some degree of certainty.

A process of chaining through the rules recursively, either in a forward or backward direction, accomplishes inference in production systems until a conclusion is reached or until failure occurs. The selection of rules used in the chaining process is determined by matching current facts against the domain knowledge or variables in rules and choosing among a candidate set of rules that meet some given criteria, such as specificity. The inference process is typically carried out in an interactive mode with the user providing input parameters needed to complete the chain rule process. Figure 4.2 shows the main components of a typical expert system.

The heuristic rules are used for distribution system planning available in Hsu and Chen (1990) that are given below after modification:

Rule 1: If a substation is located on river
then the near optimum location is taken.

Rule 2: If a substation is located on provincial highway
then the near optimum location is taken.

Rule 3: If a substation is located on freeway
then the near optimum location is taken.

Rule 4: If the substation location causes the social problem
then the near optimum location is taken.

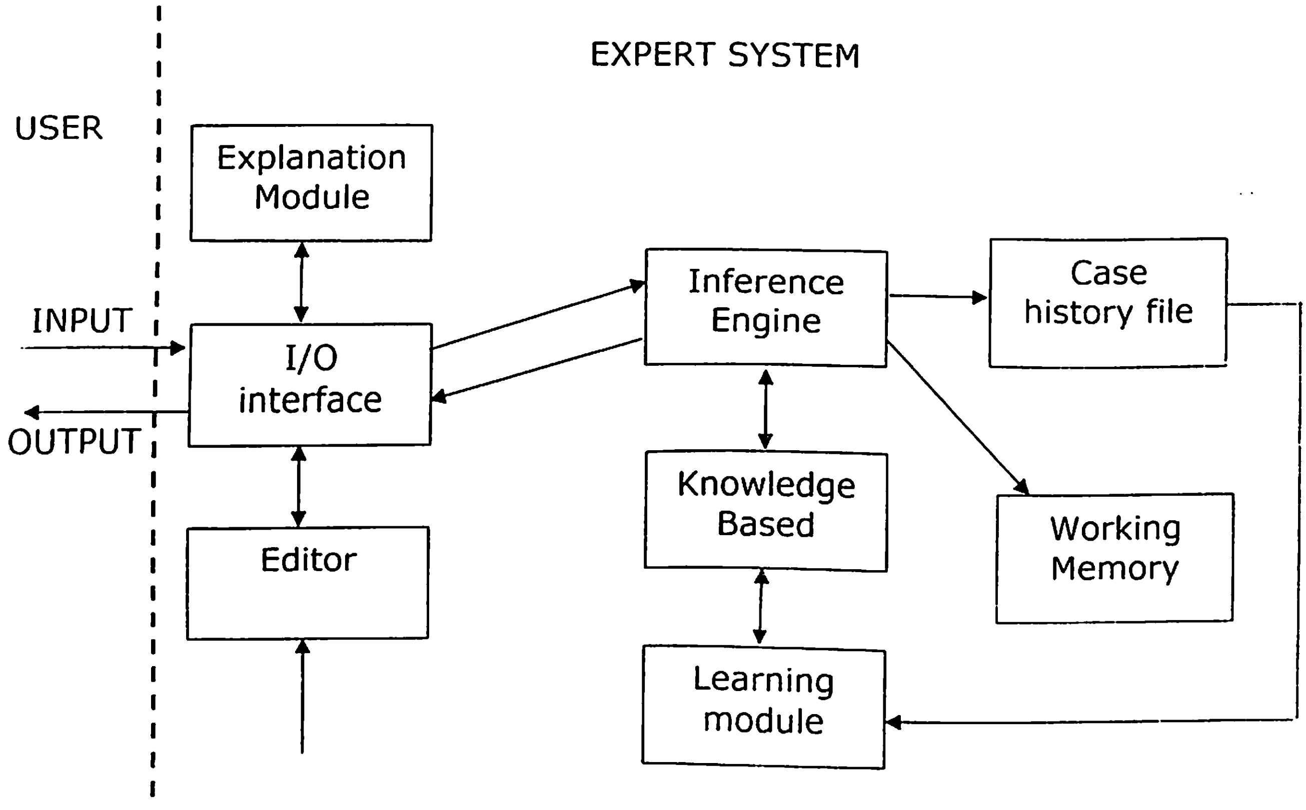


Figure 4.2 Components of Expert System

Rule 5: If a land cost for substation is too high

then the near optimum location is taken.

If the identified optimum location does not meet any of the above heuristic conditions, the near optimum location of the substation is identified.

4.5 Connection of Load Points to Substation [Chen and Hsu(1989)]

After identification of the optimum location for the substation it is required to connect all the load points in optimum route. Before connecting any two load points the following proposed heuristic rules are checked:

- Existence of residential area or commercial complex between the two load points.
- Existence of commercial plantation area between two load points.
- Existence of any cotton industries between two load points.

If any of the above heuristic rules is violated then the connection of load point (say X) to load point (say Y) is discarded and the previous load point i.e., load point X is connected to its closed neighbouring load point (say Z).

The following cases are considered for connecting the load points:

Single Feeder:

Figure 4.3 shows load points and the substation. In single feeder case only one feeder will come out.

Step 1: The distances of all load points from the substation are computed. Set N(0)= Φ and I=0.

Step 2: The minimum distance from substation (nearest load point) is found out, say load point k.

Step 3: The load point k (say load point 8) is connected to substation i.e., set I=I+1, N(I)=N(I–1) Ư k and M(I)=M(I–1)-(k)

Step 4: The distances of all remaining the load-points i.e., set M(I) are computed from the nodes in N(I).

Step 5: Select the nearest node in set M(I) say k and update set I=I+1, N(I)=N(I-1) Ư k and M(I)=M(I-1)-(k)

Step 6 : Go to Step 4 if M(I)# Φ , else stop.

The load point corresponding to this minimum distance (say load point 4) is connected to load point 8. The distances of all remaining load points will be computed from the load point 4.

Two Feeders:

Figure 4.3 is considered once again. Two feeders will come out from substation.

Step 1: The distance of all load points from the substation is computed. Set N(0)= Φ and I=0

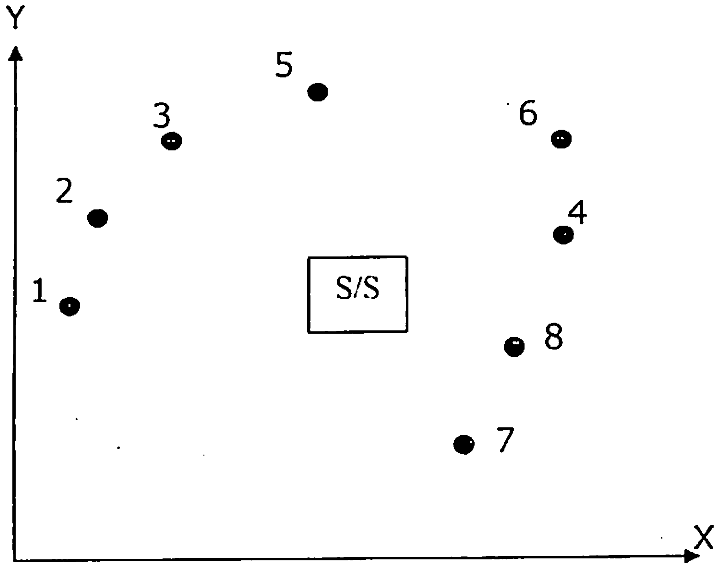


Figure 4.3 Load Points and Substation (S/S)

Step 2: The two minimum distances are found out, say load point k and k+1.

Step 3: The load points (say load point 8 and 4) corresponding to these minimum distances are connected to the substation i.e., set I=I+1, N(I)=N(I–1) ∪ k and M(I)=M(I–1)–(k).

Step 4: The distances of all remaining load points are computed from load points 4 and 8.

Step 5: The two minimum distances with respect to load point 4 and load point 8 are computed.

Step 6: Say, the load points 6 and 7 are nearest to load points 4 and 8 respectively. The load points 6 and 7 are connected to load points 4 and 8 respectively.

Now load points 6 and 7 are taken into account to compute the distances of all remaining load points.

Following steps 4, 5 and 6, it is possible to connect all the load points.

Similarly, we can connect all the load points for three and four feeder cases.

4.6 Optimal Branch Conductor Selection [Tram and Wall (1988)]

Proper selection of branch conductor further reduces the planning cost also. Although uniform conductor can reduce the loss of the system, it increases the planning cost. A compromise should be made between loss and cost. To select the optimum branch conductors, the method proposed by Tram and Wall (1988) is used taking the expression of VSI proposed in Chapter 3 as one of the constraints. Four different types of conductors Squirrel, Weasel, Rabbit and Raccon are taken in this work and the data of these conductors are available in Ranjan *et al.* (2003) that are shown in Appendix-D (Table D.1).

The general expression of branch current for branch-jj having k-type conductor is given by

$$I(jj,k) = \sum_{i=1}^{N(jj)} IL\{IE(jj,i),k\} \tag{4.2}$$

where

N(jj) is the total number of nodes beyond branch-jj,

IE{(jj,i),k} is the receiving-end node.

The load current of node i is as follows:

$$IL(i,k) = \frac{PL(i) - jQL(i)}{V^{*}(i,k)} \tag{4.3}$$

The voltage of node m2 is given by

$$V(m2) = V(m1) - I(jj)Z(jj) \tag{4.4}$$

where i = 2,3,....NB and k=1,2.....,NTYPE

Equation (4.3) suggests that as node voltages are different for different type of conductors, load currents are also different for different type of conductors.

Real power loss and Reactive power loss of branch-jj with k-type conductor are given by

$$LP(jj,k) = |I(jj,k)|^2 R(jj,k) \qquad (4.5)$$

$$LQ(jj,k) = |I(jj,k)|^2 X(jj,k) \qquad (4.6)$$

respectively.

To compute the cost of losses the following expression proposed by Tram and Wall (1988) is used.

$$L(i, k) = 10^{-5} \times C1 \times R(k) \times L(i) \times \{P(i)\}^2 \qquad (4.7)$$

where

C1 = composite cost of losses (Rs per kW)

R(k) = per unit resistances

L(i) = length of feeder segment i

P(i) = Power flow through segment i (kVA)

To compute the composite cost of losses (C1) the following expression proposed by Tram and Wall (1988) is used.

$$C1 = D + 8760 \times LSF \times E \qquad (4.8)$$

where

D = levelized annual demand cost of losses per kW = Rs 4000 per kW

LSF = Loss factor = 0.20

E = Energy cost of losses (Rs/kWh) = Rs 1.00 per kWh

To compute the cost of capital [C(i,k)], the following expression proposed by Tram and Wall (1988) is used.

$$C(i,k) = CC \times PP(k) \times L(i) \tag{4.9}$$

where

PP(k) = purchase price of conductor k (Rs/ Unit length)

L(i) = length of feeder segment i

CC = Carrying charge rate (feeders) = 0.10

The objective function to be minimized is

$$F(i,k) = L(i,k) + C(i,k) \tag{4.10}$$

The current through the feeder is compared with the maximum current carrying capacity of the conductor and proper conductor is selected. The algorithm to select the optimal branch conductor proposed by Tram and Wall (1988) is used here. It is modified taking the proposed expression for VSI as one of the constraints and presented below.

```
Step 1  :  Read real system data and assume a flat voltage start
Step 2  :  Identify the nodes beyond all the branches using IDENT
           software as discussed in Art. 3.4.
Step 3  :  IT=1 and   DVMAX = 0.0
Step 4  :  Compute the load current using Equation (4.3)
Step 5  :  jj=1
Step 6  :  m1 = IR(jj)
Step 7  :  m2 = IS(jj)
Step 8  :  k = 1
```

```
Step 9  : Compute I(jj ,k) and V(m2,k) using Equations (4.2) and
          (4.4) respectively.
Step 10 : Set VV(k)=|V(m2,k)| and CII(k)=|I(jj,k)|
Step 11 : Compute LP(jj,k) using Equation (4.5).
Step 12 : Compute L(jj,k) and CC(jj,k) using Equations (4.7) and
          (4.9) respectively.
Step 13 : Compute F(jj,k) using Equation (4.10).
Step 14 : Set FN(k) = F(jj,k)
Step 15 : k = k+1
Step 16 : If (k≤NTYPE) go to step-9 otherwise go to step 17
Step 17 : Arrange FN(k) in an ascending order for k=1,2,.......,NTYPE
          and store different k for ascending order of FN(k) in KS(j).
Step 18 : J6=1
Step 19 : M33=KS(J6)
Step 20 : If {VV(M33) > $V_{min}$ and CII(M33) ≤ CMAX(M33)
          and L(M33) ≥ 0}
          go to step 23
          otherwise go to step 21
Step 21 : J6=J6+1
Step 22 : If (J6 ≤ NTYPE) go to step 19
          otherwise go to step 23
Step 23 : Compute receiving-end voltage using equation 4.4
```

```
Step 24  :  Compute absolute change in voltage at node m2 i.e.,
            DV(m2) = ABS (|V(m2)|-VV(m2)
Step 25  :  If(DV(m2) > DVMAX)
             DVMAX = DV(m2)
Step 26  :  TYPE(jj) = M33
Step 27  :  jj = jj+1
Step 28  :  If (jj ≤ LN1) go to step 7
             otherwise go to step 29.
Step 29  :  If (DVMAX < ε) go to step 31 ,
             otherwise go to step 30
Step 30  :  If (IT≤ITMAX) go to step 6
             otherwise print diagnostics and go to step 32
Step 31  :  Solution has converged, write voltages, power losses,
            types of conductor for each branch, feeder losses etc.
Step 32  :  Stop
```

4.7 Most Sensitive Node of the Network

The VSI of all nodes of the network is computed by the new expression of VSI proposed in Chapter-3. The node having minimum value of VSI will be the most sensitive node. The algorithm for identifying the most sensitive node of the network has been given in Chapter-3 (Art. 3.5). The critical values of TPL and TQL are computed for the network selected by utility using the same algorithm used in Chapter-3 (Art. 3.6), beyond which the system will collapse.

4.8 Examples

To demonstrate the effectiveness of the proposed method, two examples have been selected. There are 53 load points in the first example. The coordinate and load kVA of each of these load points are available in Ranjan *et al.*(2002) and shown in Appendix-E (Table E.1). The total load kVA of the system is 2183 kVA. Using Genetic Algorithm technique, the optimum co-ordinate of the substation is (9.370, 11.378) for this 53 load points while the co-ordinate of the substation using the method proposed by Ranjan *et al.* (2002) is (9.137, 11.041) for this 53 load points.

The load flow results and computed value of VSI at all nodes as well as branch number, sending-end node, receiving-end node, selected optimal conductor for each branch and length of each branch have been shown in Table 4.1, Table 4.2 and Table 4.3 respectively using the method of Genetic Algorithm for case of single feeder.

The load flow results and computed value of VSI at all nodes as well as branch number, sending-end node, receiving-end node, selected optimal conductor for each branch and length of each branch have been shown in Table 4.4, Table 4.5 and Table 4.6 respectively using the method of Genetic Algorithm for case of two feeders.

Table 4.1 Load Flow Results for Example 1 having Single Feeder Computed by the Proposed Method (GA)

Node Number	Voltage Magnitude (p.u.)
S/S	1.000000
1	**0.914824**
2	0.949447
3	0.915316
4	0.919566
5	0.919823
6	0.920758
7	0.922301
8	0.915071
9	0.969019
10	0.951773
11	0.958823
12	0.962873
13	0.952840
14	0.924463
15	0.930569
16	0.917406
17	0.918249
18	0.949556
19	0.958998
20	0.956216
21	0.950313
22	0.953716
23	0.922564
24	0.918893
25	0.929724
26	0.938392
27	0.964051
28	0.949886
29	0.950062
30	0.949502
31	0.949746
32	0.949098
33	0.949412
34	0.950845
35	0.950340
36	0.949962

	Continued...
37	0.917674
38	0.915113
39	0.917224
40	0.929564
41	0.960584
42	0.959583
43	0.957541
44	0.958559
45	0.973485
46	0.948471
47	0.947740
48	0.947274
49	0.950116
50	0.916216
51	0.930748
52	0.954449
53	0.946776

Table 4.2 Values of VSI for All Nodes of Example 1 having Single Feeder Computed by the Proposed Method (GA)

Node Number	VSI
1	**0.700407**
2	0.812610
3	0.701912
4	0.715041
5	0.715839
6	0.718751
7	0.723580
8	0.701163
9	0.881678
10	0.820590
11	0.845137
12	0.859349
13	0.824286
14	0.730326
15	0.749883
16	0.708342
17	0.710953
18	0.812664
19	0.845803
20	0.836030
21	0.815577
22	0.827312
23	0.724407
24	0.712932
25	0.747163
26	0.775201
27	0.863729
28	0.814116
29	0.814713
30	0.812798
31	0.813635
32	0.811416
33	0.812492
34	0.817402
35	0.815672
36	0.814374
37	0.709174

	Continued...
38	0.701291
39	0.707784
40	0.746649
41	0.851406
42	0.847869
43	0.840672
44	0.844258
45	0.896750
46	0.809274
47	0.806781
48	0.805198
49	0.814902
50	0.704678
51	0.750359
52	0.829836
53	0.803504

Table 4.3 Branch Number, Sending–end Node, Receiving–end Node, Selected Optimal Conductor for Each Branch and Length of Each Branch for Case of Single Feeder Computed by the Proposed Method (GA) for Example 1

Branch Number (jj)	Sending-end Node (m1)	Receiving-end Node (m2)	Selected Optimal Branch Conductor	Length of Each Branch(jj) (km)
1	S/S	45	4---->RACCON	2.702551
2	45	9	4---->RACCON	1.581139
3	45	12	4---->RACCON	1.581139
4	9	27	4---->RACCON	1.802776
5	12	41	4---->RACCON	1.802776
6	41	19	3---->RABBIT	1.500000
7	19	44	1---->SQUIRREL	1.581139
8	41	42	1---->SQUIRREL	1.802776
9	19	43	2---->WEASEL	1.802776
10	43	20	1---->SQUIRREL	1.581139
11	27	11	4---->RACCON	2.061553
12	11	52	4---->RACCON	1.802776
13	52	13	4---->RACCON	1.581139
14	52	10	4---->RACCON	2.061553
15	10	29	3---->RABBIT	2.000000
16	29	28	4---->RACCON	1.581139
17	29	30	4---->RACCON	2.000000
18	10	21	3---->RABBIT	2.061553
19	21	36	4---->RACCON	1.581139
20	13	34	3---->RABBIT	2.121320
21	34	49	4---->RACCON	1.414214
22	49	33	4---->RACCON	1.581139
23	33	32	4---->RACCON	1.414214
24	34	35	1---->SQUIRREL	1.802776
25	12	18	4---->RACCON	2.549510
26	18	46	4---->RACCON	1.581139
27	46	47	4---->RACCON	1.802776
28	47	48	4---->RACCON	1.581139
29	48	53	4---->RACCON	2.236068
30	18	26	4---->RACCON	2.500000
31	26	51	4---->RACCON	1.802776
32	51	15	4---->RACCON	1.581139

				Continued...
33	51	14	4---->RACCON	1.802776
34	14	7	4---->RACCON	1.118034
35	14	23	4---->RACCON	1.500000
36	51	25	4---->RACCON	1.802776
37	25	40	4---->RACCON	1.414214
38	7	24	4---->RACCON	2.000000
39	24	16	4---->RACCON	1.581139
40	16	39	4---->RACCON	1.581139
41	16	50	4---->RACCON	1.581139
42	50	3	4---->RACCON	1.414214
43	3	38	4---->RACCON	0.500000
44	24	17	4---->RACCON	2.121320
45	3	8	4---->RACCON	2.121320
46	23	6	4---->RACCON	2.236068
47	6	5	4---->RACCON	1.802776
48	5	4	4---->RACCON	1.118034
49	38	1	4---->RACCON	2.500000
50	17	37	4---->RACCON	2.500000
51	21	31	4---->RACCON	2.549510
52	31	2	4---->RACCON	2.692582
53	20	22	1---->SQUIRREL	4.472136

Table 4.4 Load Flow Results for Example 1 having Two Feeders Computed by the Proposed Method (GA)

Node Number	Voltage Magnitude (p.u.)
S/S	1.000000
1	0.969962
2	0.962198
3	0.970999
4	0.982054
5	0.982661
6	0.984262
7	0.978126
8	0.970417
9	0.983416
10	0.966422
11	0.973369
12	0.985519
13	0.967474
14	0.980768
15	0.977026
16	0.973510
17	0.973377
18	0.973270
19	0.981734
20	0.979017
21	0.964356
22	0.976576
23	0.986416
24	0.974912
25	0.976343
26	0.977747
27	0.978522
28	0.964300
29	0.964737
30	0.963342
31	0.962944
32	**0.962140**
33	0.962923
34	0.965508
35	0.965010
36	0.963481
37	0.972006

Continued...

38	0.970649
39	0.973077
40	0.975957
41	0.983283
42	0.982305
43	0.980311
44	0.981305
45	0.987818
46	0.973547
47	0.974677
48	0.973533
49	0.964192
50	0.972081
51	0.978730
52	0.969059
53	0.972307

Table 4.5 Values of VSI for All Nodes of Example 1 having Two Feeders Computed by the Proposed Method (GA)

Node Number	VSI
1	0.885155
2	0.857152
3	0.888945
4	0.930125
5	0.932421
6	0.938510
7	0.915319
8	0.886815
9	0.935260
10	0.872289
11	0.897606
12	0.943310
13	0.876103
14	0.925202
15	0.911218
16	0.898172
17	0.897679
18	0.897291
19	0.928910
20	0.918668
21	0.864858
22	0.909530
23	0.946401
24	0.903343
25	0.908672
26	0.913914
27	0.916769
28	0.864665
29	0.866228
30	0.861232
31	0.859809
32	**0.856943**
33	0.859736
34	0.868999
35	0.867215
36	0.861732
37	0.892634
38	0.887665

	Continued...
39	0.896578
40	0.907242
41	0.934781
42	0.931075
43	0.923534
44	0.927291
45	0.951865
46	0.898310
47	0.902479
48	0.898257
49	0.864275
50	0.892911
51	0.917588
52	0.881828
53	0.893741

Table 4.6 Branch Number, Sending–end Node, Receiving–end Node, Selected Optimal Conductor for Each Branch and Length of Each Branch for Case of Two Feeders Computed by the Proposed Method (GA) for Example 1

Branch Number (jj)	Sending-end Node (m1)	Receiving-end Node (m2)	Selected Optimal Branch Conductor	Length of Each Branch(jj) (km)
1	S/S	45	4---->RACCON	2.702551
2	S/S	23	4---->RACCON	2.744410
3	23	14	4---->RACCON	1.500000
4	14	7	4---->RACCON	1.118034
5	45	9	4---->RACCON	1.581139
6	45	12	4---->RACCON	1.581139
7	14	51	4---->RACCON	1.802776
8	51	15	3---->RABBIT	1.581139
9	7	25	2---->WEASEL	1.802776
10	25	40	1---->SQUIRREL	1.414214
11	9	27	4---->RACCON	1.802776
12	12	41	4---->RACCON	1.802776
13	41	19	3---->RABBIT	1.500000
14	19	44	1---->SQUIRREL	1.581139
15	51	26	1---->SQUIRREL	1.802776
16	41	42	1---->SQUIRREL	1.802776
17	19	43	2---->WEASEL	1.802776
18	43	20	1---->SQUIRREL	1.581139
19	7	24	4---->RACCON	2.000000
20	24	16	4---->RACCON	1.581139
21	16	39	1---->SQUIRREL	1.581139
22	16	50	3---->RABBIT	1.581139
23	50	3	3---->RABBIT	1.414214
24	3	38	2---->WEASEL	0.500000
25	27	11	4---->RACCON	2.061553
26	11	52	4---->RACCON	1.802776
27	52	13	4---->RACCON	1.581139
28	52	10	4---->RACCON	2.061553
29	10	29	3---->RABBIT	2.000000
30	29	28	1---->SQUIRREL	1.581139
31	29	30	1---->SQUIRREL	2.000000
32	10	21	2---->WEASEL	2.061553

Continued...

33	21	36	1---->SQUIRREL	1.581139
34	24	17	1---->SQUIRREL	2.121320
35	3	8	1---->SQUIRREL	2.121320
36	13	34	3---->RABBIT	2.121320
37	34	49	2---->WEASEL	1.414214
38	49	33	2---->WEASEL	1.581139
39	33	32	1---->SQUIRREL	1.414214
40	34	35	1---->SQUIRREL	1.802776
41	23	6	3---->RABBIT	2.236068
42	6	5	2---->WEASEL	1.802776
43	5	4	1---->SQUIRREL	1.118034
44	15	47	3---->RABBIT	2.500000
45	47	48	1---->SQUIRREL	1.581139
46	47	46	2---->WEASEL	1.802776
47	46	18	1---->SQUIRREL	1.581139
48	48	53	1---->SQUIRREL	2.236068
49	38	1	1---->SQUIRREL	2.500000
50	17	37	1---->SQUIRREL	2.500000
51	21	31	1---->SQUIRREL	2.549510
52	31	2	1---->SQUIRREL	2.692582
53	20	22	1---->SQUIRREL	4.472136

The load flow results and computed value of VSI of all nodes as well as branch number, sending-end node, receiving-end node, selected optimal conductor for each branch and length of each branch have been shown in Table 4.7, Table 4.8 and Table 4.9 respectively using the method of Genetic Algorithm for case of three feeders.

The load flow results and computed value of VSI at all nodes as well as branch number, sending-end node, receiving-end node, selected optimal conductor for each branch and length of each branch have been shown in Table 4.10, Table 4.11 and Table 4.12 respectively using the method proposed by Ranjan *et al.* (2002) for case of single feeder.

The load flow results and computed value of VSI at all nodes as well as branch number, sending-end node, receiving-end node, selected optimal conductor for each branch and length of each branch have been shown in Table 4.13, Table 4.14 and Table 4.15 respectively using the method proposed by Ranjan *et al.* (2002) for case of two feeders.

The load flow results and computed value of VSI at all nodes as well as branch number, sending-end node, receiving-end node, selected optimal conductor for each branch and length of each branch have been shown in Table 4.16, Table 4.17 and Table 4.18 respectively using the method proposed by Ranjan *et al.* (2002) for case of three feeders.

Table 4.19 compares the losses and feeder length of the proposed method and the method proposed by Ranjan *et al.*(2002).

Table 4.7 Load Flow Results for Example 1 having Three Feeders Computed by the Proposed Method (GA)

Node Number	Voltage Magnitude (p.u.)
S/S	1.000000
1	**0.969962**
2	0.970668
3	0.970999
4	0.982054
5	0.982661
6	0.984262
7	0.978126
8	0.970417
9	0.991702
10	0.974855
11	0.981742
12	0.993096
13	0.975898
14	0.980768
15	0.977026
16	0.973510
17	0.973377
18	0.973270
19	0.989341
20	0.986644
21	0.972807
22	0.984222
23	0.986416
24	0.974912
25	0.976343
26	0.977747
27	0.986850
28	0.972751
29	0.973184
30	0.971802
31	0.971407
32	0.970610
33	0.971387
34	0.973949
35	0.973455
36	0.971940
37	0.972006

	Continued...
38	0.970649
39	0.973077
40	0.975957
41	0.990878
42	0.989907
43	0.987928
44	0.988915
45	0.995377
46	0.973547
47	0.974677
48	0.973533
49	0.972644
50	0.972081
51	0.978730
52	0.977469
53	0.972307

Table 4.8 Values of VSI for All Nodes of Example 1 having Three Feeders Computed by the Proposed Method (GA)

Node Number	VSI
1	**0.885155**
2	0.887733
3	0.888945
4	0.930125
5	0.932421
6	0.938510
7	0.915319
8	0.886815
9	0.967084
10	0.903137
11	0.928894
12	0.972657
13	0.907017
14	0.925202
15	0.911218
16	0.898172
17	0.897679
18	0.897291
19	0.958035
20	0.947633
21	0.895575
22	0.938352
23	0.946401
24	0.903343
25	0.908672
26	0.913914
27	0.948382
28	0.895378
29	0.896969
30	0.891885
31	0.890437
32	0.887521
33	0.890363
34	0.899788
35	0.897973
36	0.892394
37	0.892634
38	0.887665

	Continued...
39	0.896578
40	0.907242
41	0.963997
42	0.960232
43	0.952575
44	0.956390
45	0.981595
46	0.898310
47	0.902479
48	0.898257
49	0.894981
50	0.892911
51	0.917588
52	0.912843
53	0.893741

Table 4.9 Branch Number, Sending-end Node, Receiving-end Node, Selected Optimal Conductor for Each Branch and Length of Each Branch for Case of Three Feeders Computed by the Proposed Method (GA) for Example 1

Branch Number (jj)	Sending-end Node (m1)	Receiving-end Node (m2)	Selected Optimal Branch Conductor	Length of Each Branch(jj) (km)
1	S/S	45	4---->RACCON	2.702551
2	S/S	23	4---->RACCON	2.744410
3	S/S	9	4---->RACCON	3.006623
4	23	14	4---->RACCON	1.500000
5	14	7	4---->RACCON	1.118034
6	45	12	4---->RACCON	1.581139
7	9	27	4---->RACCON	1.802776
8	14	51	4---->RACCON	1.802776
9	51	15	3---->RABBIT	1.581139
10	7	25	2---->WEASEL	1.802776
11	25	40	1---->SQUIRREL	1.414214
12	12	41	4---->RACCON	1.802776
13	41	19	3---->RABBIT	1.500000
14	19	44	1---->SQUIRREL	1.581139
15	51	26	1---->SQUIRREL	1.802776
16	41	42	1---->SQUIRREL	1.802776
17	19	43	2---->WEASEL	1.802776
18	43	20	1---->SQUIRREL	1.581139
19	7	24	4---->RACCON	2.000000
20	24	16	4---->RACCON	1.581139
21	16	39	1---->SQUIRREL	1.581139
22	16	50	3---->RABBIT	1.581139
23	50	3	3---->RABBIT	1.414214
24	3	38	2---->WEASEL	0.500000
25	27	11	4---->RACCON	2.061553
26	11	52	4---->RACCON	1.802776
27	52	13	4---->RACCON	1.581139
28	52	10	4---->RACCON	2.061553
29	10	29	3---->RABBIT	2.000000
30	29	28	1---->SQUIRREL	1.581139
31	29	30	1---->SQUIRREL	2.000000
32	10	21	2---->WEASEL	2.061553

Continued...

33	21	36	1---->SQUIRREL	1.581139
34	24	17	1---->SQUIRREL	2.121320
35	3	8	1---->SQUIRREL	2.121320
36	13	34	3---->RABBIT	2.121320
37	34	49	2---->WEASEL	1.414214
38	49	33	2---->WEASEL	1.581139
39	33	32	1---->SQUIRREL	1.414214
40	34	35	1---->SQUIRREL	1.802776
41	23	6	3---->RABBIT	2.236068
42	6	5	2---->WEASEL	1.802776
43	5	4	1---->SQUIRREL	1.118034
44	15	47	3---->RABBIT	2.500000
45	47	48	1---->SQUIRREL	1.581139
46	47	46	2---->WEASEL	1.802776
47	46	18	1---->SQUIRREL	1.581139
48	48	53	1---->SQUIRREL	2.236068
49	38	1	1---->SQUIRREL	2.500000
50	17	37	1---->SQUIRREL	2.500000
51	21	31	1---->SQUIRREL	2.549510
52	31	2	1---->SQUIRREL	2.692582
53	20	22	1---->SQUIRREL	4.472136

Table 4.10 Load Flow Results for Example 1 having Single Feeder Computed by the Method Proposed by Ranjan *et al.* (2002)

Node Number	Voltage Magnitude (p.u.)
S/S	1.000000
1	0.952120
2	0.858800
3	0.953177
4	0.972044
5	0.972657
6	0.974275
7	0.960436
8	0.952583
9	0.880084
10	0.861024
11	0.868816
12	0.890430
13	0.862204
14	0.963128
15	0.942615
16	0.955734
17	0.955599
18	0.918319
19	0.895696
20	0.894284
21	0.859758
22	0.893227
23	0.976451
24	0.957163
25	0.958621
26	0.950942
27	0.874595
28	0.859345
29	0.859540
30	0.858920
31	0.859131
32	**0.858542**
33	0.858890
34	0.860474
35	0.860253
36	0.859369
37	0.954202

	Continued...
38	0.952820
39	0.955293
40	0.958227
41	0.897027
42	0.905648
43	0.894844
44	0.895510
45	0.885019
46	0.918435
47	0.928132
48	0.927657
49	0.859667
50	0.954279
51	0.951953
52	0.863982
53	0.927147

Table 4.11 Values of VSI for All Nodes of Example 1 having Single Feeder Computed by the Method Proposed by Ranjan *et al.* (2002)

Node Number	VSI
1	0.821801
2	0.543961
3	0.825453
4	0.892779
5	0.895029
6	0.900995
7	0.850878
8	0.823401
9	0.599886
10	0.549605
11	0.569735
12	0.628566
13	0.552633
14	0.860139
15	0.789318
16	0.834346
17	0.833871
18	0.711170
19	0.643636
20	0.639589
21	0.546389
22	0.636569
23	0.908021
24	0.839330
25	0.844469
26	0.817740
27	0.585051
28	0.545345
29	0.545835
30	0.544265
31	0.544800
32	**0.543307**
33	0.544187
34	0.548210
35	0.547651
36	0.545404
37	0.829009
38	0.824220

Continued...

39	0.832810
40	0.843091
41	0.647353
42	0.672456
43	0.641193
44	0.643103
45	0.613449
46	0.711371
47	0.741697
48	0.740540
49	0.546161
50	0.829276
51	0.820997
52	0.557175
53	0.738915

Table 4.12 Branch Number, Sending-end Node, Receiving-end Node, Selected Optimal Conductor for Each Branch and Length of Each Branch for Case of Single Feeder Computed by the Method Proposed by Ranjan *et al.* (2002) for Example 1

Branch Number (jj)	Sending-end Node (m1)	Receiving-end Node (m2)	Selected Optimal Branch Conductor	Length of Each Branch(jj) (km)
1	S/S	23	4---->RACCON	2.336333
2	23	14	4---->RACCON	1.500000
3	14	7	4---->RACCON	1.118034
4	14	51	4---->RACCON	1.802776
5	51	15	4---->RACCON	1.581139
6	7	25	2---->WEASEL	1.802776
7	25	40	1---->SQUIRREL	1.414214
8	51	26	1---->SQUIRREL	1.802776
9	7	24	4---->RACCON	2.000000
10	24	16	4---->RACCON	1.581139
11	16	39	1---->SQUIRREL	1.581139
12	16	50	3---->RABBIT	1.581139
13	50	3	3---->RABBIT	1.414214
14	3	38	2---->WEASEL	0.500000
15	24	17	1---->SQUIRREL	2.121320
16	3	8	1---->SQUIRREL	2.121320
17	23	6	3---->RABBIT	2.236068
18	6	5	2---->WEASEL	1.802776
19	5	4	1---->SQUIRREL	1.118034
20	15	47	4---->RACCON	2.500000
21	47	48	4---->RACCON	1.581139
22	47	46	4---->RACCON	1.802776
23	46	18	4---->RACCON	1.581139
24	48	53	4---->RACCON	2.236068
25	38	1	1---->SQUIRREL	2.500000
26	17	37	1---->SQUIRREL	2.500000
27	46	42	4---->RACCON	2.549510
28	42	41	4---->RACCON	1.802776
29	41	19	4---->RACCON	1.500000
30	19	44	4---->RACCON	1.581139
31	41	12	4---->RACCON	1.802776
32	12	45	4---->RACCON	1.581139

Continued...

33	45	9	4---->RACCON	1.581139
34	19	43	4---->RACCON	1.802776
35	43	20	4---->RACCON	1.581139
36	9	27	4---->RACCON	1.802776
37	27	11	4---->RACCON	2.061553
38	11	52	4---->RACCON	1.802776
39	52	13	4---->RACCON	1.581139
40	52	10	4---->RACCON	2.061553
41	10	29	4---->RACCON	2.000000
42	29	28	4---->RACCON	1.581139
43	29	30	4---->RACCON	2.000000
44	10	21	4---->RACCON	2.061553
45	21	36	4---->RACCON	1.581139
46	13	34	4---->RACCON	2.121320
47	34	49	4---->RACCON	1.414214
48	49	33	4---->RACCON	1.581139
49	33	32	4---->RACCON	1.414214
50	34	35	4---->RACCON	1.802776
51	21	31	4---->RACCON	2.549510
52	31	2	4---->RACCON	2.692582
53	20	22	4---->RACCON	4.472136

Table 4.13 Load Flow Results for Example 1 having Two Feeders Computed by the Method Proposed by Ranjan *et al.* (2002)

Node Number	Voltage Magnitude (p.u.)
S/S	1.000000
1	0.972042
2	0.960710
3	0.973076
4	0.984107
5	0.984713
6	0.986311
7	0.980188
8	0.972495
9	0.981961
10	0.964940
11	0.971899
12	0.984067
13	0.965994
14	0.982824
15	0.979090
16	0.975581
17	0.975449
18	0.975342
19	0.980277
20	0.977555
21	0.962871
22	0.975110
23	0.988460
24	0.976981
25	0.978409
26	0.979810
27	0.977059
28	0.962815
29	0.963252
30	0.961856
31	0.961457
32	**0.960652**
33	0.961436
34	0.964025
35	0.963526
36	0.961995
37	0.974081

	Continued...
38	0.972727
39	0.975149
40	0.978024
41	0.981828
42	0.980848
43	0.978851
44	0.979847
45	0.986369
46	0.975618
47	0.976746
48	0.975604
49	0.962707
50	0.974156
51	0.980790
52	0.967582
53	0.974381

Table 4.14 Values of VSI for All Nodes of Example 1 having Two Feeders Computed by the Method Proposed by Ranjan *et al.* (2002)

Node Number	VSI
1	0.892769
2	0.851862
3	0.896575
4	0.937928
5	0.940234
6	0.946348
7	0.923061
8	0.894436
9	0.929736
10	0.866953
11	0.892193
12	0.937763
13	0.870755
14	0.932985
15	0.918942
16	0.905841
17	0.905347
18	0.904956
19	0.923406
20	0.913194
21	0.859544
22	0.904083
23	0.954373
24	0.911034
25	0.916386
26	0.921649
27	0.911299
28	0.859351
29	0.860910
30	0.855929
31	0.854511
32	**0.851654**
33	0.854438
34	0.863672
35	0.861894
36	0.856428
37	0.900280
38	0.895290

	Continued...
39	0.904241
40	0.914949
41	0.929259
42	0.925563
43	0.918046
44	0.921791
45	0.946220
46	0.905980
47	0.910167
48	0.905927
49	0.858963
50	0.900559
51	0.925339
52	0.876462
53	0.901391

Table 4.15 Branch Number, Sending-end Node, Receiving-end Node, Selected Optimal Conductor for Each Branch and Length of Each Branch for Case of Two Feeders Computed by the Method Proposed by Ranjan *et al.* (2002) for Example 1

Branch Number (jj)	Sending-end Node (m1)	Receiving-end Node (m2)	Selected Optimal Branch Conductor	Length of Each Branch(jj) (km)
1	S/S	23	4---->RACCON	2.336333
2	S/S	45	4---->RACCON	3.019346
3	23	14	4---->RACCON	1.500000
4	14	7	4---->RACCON	1.118034
5	45	9	4---->RACCON	1.581139
6	45	12	4---->RACCON	1.581139
7	14	51	4---->RACCON	1.802776
8	51	15	3---->RABBIT	1.581139
9	7	25	2---->WEASEL	1.802776
10	25	40	1---->SQUIRREL	1.414214
11	9	27	4---->RACCON	1.802776
12	12	41	4---->RACCON	1.802776
13	41	19	3---->RABBIT	1.500000
14	19	44	1---->SQUIRREL	1.581139
15	51	26	1---->SQUIRREL	1.802776
16	41	42	1---->SQUIRREL	1.802776
17	19	43	2---->WEASEL	1.802776
18	43	20	1---->SQUIRREL	1.581139
19	7	24	4---->RACCON	2.000000
20	24	16	4---->RACCON	1.581139
21	16	39	1---->SQUIRREL	1.581139
22	16	50	3---->RABBIT	1.581139
23	50	3	3---->RABBIT	1.414214
24	3	38	2---->WEASEL	0.500000
25	27	11	4---->RACCON	2.061553
26	11	52	4---->RACCON	1.802776
27	52	13	4---->RACCON	1.581139
28	52	10	4---->RACCON	2.061553
29	10	29	3---->RABBIT	2.000000
30	29	28	1---->SQUIRREL	1.581139
31	29	30	1---->SQUIRREL	2.000000
32	10	21	2---->WEASEL	2.061553

Continued...

33	21	36	1---->SQUIRREL	1.581139
34	24	17	1---->SQUIRREL	2.121320
35	3	8	1---->SQUIRREL	2.121320
36	13	34	3---->RABBIT	2.121320
37	34	49	2---->WEASEL	1.414214
38	49	33	2---->WEASEL	1.581139
39	33	32	1---->SQUIRREL	1.414214
40	34	35	1---->SQUIRREL	1.802776
41	23	6	3---->RABBIT	2.236068
42	6	5	2---->WEASEL	1.802776
43	5	4	1---->SQUIRREL	1.118034
44	15	47	3---->RABBIT	2.500000
45	47	48	1---->SQUIRREL	1.581139
46	47	46	2---->WEASEL	1.802776
47	46	18	1---->SQUIRREL	1.581139
48	48	53	1---->SQUIRREL	2.236068
49	38	1	1---->SQUIRREL	2.500000
50	17	37	1---->SQUIRREL	2.500000
51	21	31	1---->SQUIRREL	2.549510
52	31	2	1---->SQUIRREL	2.692582
53	20	22	1---->SQUIRREL	4.472136

Table 4.16 Load Flow Results for Example 1 having Three Feeders Computed by the Method Proposed by Ranjan *et al.* (2002)

Node Number	Voltage Magnitude (p.u.)
S/S	1.000000
1	0.975389
2	0.960710
3	0.976421
4	0.994371
5	0.995239
6	0.996830
7	0.983075
8	0.975841
9	0.981961
10	0.964940
11	0.971899
12	0.984067
13	0.965994
14	0.985462
15	0.981737
16	0.978917
17	0.979943
18	0.977570
19	0.980277
20	0.977555
21	0.962871
22	0.975110
23	0.990757
24	0.980312
25	0.981302
26	0.982455
27	0.977059
28	0.962815
29	0.963252
30	0.961856
31	0.961457
32	**0.960652**
33	0.961436
34	0.964025
35	0.963526
36	0.961995
37	0.993029

Continued...

38	0.976073
39	0.978486
40	0.980918
41	0.981828
42	0.980848
43	0.978851
44	0.979847
45	0.986369
46	0.977846
47	0.979399
48	0.978260
49	0.962707
50	0.977497
51	0.983433
52	0.967582
53	0.977040

Table 4.17 Values of VSI for All Nodes of Example 1 having Three Feeders Computed by the Method Proposed by Ranjan *et al.* (2002)

Node Number	VSI
1	0.905132
2	0.851862
3	0.908964
4	0.977670
5	0.981088
6	0.987359
7	0.933990
8	0.906810
9	0.929736
10	0.866953
11	0.892193
12	0.937763
13	0.870755
14	0.943049
15	0.928921
16	0.918294
17	0.922152
18	0.913254
19	0.923406
20	0.913194
21	0.859544
22	0.904083
23	0.963369
24	0.923527
25	0.927273
26	0.931644
27	0.911299
28	0.859351
29	0.860910
30	0.855929
31	0.854511
32	**0.851654**
33	0.854438
34	0.863672
35	0.861894
36	0.856428
37	0.972400
38	0.907670

	Continued...
39	0.916683
40	0.925828
41	0.929259
42	0.925563
43	0.918046
44	0.921791
45	0.946220
46	0.914280
47	0.920096
48	0.915833
49	0.858963
50	0.912975
51	0.935353
52	0.876462
53	0.911273

Table 4.18 Branch Number, Sending-end Node, Receiving-end Node, Selected Optimal Conductor for Each Branch and Length of Each Branch for Case of Three Feeders Computed by the Method Proposed by Ranjan *et al.* (2002) for Example 1

Branch Number (jj)	Sending-end Node (m1)	Receiving -end Node (m2)	Selected Optimal Branch Conductor	Length of Each Branch(jj) (km)
1	S/S	23	4---->RACCON	2.336333
2	S/S	45	4---->RACCON	3.019346
3	S/S	6	4---->RACCON	3.305216
4	23	14	4---->RACCON	1.500000
5	14	7	4---->RACCON	1.118034
6	45	9	4---->RACCON	1.581139
7	45	12	4---->RACCON	1.581139
8	6	5	3---->RABBIT	1.802776
9	5	4	2---->WEASEL	1.118034
10	14	51	4---->RACCON	1.802776
11	51	15	3---->RABBIT	1.581139
12	7	25	2---->WEASEL	1.802776
13	25	40	1---->SQUIRREL	1.414214
14	9	27	4---->RACCON	1.802776
15	12	41	4---->RACCON	1.802776
16	41	19	3---->RABBIT	1.500000
17	19	44	1---->SQUIRREL	1.581139
18	51	26	1---->SQUIRREL	1.802776
19	41	42	1---->SQUIRREL	1.802776
20	19	43	2---->WEASEL	1.802776
21	43	20	1---->SQUIRREL	1.581139
22	7	24	4---->RACCON	2.000000
23	24	16	4---->RACCON	1.581139
24	16	39	1---->SQUIRREL	1.581139
25	16	50	3---->RABBIT	1.581139
26	50	3	3---->RABBIT	1.414214
27	3	38	2---->WEASEL	0.500000
28	27	11	4---->RACCON	2.061553
29	11	52	4---->RACCON	1.802776
30	52	13	4---->RACCON	1.581139
31	52	10	4---->RACCON	2.061553
32	10	29	3---->RABBIT	2.000000

				Continued...
33	29	28	1---->SQUIRREL	1.581139
34	29	30	1---->SQUIRREL	2.000000
35	10	21	2---->WEASEL	2.061553
36	21	36	1---->SQUIRREL	1.581139
37	24	17	1---->SQUIRREL	2.121320
38	3	8	1---->SQUIRREL	2.121320
39	13	34	3---->RABBIT	2.121320
40	34	49	2---->WEASEL	1.414214
41	49	33	2---->WEASEL	1.581139
42	33	32	1---->SQUIRREL	1.414214
43	34	35	1---->SQUIRREL	1.802776
44	4	37	1---->SQUIRREL	2.500000
45	15	47	3---->RABBIT	2.500000
46	47	48	1---->SQUIRREL	1.581139
47	47	46	1---->SQUIRREL	1.802776
48	46	18	1---->SQUIRREL	1.581139
49	48	53	1---->SQUIRREL	2.236068
50	38	1	1---->SQUIRREL	2.500000
51	21	31	1---->SQUIRREL	2.549510
52	31	2	1---->SQUIRREL	2.692582
53	20	22	1---->SQUIRREL	4.472136

Table 4.19 Comparison of the Results Computed by the Proposed Method (GA) and the Method Proposed by Ranjan *et al.* (2002) for Example 1

Methods	Number of Feeder(s)		Real Power Loss (kW)	Reactive Power Loss (kVAr)	Total Feeder Length (km)
Proposed Method	One		100.39	97.64	98.84
	Two		41.31	38.36	99.03
	Three		34.98	32.19	100.46
Method Proposed by Ranjan *et al.* (2002)	One	Computed	145.78	141.98	98.48
		Computed by author	173.5	125.06	97.63
	Two	Computed	40.70	37.77	98.95
		Computed by author	56.18	37.49	99.00
	Three	Computed	36.61	33.91	100.02
		Computed by author	50.12	31.43	100.67

Power Factor of the load is taken as 0.75 lagging. Base values are 11 kV and 100 MVA respectively.

In second example there are 16 load points. The co-ordinates and load kVA of each of these 16 load points are shown in Appendix-F (Table F.1). The co-ordinate of substation is (14.7491,12.1252). The load points 3 & 5 and 7 & 12 cannot be connected due to violation of rules given in Art. 4.4. Figure 4.4 shows the load points of the second example. The substation (S/S) has also been shown. Power factor of all loads is taken as 0.75 lagging. Base kV and Base MVA are 11 kV and 100 MVA respectively.

Table 4.20 and Table 4.21 show the load flow results and the computed value of VSI at all nodes respectively for case of single feeder. Table 4.22 shows branch number, sending-end node, receiving-end node, selected optimal conductor of each branch and length of each branch for case of single feeder. Figure 4.5 shows the connection of all load points to substation (S/S) for case of single feeder. The bold numbers **1,2,3** and **4** give the selected optimal branch conductors where **1**→ SQUIRREL, **2**→ WEASEL, **3**→ RABBIT and **4**→ RACCON respectively.

Table 4.23 and Table 4.24 show the load flow results and the computed value of VSI at all nodes respectively for case of two feeders. Table 4.25 shows branch number, sending-end node, receiving-end node, selected optimal conductor of each branch and length of each branch for case of

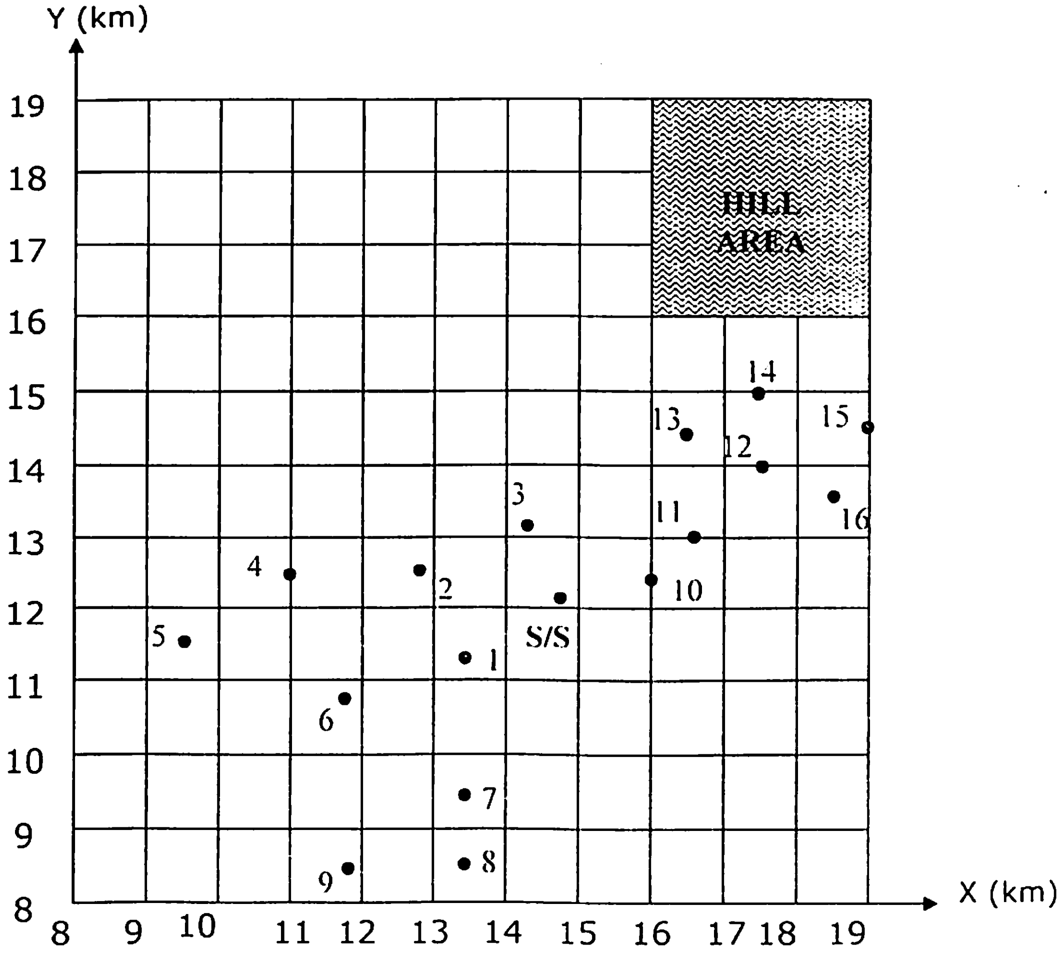


Figure 4.4 Load Points of Second Example

Table 4.20 Load Flow Results for Example 2 having Single Feeder Computed by the Proposed Method (GA)

Node Number	Voltage Magnitude (p.u.)
S/S	1.000000
1	0.986697
2	0.989216
3	0.993750
4	0.987441
5	0.986213
6	0.985285
7	0.984249
8	0.983153
9	**0.981816**
10	0.989621
11	0.987984
12	0.985676
13	0.984831
14	0.984892
15	0.983881
16	0.984759

Table 4.21 Values of VSI for All Nodes of Example 2 having Single Feeder Computed by the Proposed Method (GA)

Node Number	VSI
1	0.947830
2	0.957515
3	0.975158
4	0.950695
5	0.945979
6	0.942420
7	0.938456
8	0.934295
9	**0.929222**
10	0.959091
11	0.952788
12	0.943911
13	0.940690
14	0.940921
15	0.937066
16	0.940413

Table 4.22 Branch Number, Sending-End Node, Receiving-end Node, Selected Optimal Conductor for Each Branch and Length of Each Branch for Case of Single Feeder Computed by the Proposed Method (GA) for Example 2

Branch Number (jj)	Sending-end node (m1)	Receiving-end node (m2)	Selected Optimal Branch Conductor	Length of Each Branch(jj) (km)
1	S/S	3	4---->RACCON	1.165386
2	3	2	4---->RACCON	1.655294
3	2	1	4---->RACCON	1.303841
4	2	4	2---->WEASEL	1.800000
5	1	6	2---->WEASEL	1.802775
6	4	5	1---->SQUIRREL	1.802776
7	3	10	4---->RACCON	1.878829
8	10	11	4---->RACCON	0.848529
9	11	12	4---->RACCON	1.345362
10	12	14	2---->WEASEL	1.000000
11	12	13	2---->WEASEL	1.077033
12	12	16	3---->RABBIT	1.118034
13	16	15	2---->WEASEL	1.118034
14	1	7	4---->RACCON	1.900000
15	7	8	3---->RABBIT	1.000000
16	8	9	2---->WEASEL	1.700000

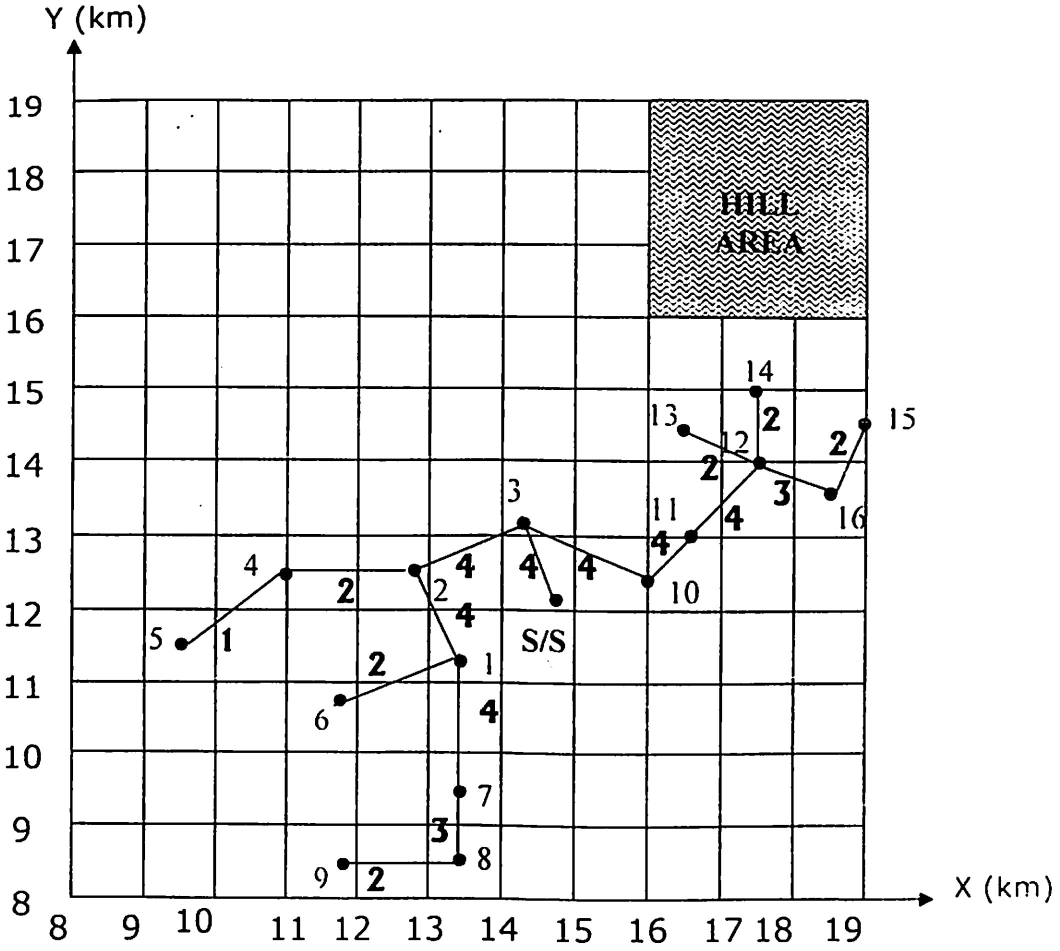


Figure 4.5 Case of Single Feeder

Table 4.23 Load Flow Results for Example 2 having Two Feeders Computed by the Proposed Method (GA)

Node Number	Voltage Magnitude (p.u.)
S/S	1.000000
1	0.989287
2	0.991799
3	0.996322
4	0.990029
5	0.988804
6	0.987878
7	0.986845
8	0.985753
9	**0.984419**
10	0.997208
11	0.995584
12	0.993294
13	0.992456
14	0.992516
15	0.991513
16	0.992384

Table 4.24 Values of VSI for All Nodes of Example 2 having Two Feeders Computed by the Proposed Method (GA)

Node Number	VSI
1	0.957820
2	0.967556
3	0.985341
4	0.960700
5	0.955960
6	0.952383
7	0.948398
8	0.944215
9	**0.939115**
10	0.988864
11	0.982447
12	0.973432
13	0.970161
14	0.970396
15	0.966480
16	0.969880

Table 4.25 Branch Number, Sending-end Node, Receiving-end Node, Selected Optimal Conductor for Each Branch and Length of Each Branch for Case of Two Feeders Computed by the Proposed Method (GA) for Example 2

Branch Number (jj)	Sending-end Node (m1)	Receiving-end Node (m2)	Selected Optimal Branch Conductor	Length of Each Branch(jj) (km)
1	S/S	3	4---->RACCON	1.165386
2	S/S	10	4---->RACCON	1.279892
3	10	11	4---->RACCON	0.848529
4	11	12	4---->RACCON	1.345362
5	12	14	2---->WEASEL	1.000000
6	12	13	2---->WEASEL	1.077033
7	12	16	3---->RABBIT	1.118034
8	16	15	2---->WEASEL	1.118034
9	3	2	4---->RACCON	1.655294
10	2	1	4---->RACCON	1.303841
11	2	4	2---->WEASEL	1.800000
12	1	6	2---->WEASEL	1.802775
13	4	5	1---->SQUIRREL	1.802776
14	1	7	4---->RACCON	1.900000
15	7	8	3---->RABBIT	1.000000
16	8	9	2---->WEASEL	1.700000

two feeders. Figure 4.6 shows the connection of all load points to substation (S/S) for case of two feeders. The bold numbers **1,2,3** and **4** show the selected optimal branch conductors where **1**→ SQUIRREL,**2**→ WEASEL, **3**→ RABBIT and **4**→ RACCON respectively.

Table 4.26 and Table 4.27 show the load flow results and the computed value of VSI at all nodes respectively for case of three feeders. Table 4.28 shows branch number, sending-end node, receiving-end node, selected optimal conductor of each branch and length of each branch for case of three feeders. Figure 4.7 shows the connection of all load points to substation (S/S) for case of three feeders. The bold numbers **1, 2, 3** and **4** show the selected optimal branch conductors where **1**→ SQUIRREL,**2**→ WEASEL, **3**→ RABBIT and **4**→ RACCON respectively.

Table 4.29 shows the comparison of all of three cases. Utility can select three feeders' case. Figure 4.8 and Figure 4.9 show the plot of VSI of the most sensitive node and V_{min} vs TPL and VSI of the most sensitive node and V_{min} vs TQL respectively of the system selected by utility. The critical values of TPL and TQL are 6.3 MW and 5.8 MVAr respectively, beyond which the system will actually collapse.

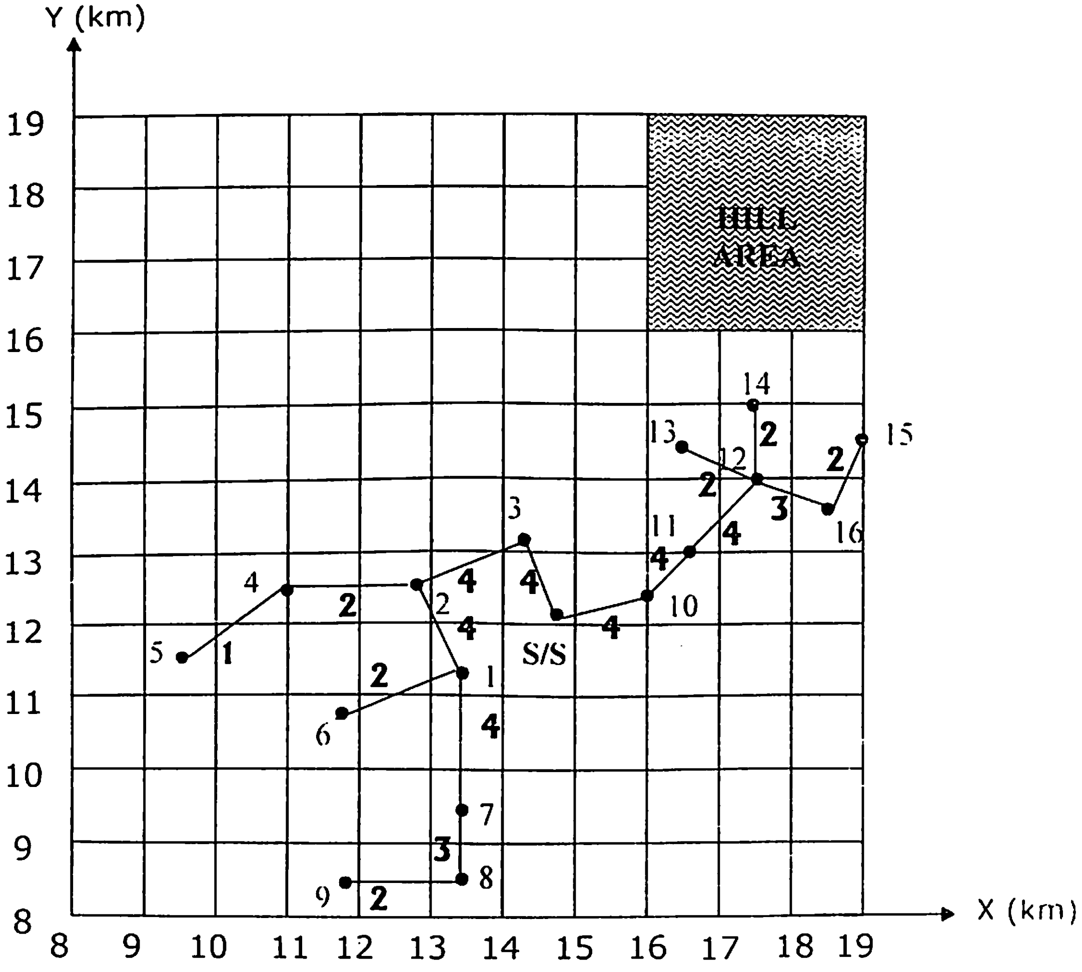


Figure 4.6 Case of Two Feeders

Table 4.26 Load Flow Results for Example 2 having Three Feeders Computed by the Proposed Method (GA)

Node Number	Voltage Magnitude (p.u.)
S/S	1.000000
1	0.996074
2	0.994739
3	0.999099
4	0.992975
5	0.991754
6	0.994675
7	0.993649
8	0.992564
9	**0.991240**
10	0.997208
11	0.995584
12	0.993294
13	0.992456
14	0.992516
15	0.991514
16	0.992384

Table 4.27 Values of VSI for All Nodes of Example 2 having Three Feeders Computed by the Proposed Method (GA)

Node Number	VSI
1	0.984359
2	0.979119
3	0.996400
4	0.972185
5	0.967417
6	0.978865
7	0.974825
8	0.970585
9	**0.965414**
10	0.988865
11	0.982448
12	0.973434
13	0.970162
14	0.970397
15	0.966482
16	0.969881

Table 4.28 Branch Number, Sending-end Node, Receiving-end Node, Selected Optimal Conductor for Each Branch and Length of Each Branch for Case of Three Feeders Computed by the Proposed Method (GA) for Example 2

Branch Number (jj)	Sending-end Node (m1)	Receiving-end Node (m2)	Selected Optimal Branch Conductor	Length of Each Branch(jj) (km)
1	S/S	3	2---->WEASEL	1.165386
2	S/S	10	4---->RACCON	1.279892
3	S/S	1	4---->RACCON	1.445035
4	10	11	4---->RACCON	0.848529
5	1	2	3---->RABBIT	1.303841
6	11	12	4---->RACCON	1.345362
7	12	14	2---->WEASEL	1.000000
8	12	13	2---->WEASEL	1.077033
9	12	16	3---->RABBIT	1.118034
10	16	15	2---->WEASEL	1.118034
11	2	4	2---->WEASEL	1.800000
12	1	6	2---->WEASEL	1.802775
13	4	5	1---->SQUIRREL	1.802776
14	1	7	4---->RACCON	1.900000
15	7	8	3---->RABBIT	1.000000
16	8	9	2---->WEASEL	1.700000

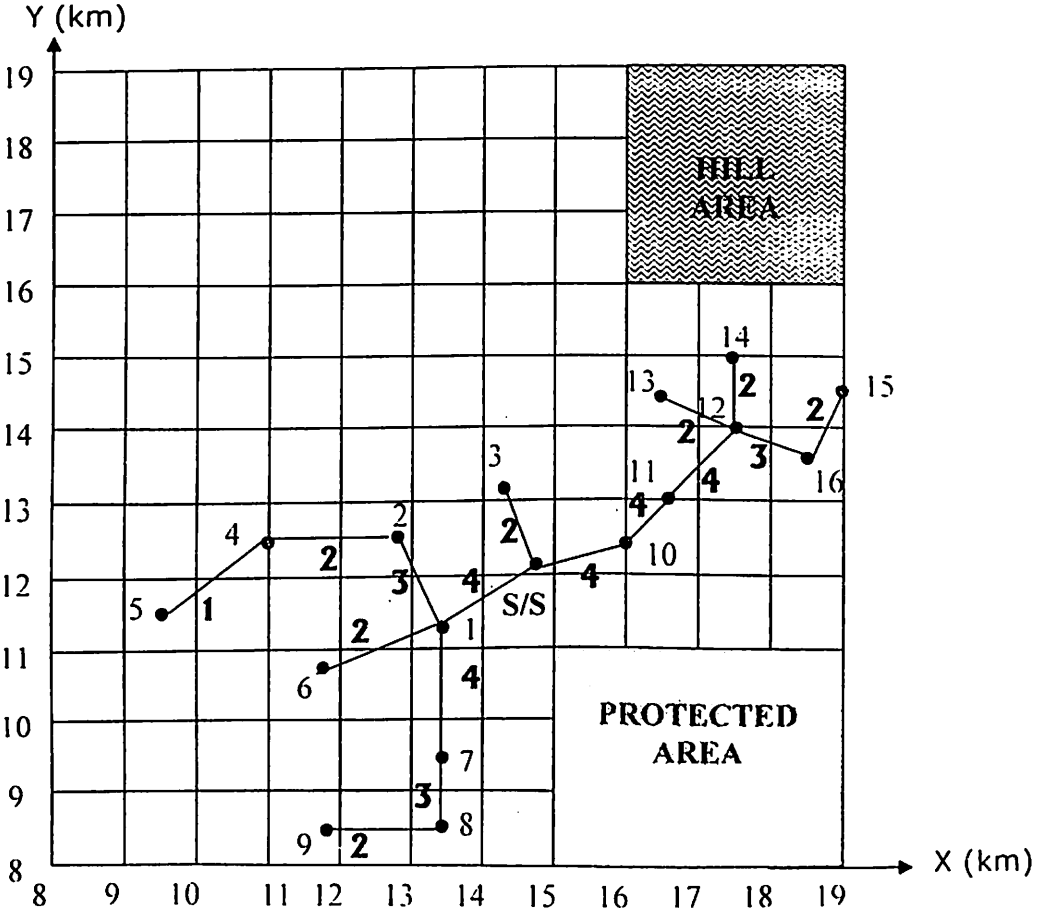


Figure 4.7 Case of Three Feeders

Table 4.29 Comparison of Cases for Single Feeder, Two Feeders and Three Feeders Computed by the Proposed Method (GA) for Example 2

Number of Feeder (s)	Real Power Loss (kW)	Reactive Power Loss (kVAr)	Total Feeder Length (km)	Total Cost (Rs)	Highest Sensitive Node	Minimum Voltage (p.u.)
One	13.01	12.17	22.51	91679.68	9	$\lvert V_9 \rvert = 0.981816$
Two	8.75	8.00	21.91	66494.57	9	$\lvert V_9 \rvert = 0.984419$
Three	5.96	5.16	21.70	48972.32	9	$\lvert V_9 \rvert = 0.991240$

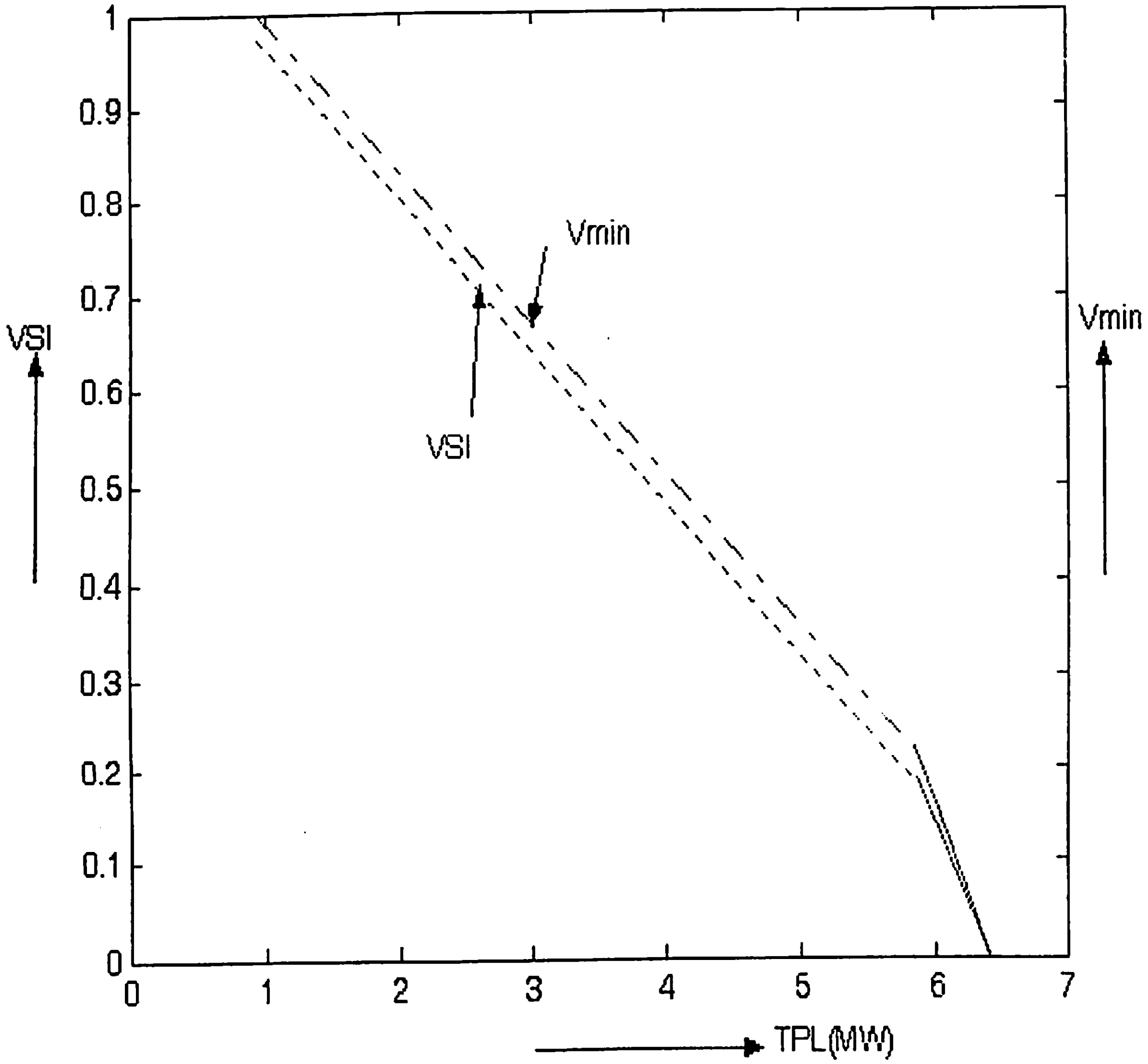


Figure 4.8 Plot of VSI of the Most Sensitive Node and V_{min} vs TPL of the System Selected by Utility

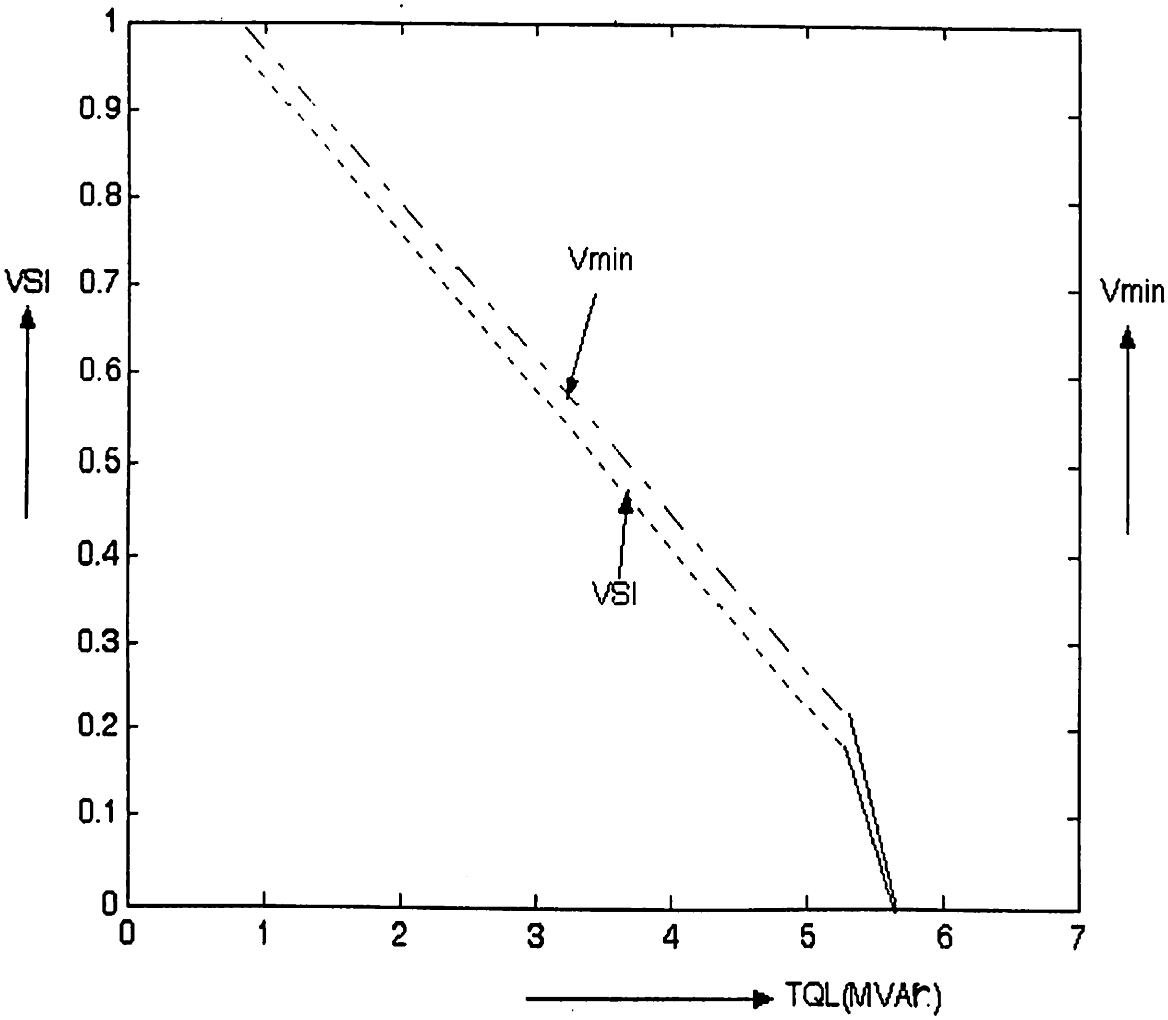


Figure 4.9 Plot of VSI of the Most Sensitive Node and V_{min} vs TQL of the System Selected by Utility

4.9 Summary

A method is proposed to identify the optimum location of substation using Genetic Algorithm using the expression VSI proposed in Chapter 3 in fitness function. All the load points are connected in optimum route using heuristic rules proposed by Chen and Hsu (1989) and Hsu and Chen (1990) respectively. For selection of optimal branch conductor the method proposed by Tram and Wall (1988) has been used using the proposed VSI as one of the constraints. The value of VSI at each node has been computed taking the proposed expression for VSI and the most sensitive node of the network has also been identified. To demonstrate the effectiveness of the proposed method two examples have been selected. The superiority of the proposed method has also been checked by comparing it with the method proposed by Ranjan *et al.* (2002) with the help of 53 load points i.e., Example 1. The identified optimum location of the substation gives the better result compared to that of identified by classical technique. A comparison for the cases of single feeder, two feeders and three feeders have been shown for second example also. Utility can take three feeders' case. The critical values of TPL and TQL of the network selected by utility have also been computed, beyond which the system will collapse. If alternate algorithms are used for connection of load points in optimum route and selection of optimal branch conductors, the results may be different.

CHAPTER 5

PLANNING OF DISTRIBUTION SYSTEM USING DIFFERENTIAL EVOLUTION WITH THE HELP OF VOLTAGE STABILITY INDEX (VSI)

5.1 Introduction

Effective planning, design and operation of electric power distribution systems not only provide a high standard of power reliability, security but it also ensures the maximum utilization of optimal investment. The exact optimum location of substation is most important for substation planning because it reduces the system cost and system loss. Literature survey shows that a good amount of research work has been carried out for distribution system planning. Literature survey of distribution system planning has already been presented in Chapter-2.

In the present chapter the following have been carried out:

(i) Identification of the optimum location for the substation using Differential Evolution (DE) using the expression of VSI proposed in Chapter 3 in fitness function,

(ii) connection of load points in optimum route using knowledge-based expert systems proposed by Chen and Hsu (1989) and Hsu and Chen (1990),

(iii) selection of optimal branch conductors using the method proposed by Tram and Wall (1988) taking the proposed expression for VSI as one of the constraints and

(iv) identification of the most sensitive node of the network using the proposed expression for VSI.

The critical values of TPL and TQL of the system selected by utility have been computed, beyond which the system will collapse.

5.2 Differential Evolution (DE) [Price and Storn (1997)]

Differential Evolution is an efficient technique and it gives the exact optimum location of substation compared to Genetic algorithm. The Differential Evolution is introduced at first.

Differential Evolution grew out of Price's attempts to solve the Chebyshev Polynomial fitting Problem that had been posed to him by Price and Storn (1997). A breakthrough happened, when Price came up with the idea of using vector differences for perturbing the vector population. This seminal idea was a lively discussion between Price and Storn (1997) and endless ruminations and computer simulations on both parts yielded many substantial improvements, which make DE the versatile and robust tool today. The "DE community" has been growing since the early DE years of 1994 -1996 and ever more researchers are working on and with DE. It is the strong wish of Price and Storn (1997) that DE will be developed further by scientists around the world and that DE may improve to help more users in their daily work. The crucial idea behind DE is a scheme for generating trial parameter vectors.

A Differential Evolution method is used to minimize functions of real variables. Evolution strategies are significantly faster at numerical optimization than traditional Genetic Algorithms and also more likely to find a function's true global extremum. These methods heuristically 'mimic' biological evolution: namely, the process of natural selection and the `survival of the fittest' principle. An adaptive search procedure based on a 'population' of candidate solution points is used. Iterations involve a competitive selection that drops the poorer solutions. The remaining pool of candidates with higher 'fitness value' are then 'recombined' with other solutions by swapping components with another; they can also be 'mutated' by making some smaller-scale change to a candidate. The recombination and mutation are applied sequentially. The aim is to generate new solutions that are biased towards subsets of D in which good, although not necessarily globally optimized, solutions have already been found. Numerous variants of this general strategy based on diverse evolution 'game rules' can be constructed. The different types of evolutionary search methods include approaches that are aimed at continuous global optimization problems, and also others that are targeted towards solving combinatorial problems.

Differential Evolution uses mutations as search mechanisms and selection to direct the search toward the prospective regions in the search space. Genetic Algorithm generate a sequence of populations by using selection mechanism. Genetic Algorithms use crossover and mutation as search mechanisms. The principal difference between Genetic Algorithms and Differential Evolution is that Genetic Algorithm rely on crossover, a mechanism of probabilistic and useful exchange of information among solutions to locate better solutions, while evolutionary strategies use mutation as the primary search mechanism. Differential Evolution uses a non uniform crossover that can take child vector parameters from one parent more often than it does from others. By using components of existing population members to construct trial vectors, recombination efficiently shuffles information about successful combinations, enabling the search for an optimum to focus on the most promising area of solution space proposed by Price and Storn (1997).

Once new trial solutions have been generated, selected, selection determines which among them will survive into the next generation. DE maintain two arrays. The primary array holds the current vector population while the secondary array accumulates vectors that are selected for the next generation. In each generation, competitions are held to determine the composition of next generation. In particular, the competition pits the population vector, known as the "target" against its adversary, the trial vector. The trial vector's other parent is a randomly chosen population vector to which a weighted random difference vector has been added. Mating between this noisy random vector and the target vector is controlled by a nonuniform crossover operation that determines which trial vector parameters are inherited from which parent. If the fitness of the trial vector turns out to be less than or equal to that of its parent target, the trial vector replaces the target as the population vector of the next generation. Similar to GA, DE is used to find the optimum values for network parameters such that the network learning time is reduced and recognition accuracy is increased.

Basically, DE adds the weighted difference between two population vectors to a third vector. This way no separate probability distribution has to be used which makes the scheme completely self-organizing. To optimize the objective function with DE, the following settings for the input file first is tried at first : DE/rand/1/exp, set the number of parents (NP) to 10 times the number of parameters, select weighting factor F=0.8 and crossover constant (CR) = 0.9. The parameter vectors is initialized by exploiting their full numerical range, i.e. if a parameter is allowed to exhibit values in the range [-100, 100] it's a good idea to pick the initial values from this range instead of unnecessarily restricting diversity. For any non-convergence the value for NP is usually increased. But often F is to be adjusted a little lower or higher than 0.8. If NP is increased and simultaneously F is lowered a little, convergence is more likely to occur but it generally takes longer, i.e. DE is getting more robust since there is always a convergence speed/robustness tradeoff.

DE is much more sensitive to the choice of F than it is to the choice of CR. CR is more like a fine tuning element. High values of CR like CR=1 give faster convergence if convergence occurs. Sometimes, however, CR can be taken as much as 0 to make DE robust enough for a particular problem. If the binomial crossover is taken like, DE/rand/1/bin, CR is usually higher than in the exponential crossover variant (in this example DE/rand/1/exp). Still, F and CR are both generally in the range [0.5, 1.] for most problems have been encountered. But different problems usually require different settings for NP, F and CR. The crossover method is not so important although Price and Storn (1997) claims that binomial is never worse than exponential. In case of non-convergence, it is better to check the choice of objective function. There might be a better one to describe the problem.

The Steps of Differential Evolution are presented below.

Step -1 : Generate NP random vectors as the initial population and linearize the range between 0 and 1.

Step -2 : Choose a target vector from the population of size NP. First generate a random number between 0 and 1. From the above random number decide which population number is to be selected as the target vector (X_t).

Step -3 : Choose two vectors at random from the population and find the weighted difference and generate two random numbers i.e., select two populations (X_a, X_b) and find $X_a - X_b$. Multiply this difference by F to obtain the weighted difference.

Step -4 : Find the noisy random vector. Generate a random number. Choose a third random vector from the population (X_c). Add this vector to the weighted difference to obtain the noisy random vector (X'_c).

Step -5 : Perform cross over between X_l and X'_c to find X_t , the trial vector. Generate D random numbers. If the random number is greater than cross over rate, copy the value from X_l into the trial vector. If the random number is less than cross over rate, copy the value from X'_c into the trial vector.

Step -6 : Compute the cost of the trial vector and the target vector.

Step -7 : Repeat the steps 1-6 until the optimality achieved.

Figure 5.1 shows the flow chart of Differential Evolution.

5.3 Identification of the Optimum Location for the Substation Using Differential Evolution [Price and Storn (1997a)]

A brief description of the elements in the process of using DE to solve the problem is given below.

The real parameters X_j of a D-dimensional function can be represented notation as

$$\mathbf{X} = \{X_j\},\ 0<=j<=D-1.$$

In minimization problem, the goal of the global optimizer is to find an optimal vector, $\mathbf{X}_{\mathbf{opt}}$, such that

$$f(\mathbf{X}_{\mathbf{opt}}) = \min(f(\mathbf{X})).$$

Usually the ranges of the parameters comprising X are restricted by design constraints. If not, these limits must be established.

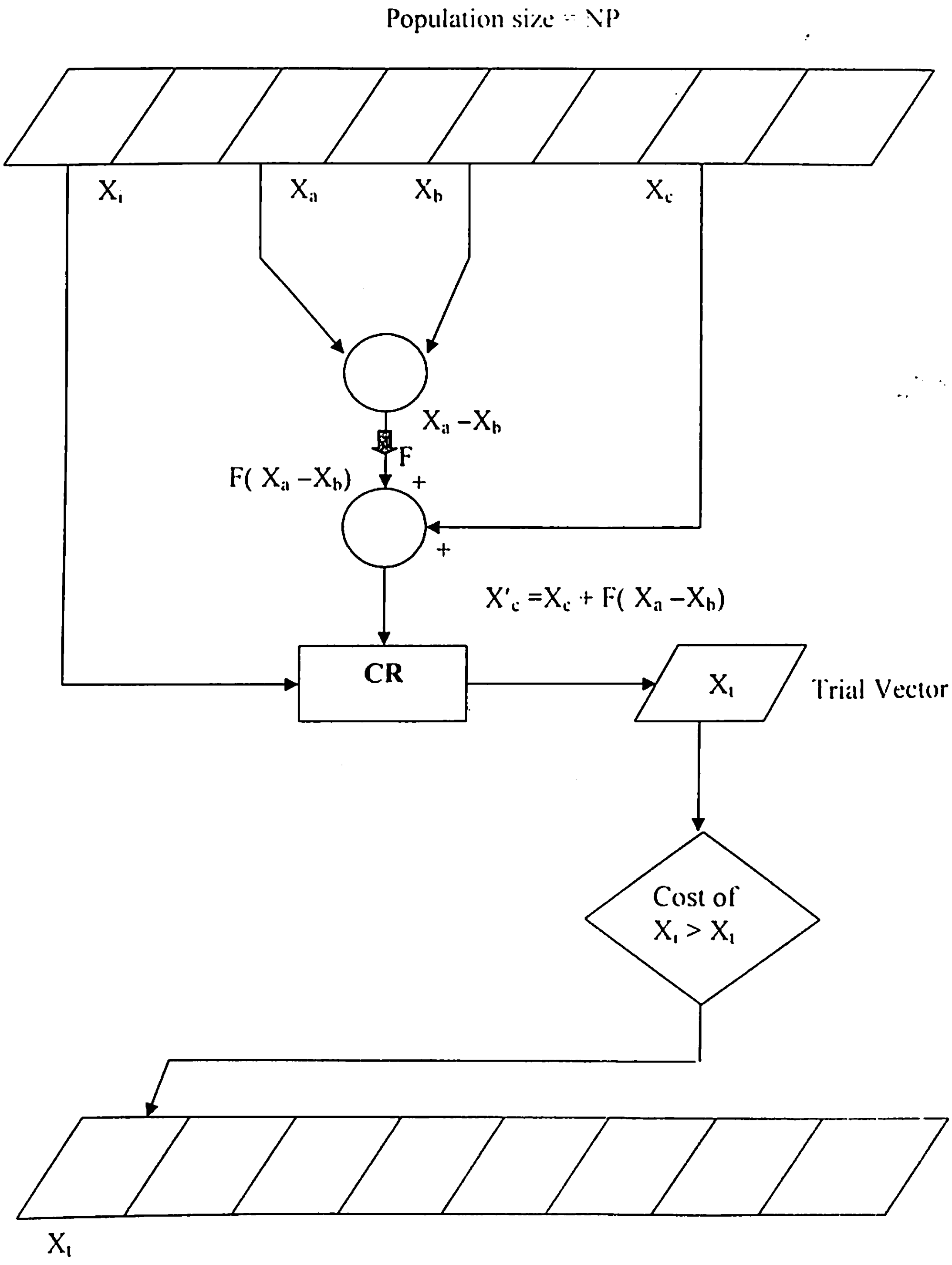


Figure 5.1 Flow chart of Differential Evolution (DE)

The primary data structure in the DE algorithm is a floating-point array designed to hold a population of N,D-dimensional, real-valued vectors. Vectors are initialized by assigning each parameter a randomly chosen value from within its allowed range. Once the parameters of the i th population vector, $\mathbf{X}_i$, have been initialized, $f(\mathbf{X}_i)$ is evaluated and the result is stored in one dimensional array: fitness[i]. After each vector has been evaluated, the best-so-far solution is found and stored as separate vector, $\mathbf{B}$ = best[j]. $\mathbf{B}$ is updated whenever an equal or better solution than the current best-so-far vector is found.

The essential ingredient in DE's mutation recipe is the difference vector. Ecah vector pair ($\mathbf{X_a}$, $\mathbf{X_b}$) defines a difference vector, $\mathbf{D}_{ab}$, such that:

$\mathbf{D}_{ab} = \mathbf{X}_a - \mathbf{X}_b$

The mutation process begins by randomly selecting four population vectors, $\mathbf{X}_a$, $\mathbf{X}_b$, $\mathbf{X}_c$ and $\mathbf{X}_d$ for any a,b,c and d. The four vectors are combined to form $\mathbf{D}_{abcd}$, i.e., the sum of two difference vectors:

$\mathbf{D}_{abcd} = \mathbf{D}_{ab} + \mathbf{D}_{cd} = (\mathbf{X}_a - \mathbf{X}_b) + (\mathbf{X}_c - \mathbf{X}_d)$

As population vector converge, the differences between them diminish. Consequently, vectors like $\mathbf{D}_{ab}$ and $\mathbf{D}_{abcd}$ remain scaled to a size that is appropriate for the population as it evolves. To ensure the fastest possible convergence, $\mathbf{D}_{abcd}$ is multiplied by a scaling factor F where ($0 < F < 1.2$). The upper limit $F = 1.2$ for F has been determined empirically. Once $\mathbf{D}_{abcd}$

has been computed and scaled by F, it is added to the best-so-far vector **B** **i.e.,** $\beta = \mathbf{B} + \mathbf{F}^* \mathbf{D}_{abcd}$

The vector β is the noisy replica of **B**. With β now in hand the trial vector will compete against $\mathbf{X}_i$ can be assembled. Starting with a randomly chosen parameter, values for the trial vector, **T**, are loaded consecutively modulo D, from either **B** or from $\mathbf{X}_i$ itself. If the output of the random number generator is less than CR, then the j-th parameter of **T** is loaded with the j-th parameter from β. If the random number is greater than or equal to CR, **T** takes its j-th parameter from $\mathbf{X}_i$. After D-1 trials, **T** takes its j-th parameter from β, since every mutation ought to make **T** different from $\mathbf{X}_i$ by at least one parameter. DE replaces $\mathbf{X}_i$ with **T** only if:

$F(\mathbf{T}) <= f(\mathbf{X}_i) = \text{fitness}[i]$ otherwise $\mathbf{X}_i$ remains a population number.

The cost function is

$$\mathbf{X}_i = \text{Max}\{\text{Min}(\text{VSI})\} \tag{5.1}$$

5.4 Knowledge Based Expert System

This has already been discussed in Chapter-4 (Art.4.4).

5.5 Connection of Load Points to Substation

This has already been discussed in Chapter-4 (Art.4.5).

5.6 Optimal Branch Conductor Selection

This has already been discussed in Chapter-4 (Art.4.6).

5.7 Most Sensitive Node of the Network

This has already been discussed in Chapter-3 (Art. 3.5).

5.8 Example

An example of 16 load points is considered. The co-ordinate and load kVA of each of these load points are already shown in Appendix-F (Table F.1). The optimum co-ordinate of the substation is (14.592, 12.102). There are physical obstructions between load points 3 & 5 and 7 & 12 and hence they cannot be connected due to violation of rules given in Art. 4.4. Figure 5.2 shows the distribution of load points and the location of substation (S/S). Power factor of load is taken as 0.75 lagging. Base values are 11 kV and 100 MVA respectively.

Table 5.1 and Table 5.2 show the load flow results and the computed value of VSI at all nodes respectively for case of single feeder. Table 5.3 shows branch number, sending-end node, receiving-end node, selected optimal conductor for each branch and length of each branch for case of single feeder. Figure 5.3 shows the connection of all load points to substation (S/S) for case of single feeder. The bold numbers **1,2,3** and **4** shows the selected optimal branch conductors where **1**→ SQUIRREL,**2**→ WEASEL, **3**→ RABBIT and **4**→ RACCON respectively.

Table 5.4 and Table 5.5 show the load flow results and the computed value of VSI at all nodes respectively for case of two feeders. Table 5.6 shows branch number, sending-end node, receiving-end node, selected

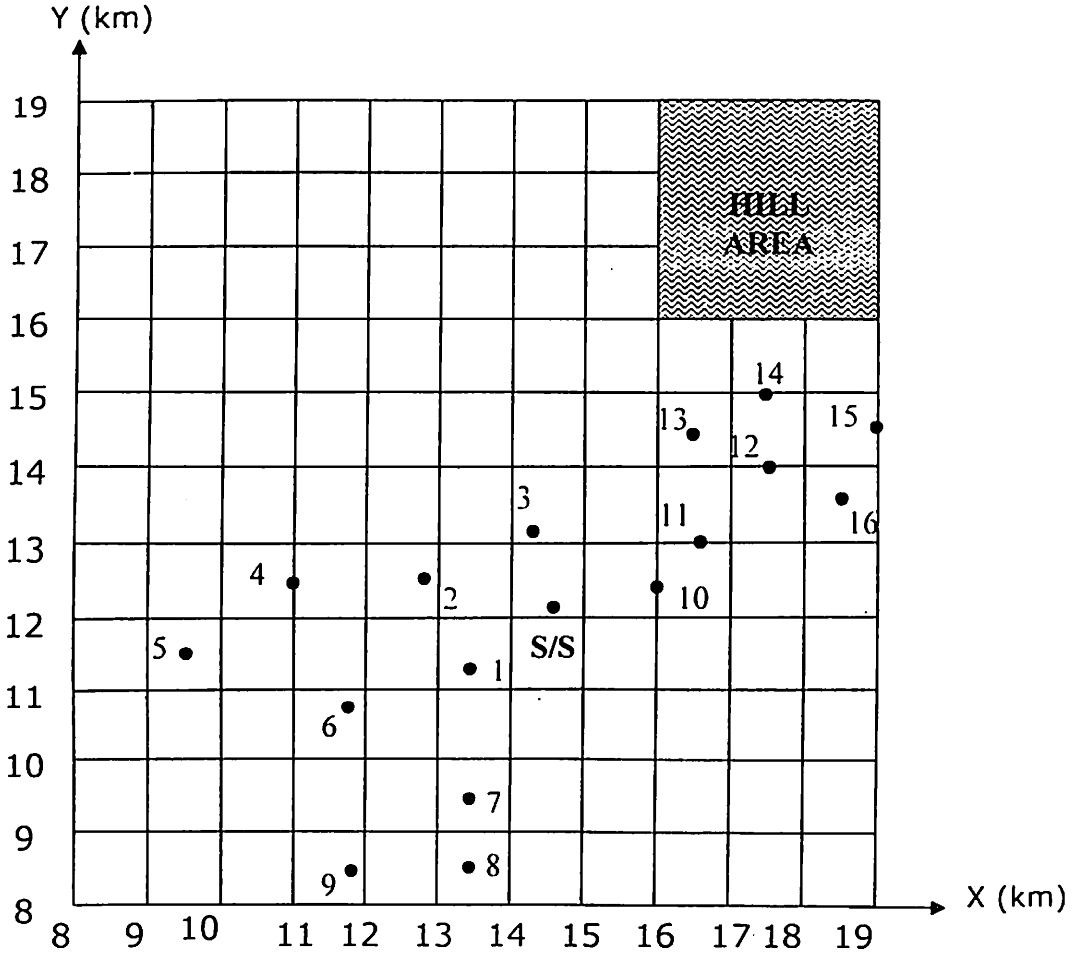


Figure 5.2 Load Points of the Example

Table 5.1 Load Flow Results for the Example having Single Feeder Computed by the Proposed Method (DE)

Node Number	Voltage Magnitude (p.u.)
S/S	1.000000
1	0.986834
2	0.989352
3	0.993886
4	0.987578
5	0.986350
6	0.985422
7	0.984386
8	0.983291
9	**0.981954**
10	0.989757
11	0.988120
12	0.985813
13	0.984969
14	0.985029
15	0.984019
16	0.984896

Table 5.2 Values of VSI for All Nodes of the Example having Single Feeder Computed by the Proposed Method (DE)

Node Number	VSI
1	0.948356
2	0.958044
3	0.975695
4	0.951222
5	0.946505
6	0.942946
7	0.938981
8	0.934818
9	**0.929744**
10	0.959621
11	0.953316
12	0.944437
13	0.941215
14	0.941446
15	0.937590
16	0.940938

Table 5.3 Branch Number, Sending-end Node, Receiving-end Node, Selected Optimal Conductor for Each Branch and Length of Each Branch for Case of Single Feeder Computed by the Proposed Method (DE) for the Example

Branch Number (jj)	Sending-end Node (m1)	Receiving-end Node (m2)	Selected Optimal Branch Conductor	Length of Each Branch(jj) (km)
1	S/S	3	4---->RACCON	1.140175
2	3	2	4---->RACCON	1.655294
3	2	1	4---->RACCON	1.303841
4	2	4	2---->WEASEL	1.800000
5	1	6	2---->WEASEL	1.802775
6	4	5	1---->SQUIRREL	1.802776
7	3	10	4---->RACCON	1.878829
8	10	11	4---->RACCON	0.848529
9	11	12	4---->RACCON	1.345362
10	12	14	2---->WEASEL	1.000000
11	12	13	2---->WEASEL	1.077033
12	12	16	3---->RABBIT	1.118034
13	16	15	2---->WEASEL	1.118034
14	1	7	4---->RACCON	1.900000
15	7	8	3---->RABBIT	1.000000
16	8	9	2---->WEASEL	1.700000

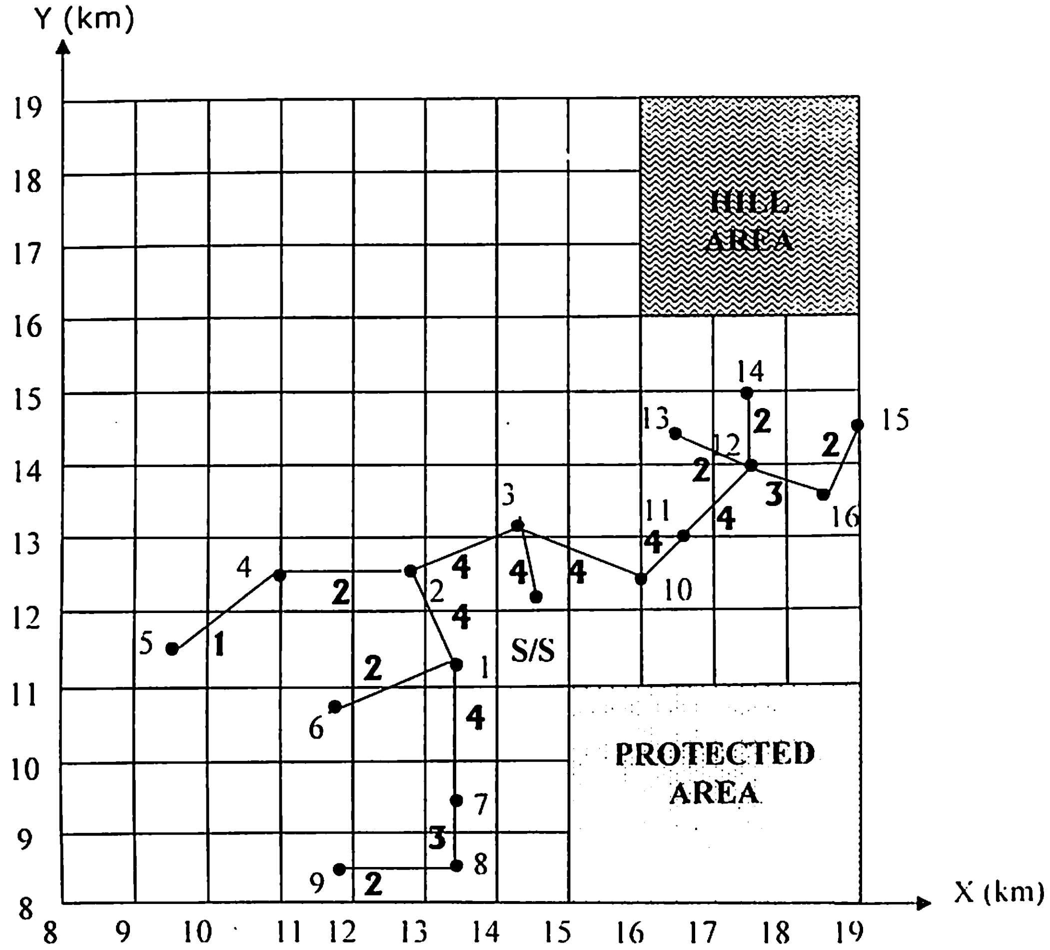


Figure 5.3 Case of Single Feeder

Table 5.4 Load Flow Results for the Example having Two Feeders Computed by the Proposed Method (DE)

Node Number	Voltage Magnitude (p.u.)
S/S	1.000000
1	0.996459
2	0.995125
3	0.997019
4	0.993360
5	0.992140
6	0.995060
7	0.994035
8	0.992950
9	0.991626
10	0.992903
11	0.991272
12	0.988971
13	0.988130
14	0.988190
15	**0.987183**
16	0.988058

Table 5.5 Values of VSI for All Nodes of the Example having Two Feeders Computed by the Proposed Method (DE)

Node Number	VSI
1	0.985887
2	0.980637
3	0.988112
4	0.973698
5	0.968925
6	0.980382
7	0.976340
8	0.972095
9	0.966920
10	0.971880
11	0.965536
12	0.956600
13	0.953356
14	0.953589
15	**0.949708**
16	0.953078

Table 5.6 Branch Number, Sending-end Node, Receiving-end Node, Selected Optimal Conductor for Each Branch and Length of Each Branch for Case of Two Feeders Computed by the Proposed Method (DE) for the Example

Branch Number (jj)	Sending-end Node (m1)	Receiving-end Node (m2)	Selected Optimal Branch Conductor	Length of Each Branch(jj) (km)
1	S/S	3	4---->RACCON	1.140175
2	S/S	1	4---->RACCON	1.303841
3	1	2	3---->RABBIT	1.303841
4	2	4	2---->WEASEL	1.800000
5	1	6	2---->WEASEL	1.802775
6	4	5	1---->SQUIRREL	1.802776
7	3	10	4---->RACCON	1.878829
8	10	11	4---->RACCON	0.848529
9	11	12	4---->RACCON	1.345362
10	12	14	2---->WEASEL	1.000000
11	12	13	2---->WEASEL	1.077033
12	12	16	3---->RABBIT	1.118034
13	16	15	2---->WEASEL	1.118034
14	1	7	4---->RACCON	1.900000
15	7	8	3---->RABBIT	1.000000
16	8	9	2---->WEASEL	1.700000

optimal conductor for each branch and length of each branch for case of two feeders. Figure 5.4 shows the connection of all load points to substation (S/S) for case of two feeders. The bold numbers **1,2,3** and **4** shows the selected optimal branch conductors where **1**→ SQUIRREL,**2**→ WEASEL, **3**→ RABBIT and **4**→ RACCON respectively.

Table 5.7 and Table 5.8 shows the load flow results and the computed value of VSI at all nodes respectively for case of three feeders. Table 5.9 shows branch number, sending-end node, receiving-end node, selected optimal conductor for each branch and length of each branch for case of three feeders. Figure 5.5 shows the connection of all load points to substation (S/S) for case of three feeders. The bold numbers The bold numbers **1,2,3** and **4** shows the selected optimal branch conductors where **1**→ SQUIRREL,**2**→ WEASEL, **3**→ RABBIT and **4**→ RACCON respectively.

Table 5.10 shows the comparison of the results obtained by this method with the result obtained in Chapter 4 for example 2 for all three cases. Utility can select third feeders' cases. Figure 5.6 and Figure 5.7 show the plot of VSI of the most sensitive node and V_{min} vs TPL and VSI of the most sensitive node and V_{min} vs TQL respectively of the system selected by utility. The critical values of TPL and TQL are 6.6 MW and 6.0 MVAr respectively, beyond which the system will collapse.

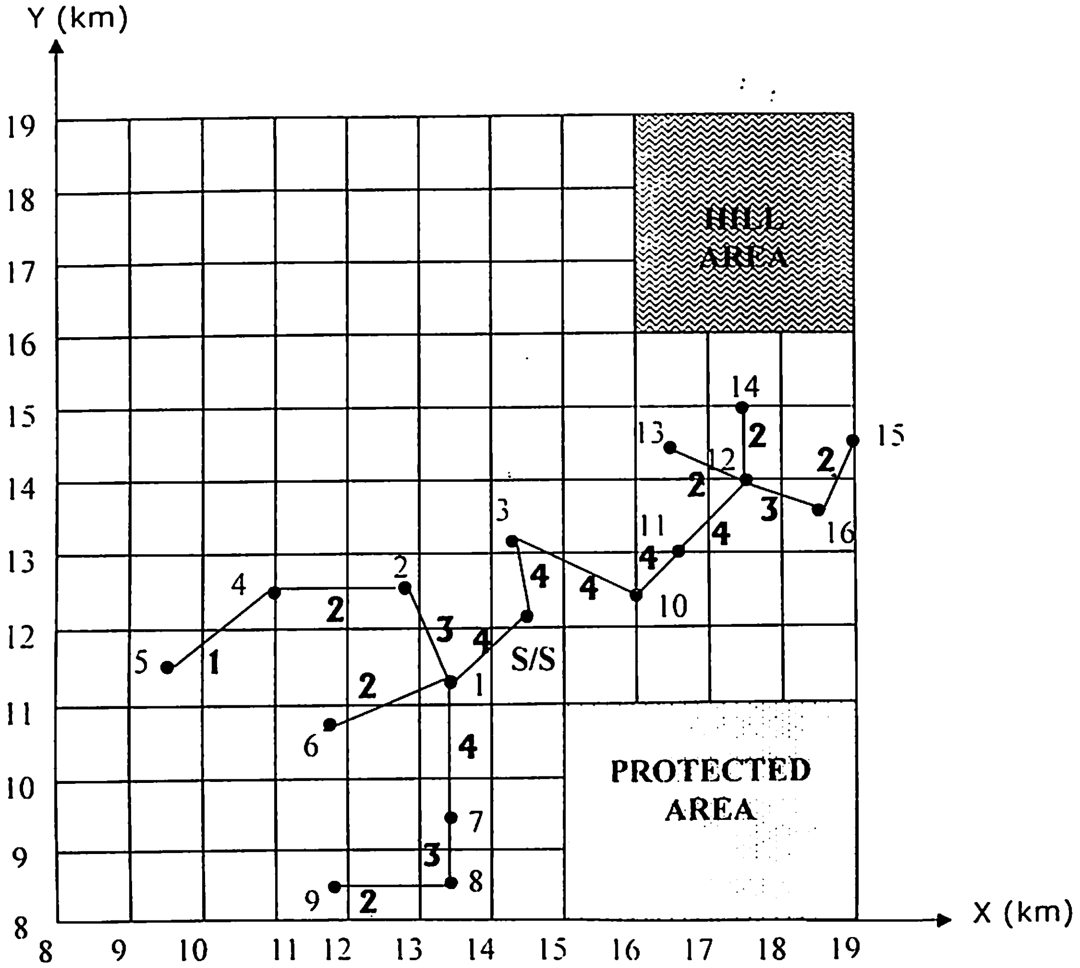


Figure 5.4 Case of Two Feeders

Table 5.7 Load Flow Results for the Example having Three Feeders Computed by the Proposed Method (DE)

Node Number	Voltage Magnitude (p.u.)
S/S	1.000000
1	0.996459
2	0.995125
3	0.999119
4	0.993361
5	0.992140
6	0.995060
7	0.994035
8	0.992951
9	0.991627
10	0.996876
11	0.995251
12	0.992960
13	0.992122
14	0.992182
15	**0.991179**
16	0.992050

Table 5.8 Values of VSI for All Nodes of the Example having Three Feeders Computed by the Proposed Method (DE)

Node Number	VSI
1	0.985887
2	0.980637
3	0.996478
4	0.973698
5	0.968926
6	0.980383
7	0.976340
8	0.972097
9	0.966922
10	0.987543
11	0.981134
12	0.972127
13	0.968857
14	0.969092
15	**0.965180**
16	0.968576

Table 5.9 Branch Number, Sending-end Node, Receiving-end Node, Selected Optimal Conductor for Each Branch and Length of Each Branch for Case of Three Feeders Computed by the Proposed Method (DE) for the Example

Branch Number (jj)	Sending-end Node (m1)	Receiving-end Node (m2)	Selected optimal Branch Conductor	Length of Each Branch(jj)
1	S/S	3	2---->WEASEL	1.140175
2	S/S	1	4---->RACCON	1.303841
3	S/S	10	4---->RACCON	1.431782
4	10	11	4---->RACCON	0.848529
5	1	2	3---->RABBIT	1.303841
6	11	12	4---->RACCON	1.345362
7	12	14	2---->WEASEL	1.000000
8	12	13	2---->WEASEL	1.077033
9	12	16	3---->RABBIT	1.118034
10	16	15	2---->WEASEL	1.118034
11	2	4	2---->WEASEL	1.800000
12	1	6	2---->WEASEL	1.802775
13	4	5	1---->SQUIRREL	1.802776
14	1	7	4---->RACCON	1.900000
15	7	8	3---->RABBIT	1.000000
16	8	9	2---->WEASEL	1.700000

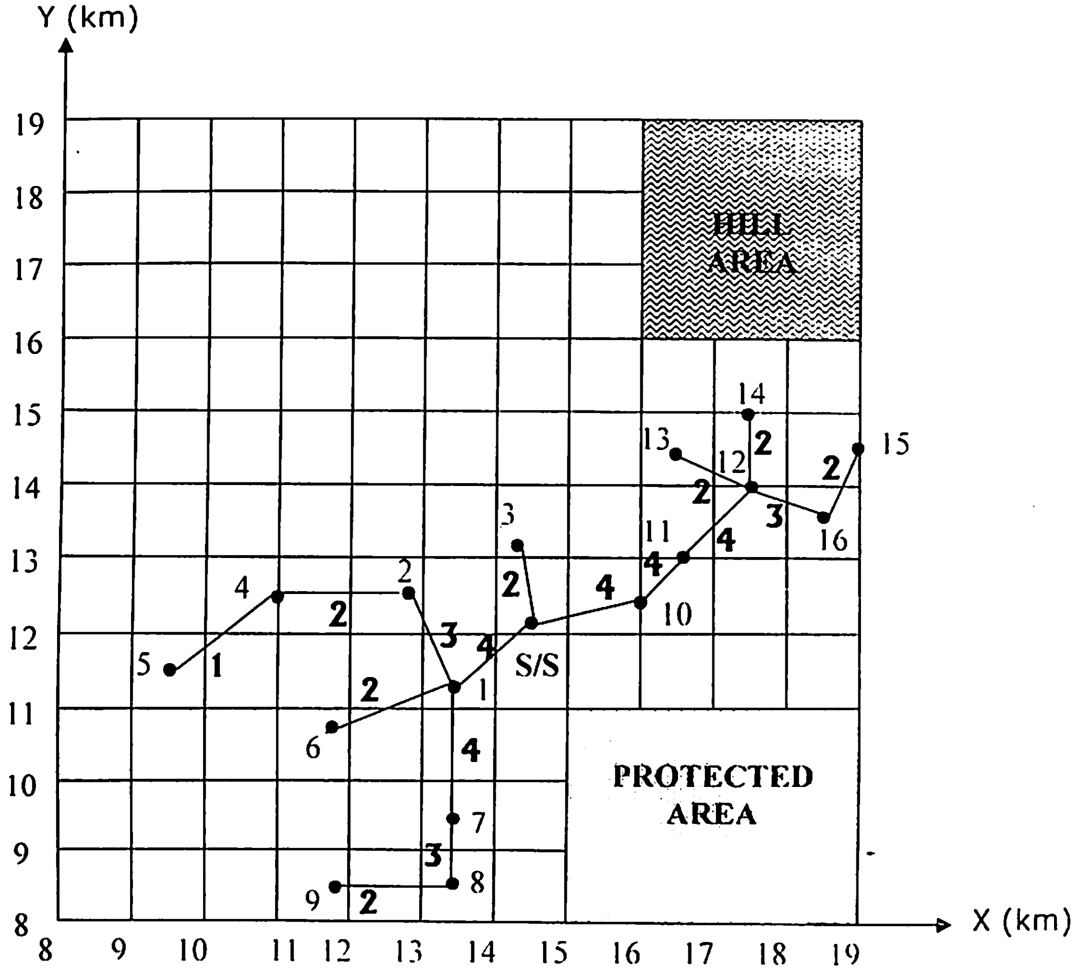


Figure 5.5 Case of Three Feeders

Table 5.10 Comparison of Cases for Single Feeder, Two Feeders, Three Feeders of the Example Computed by using the Proposed Method (DE) and the Method Proposed (GA) in Chapter 4

Number of Feeder (s)	Real Power Loss (kW)	Reactive Power Loss (kVAr)	Total Feeder Length (km)	Total Cost (Rs)	Most Sensitive Node	Minimum Voltage (p.u.)
One (Using DE)	12.88	12.04	22.49	90924.75	9	$\lvert V_9 \rvert$ = 0.981954
One(Using GA)	13.01	12.17	22.51	91679.68	9	$\lvert V_9 \rvert$ = 0.981816
Two (Using DE)	7.52	6.74	22.13	59212.52	15	$\lvert V_{15} \rvert$ = 0.987183
Two (Using GA)	8.75	8.00	21.91	66494.57	9	$\lvert V_9 \rvert$ = 0.984419
Three (Using DE)	5.90	5.10	21.69	48647.30	15	$\lvert V_{15} \rvert$ = 0.991179
Three (Using GA)	5.96	5.16	21.70	48972.32	9	$\lvert V_9 \rvert$ = 0.991240

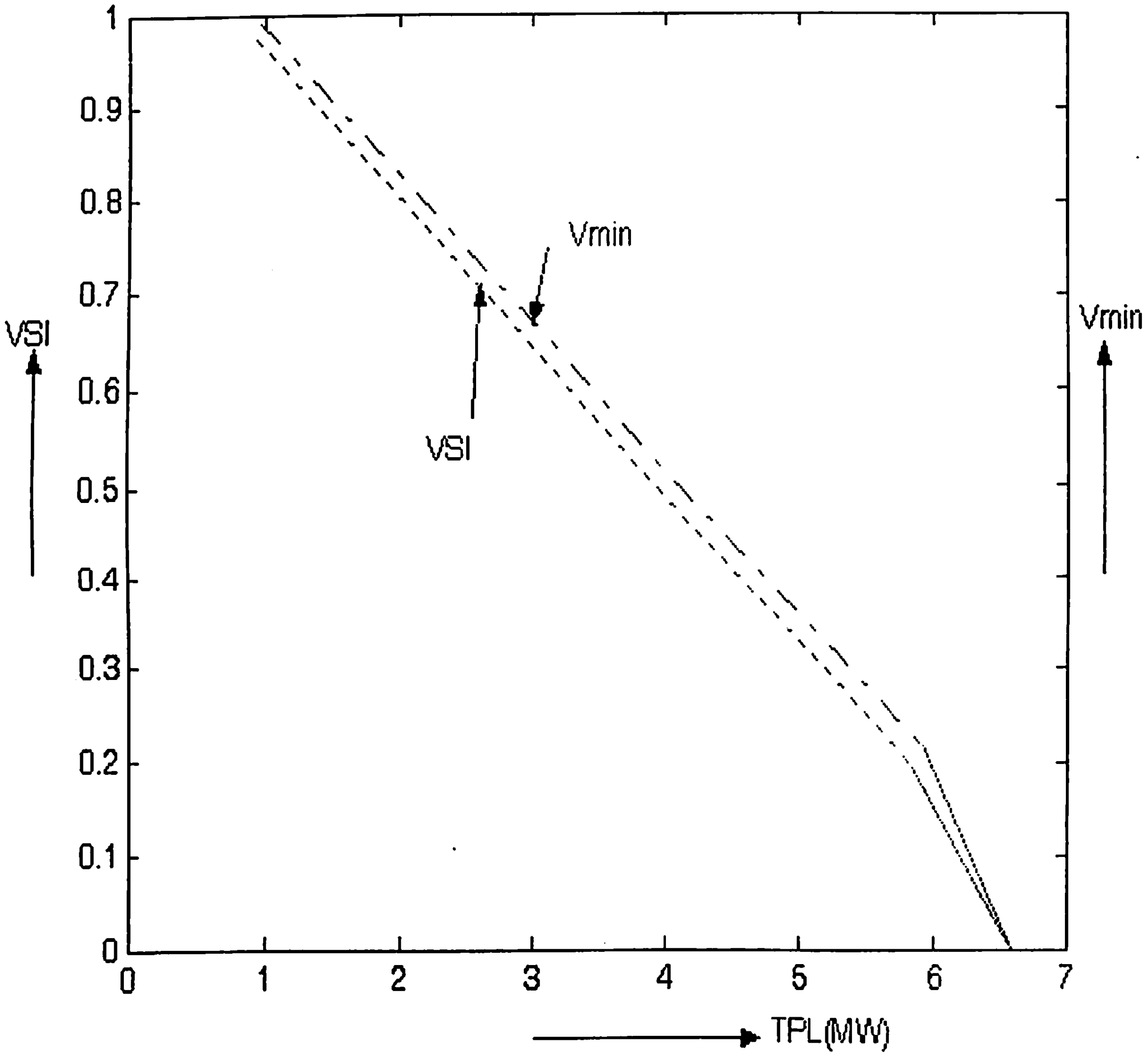


Figure 5.6 Plot of VSI of the Most Sensitive Node and V_{min} vs TPL of the System Selected by Utility

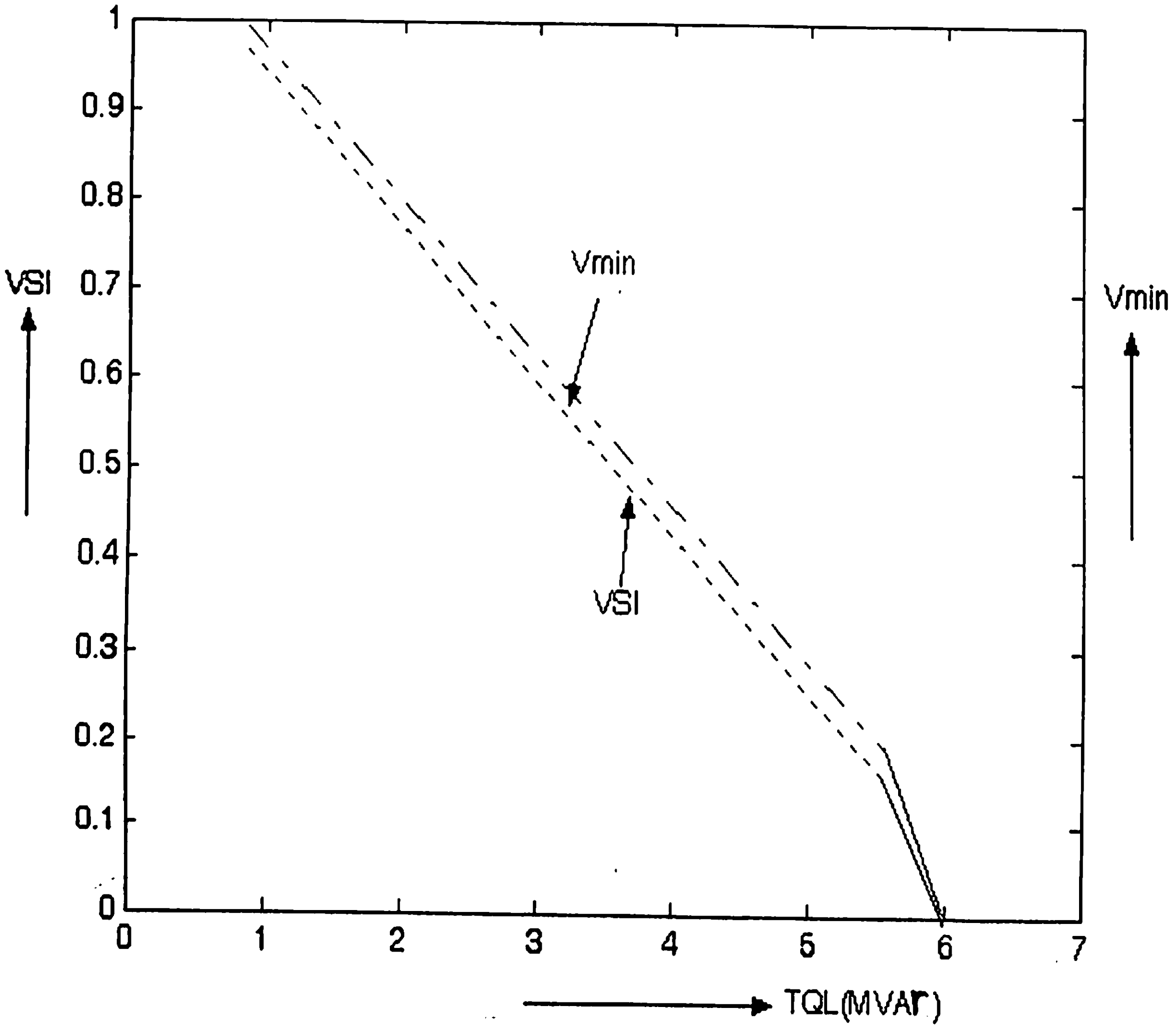


Figure 5.7 Plot of VSI of the Most Sensitive Node and V_{min} vs TQL of the System Selected by Utility

5.9 Summary

A method is proposed to identify the optimum location for the substation using Differential Evolution with the help of proposed expression for VSI in Chapter 3. All the load points are connected in optimum route by the methods of Chen and Hsu (1989) and Hsu and Chen (1990). The selection of optimal branch conductors have been carried out using the method proposed by Tram and Wall (1988) taking the proposed VSI as one of the constraints. The voltage stability index at all nodes has been computed by the proposed expression for VSI. The most sensitive node of the network has also been identified. To demonstrate the effectiveness of the proposed method one example has been selected. The superiority of the proposed method has been demonstrated by comparing it with the method proposed in Chapter 4 using Genetic Algorithm for the same example. This method gives better result compared to the method proposed in Chapter 4. The critical values of TPL and TQL the network selected by utility have also been computed, beyond which the system will collapse. If alternate algorithms are used for connection of load points in optimum route and selection of optimal branch conductors, the results may be different.

CHAPTER 6

PLANNING OF DISTRIBUTION SYSTEM WITH NEAR OPTIMUM LOCATION AND FROM GIVEN MULTIPLE LOCATIONS FOR SUBSTATION

6.1 Introduction

In Chapter 4 and Chapter 5 planning of electric power distribution systems have been carried out using Genetic algorithm (GA) and Differential Evolution (DE) respectively and their most sensitive nodes have also been identified. Using GA and DE the optimum locations for the substation have been identified. But in practice it may happen that the optimum location of the substation cannot be used due to social reasons or if the location of substation violates the Heuristic rules given in Chapter 4 (Art. 4.4) and hence the near optimal location for the substation must be identified. If the optimum or the near optimum locations also cannot be used due to social reasons, multiple locations for substation are marked at first. The location of substation that gives the minimum planning cost is selected from these given multiple locations.

Literature survey of planning of distribution substation has been presented in Chapter 2.

The aim of this chapter is to find the following:

(i) Identification of the near optimum location when the exact optimum position of substation violates the heuristic rules given in Chapter 4 (Art. 4.4) and

(ii) identification of substation location from given multiple locations of substation corresponding to the minimum planning cost.

The connection of load points in optimum route, selection of optimal branch conductors with the help of methods already given in Chapter 4 and VSI of all nodes are computed with the help of expression of VSI proposed in Chapter 3. The critical values of TPL and TQL have also been computed, beyond which the system will collapse.

6.2 Near Optimum Location for Substation

Figure 6.1 shows the 28 load points. The co-ordinates and load kVA of each of these 28 load points are given in Appendix–G (Table G.1). The total load kVA is 1169 kVA. The optimum location for the substation is (11.869, 15.75) using Differential Evolution. This location cannot be used due to social reasons. The point (13.01, 14.98) gives the near

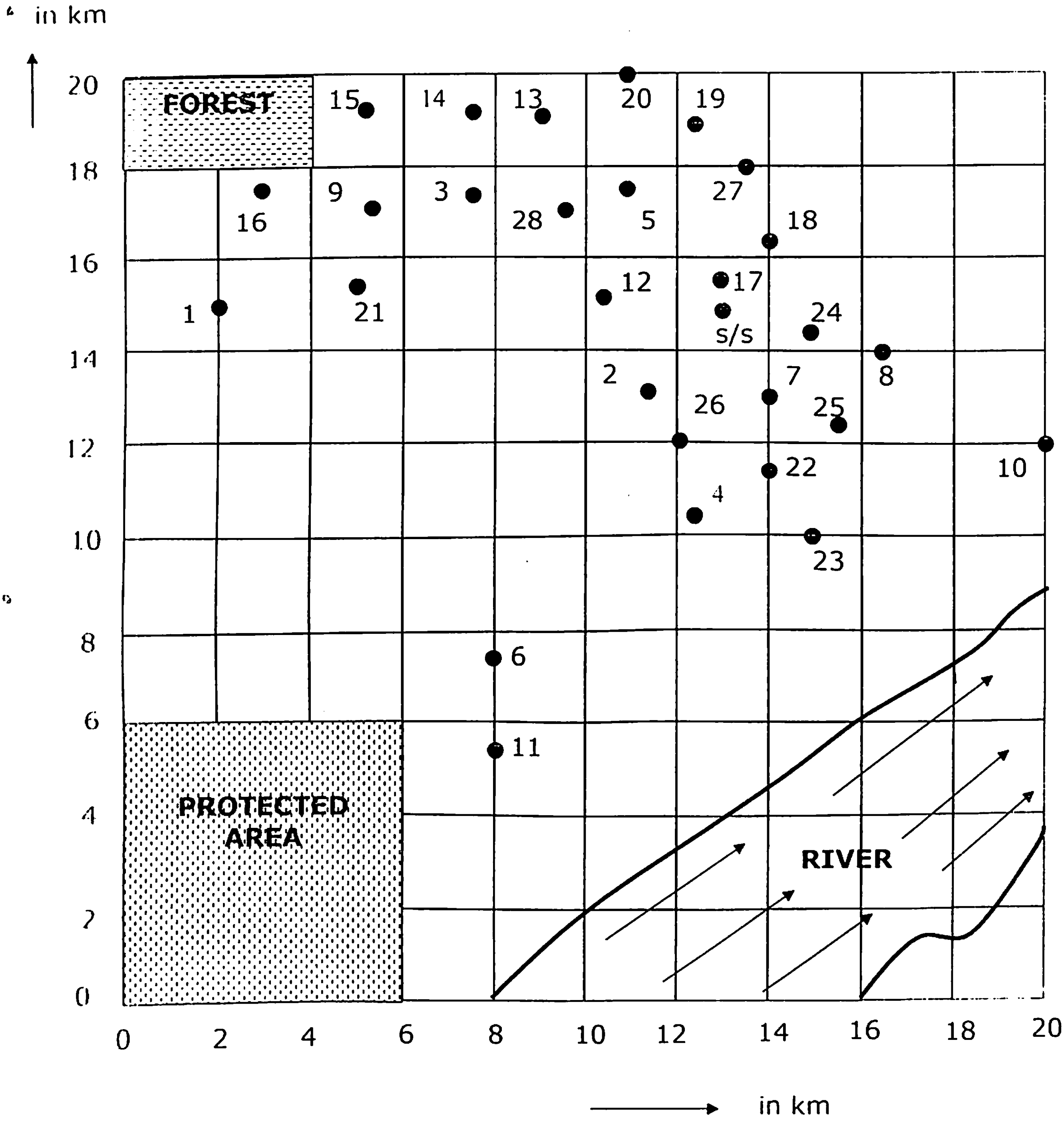


Figure 6.1 28 Load Points

optimum location. The nodes 17, 24 and 4, 26 cannot be connected due to physical obstruction. The connection of load points to substations, knowledge based expert systems and selection of optimal branch conductors has already been discussed in Chapter-4. The same methods are also used here.

Table 6.1 and Table 6.2 show the load flow results and the computed value of VSI at all nodes respectively for case of single feeder. Table 6.3 shows branch number, sending-end node, receiving-end node, selected optimal conductor for each branch and length of each branch for case of single feeder. Figure 6.2 shows the connection of all load points to substation (S/S) for case of single feeder. The bold numbers **1,2,3** and **4** show the selected optimal branch conductors where **1**→ SQUIRREL,**2**→ WEASEL, **3**→ RABBIT and **4**→ RACCON respectively.

Table 6.4 and Table 6.5 show the load flow results and the computed value of VSI at all nodes respectively for case of two feeders. Table 6.6 shows branch number, sending-end node, receiving-end node, selected optimal conductor for each branch and length of each branch for case of two feeders. Figure 6.3 shows the connection of all load points to substation (S/S) for case of two feeders. The bold numbers **1,2,3** and **4** show the selected optimal branch conductors where **1**→ SQUIRREL,**2**→ WEASEL, **3**→ RABBIT and **4**→ RACCON respectively.

Table 6.1 Load Flow Results for the Example having Single Feeder

Node Number	Voltage Magnitude (p.u.)
S/S	1.000000
1	0.972940
2	0.974426
3	0.976926
4	0.975914
5	0.981895
6	0.971457
7	0.980141
8	0.983144
9	0.975457
10	0.981930
11	**0.970358**
12	0.972996
13	0.974223
14	0.975088
15	0.974738
16	0.973677
17	0.997477
18	0.990642
19	0.985100
20	0.984788
21	0.975025
22	0.977703
23	0.976720
24	0.984237
25	0.979281
26	0.975994
27	0.987637
28	0.979677

Table 6.2 Values of VSI for All Nodes of the Example having Single Feeder

Node Number	VSI
1	0.896072
2	0.901557
3	0.910835
4	0.907073
5	0.929504
6	0.890577
7	0.922868
8	0.934257
9	0.905379
10	0.929651
11	**0.886599**
12	0.896275
13	0.900808
14	0.904006
15	0.902716
16	0.898787
17	0.989935
18	0.962998
19	0.941706
20	0.940526
21	0.903779
22	0.913741
23	0.910077
24	0.938342
25	0.919661
26	0.907375
27	0.951439
28	0.921141

Table 6.3 Branch Number, Sending-end Node, Receiving-end Node, Selected Optimal Conductor for Each Branch and Length of Each Branch for Case of Single Feeder for the Example

Branch Number (jj)	Sending-end Node (m1)	Receiving-end Node (m2)	Selected Optimal Branch Conductor	Length of Each Branch(jj) (km)
1	S/S	17	4---->RACCON	0.500000
2	17	18	4---->RACCON	1.414214
3	18	27	4---->RACCON	1.581139
4	27	19	4---->RACCON	1.414214
5	19	20	1---->SQUIRREL	1.802776
6	19	5	4---->RACCON	2.121320
7	5	28	4---->RACCON	1.581139
8	28	3	4---->RACCON	2.061553
9	3	14	2---->WEASEL	2.000000
10	14	13	1---->SQUIRREL	1.581139
11	14	15	1---->SQUIRREL	2.000000
12	3	9	3---->RABBIT	2.061553
13	9	21	1---->SQUIRREL	1.581139
14	18	24	4---->RACCON	2.236068
15	24	8	2---->WEASEL	1.581139
16	24	7	4---->RACCON	1.802776
17	7	22	4---->RACCON	1.500000
18	7	25	1---->SQUIRREL	1.581139
19	22	4	2---->WEASEL	1.802776
20	22	23	1---->SQUIRREL	1.581139
21	22	26	3---->RABBIT	1.581139
22	26	2	2---->WEASEL	1.802776
23	2	12	2---->WEASEL	1.802776
24	9	16	2---->WEASEL	2.549510
25	16	1	1---->SQUIRREL	2.692582
26	8	10	1---->SQUIRREL	4.472136
27	4	6	1---->SQUIRREL	5.408327
28	6	11	1---->SQUIRREL	2.000000

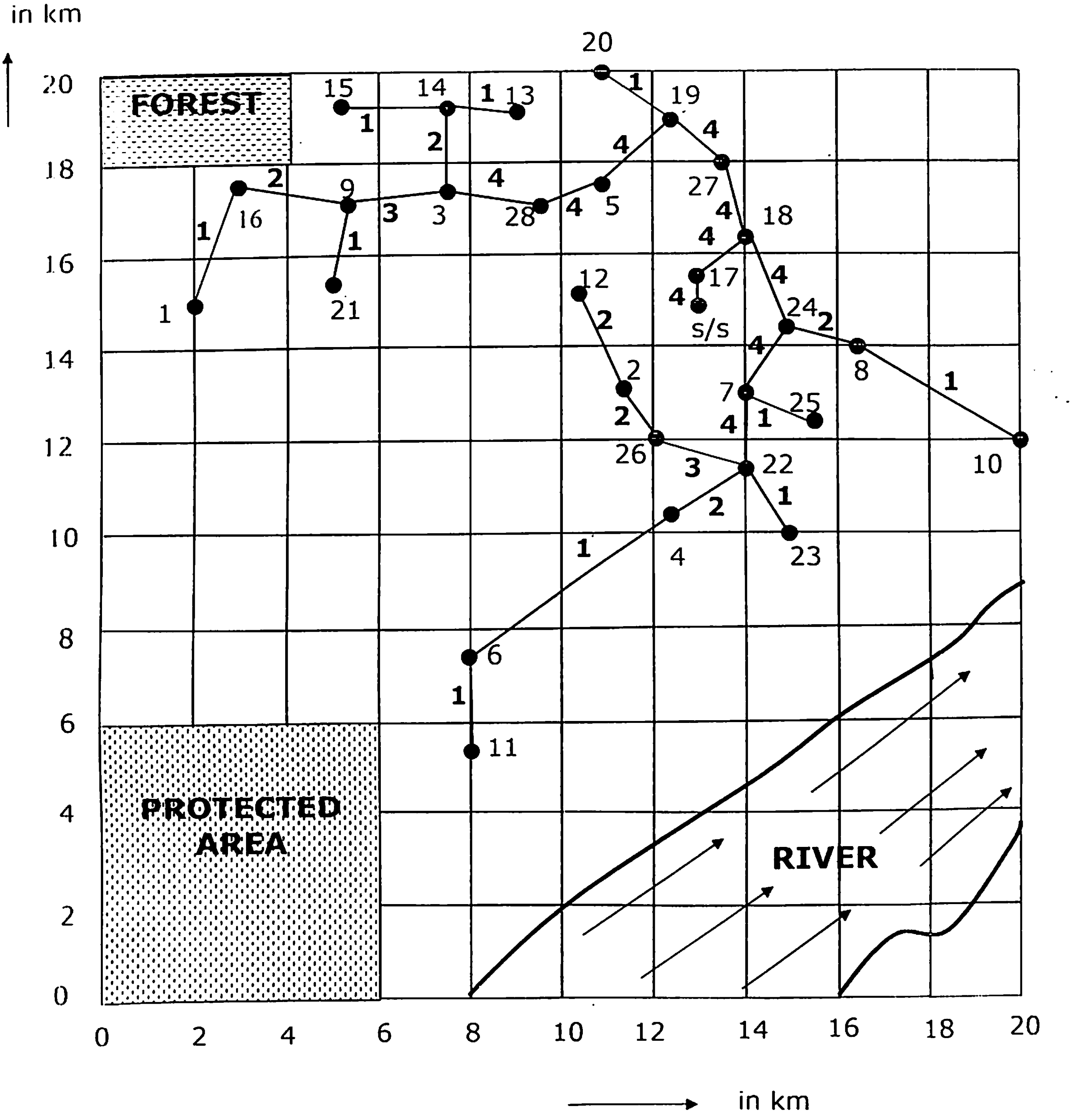


Figure 6.2 Case of Single Feeder

Table 6.4 Load Flow Results for the Example having Two Feeders

Node Number	Voltage Magnitude (p.u.)
S/S	1.000000
1	0.973602
2	0.975088
3	0.977586
4	0.976574
5	0.982552
6	0.972120
7	0.980799
8	0.983799
9	0.976117
10	0.982586
11	**0.971022**
12	0.973658
13	0.974884
14	0.975749
15	0.975399
16	0.974339
17	0.999733
18	0.991292
19	0.985754
20	0.985442
21	0.975686
22	0.978362
23	0.977379
24	0.984891
25	0.979939
26	0.976655
27	0.988289
28	0.980334

Table 6.5 Values of VSI for All Nodes of the Example having Two Feeders

Node Number	VSI
1	0.898514
2	0.904007
3	0.913297
4	0.909531
5	0.931992
6	0.893012
7	0.925346
8	0.936751
9	0.907834
10	0.932139
11	**0.889028**
12	0.898718
13	0.903257
14	0.906459
15	0.905168
16	0.901233
17	0.998934
18	0.965472
19	0.944210
20	0.943028
21	0.906232
22	0.916207
23	0.912539
24	0.940842
25	0.922136
26	0.909833
27	0.953955
28	0.923618

Table 6.6 Branch Number, Sending-end Node, Receiving-end Node, Selected Optimal Conductor for Each Branch and Length of Each Branch for Case of Two Feeders for the Example

Branch Number (jj)	Sending-end Node (m1)	Receiving-end Node (m2)	Selected Optimal Branch Conductor	Length of Each Branch(jj) (km)
1	S/S	17	1---->SQUIRREL	0.500000
2	S/S	18	4---->RACCON	1.802776
3	18	27	4---->RACCON	1.581139
4	27	19	4---->RACCON	1.414214
5	19	20	1---->SQUIRREL	1.802776
6	19	5	4---->RACCON	2.121320
7	5	28	4---->RACCON	1.581139
8	28	3	4---->RACCON	2.061553
9	3	14	2---->WEASEL	2.000000
10	14	13	1---->SQUIRREL	1.581139
11	14	15	1---->SQUIRREL	2.000000
12	3	9	3---->RABBIT	2.061553
13	9	21	1---->SQUIRREL	1.581139
14	18	24	4---->RACCON	2.236068
15	24	8	2---->WEASEL	1.581139
16	24	7	4---->RACCON	1.802776
17	7	22	4---->RACCON	1.500000
18	7	25	1---->SQUIRREL	1.581139
19	22	4	2---->WEASEL	1.802776
20	22	23	1---->SQUIRREL	1.802776
21	22	26	3---->RABBIT	2.061553
22	26	2	2---->WEASEL	1.581139
23	2	12	2---->WEASEL	1.802776
24	9	16	2---->WEASEL	2.549510
25	16	1	1---->SQUIRREL	2.692582
26	8	10	1---->SQUIRREL	4.472136
27	4	6	1---->SQUIRREL	5.408327
28	6	11	1---->SQUIRREL	2.000000

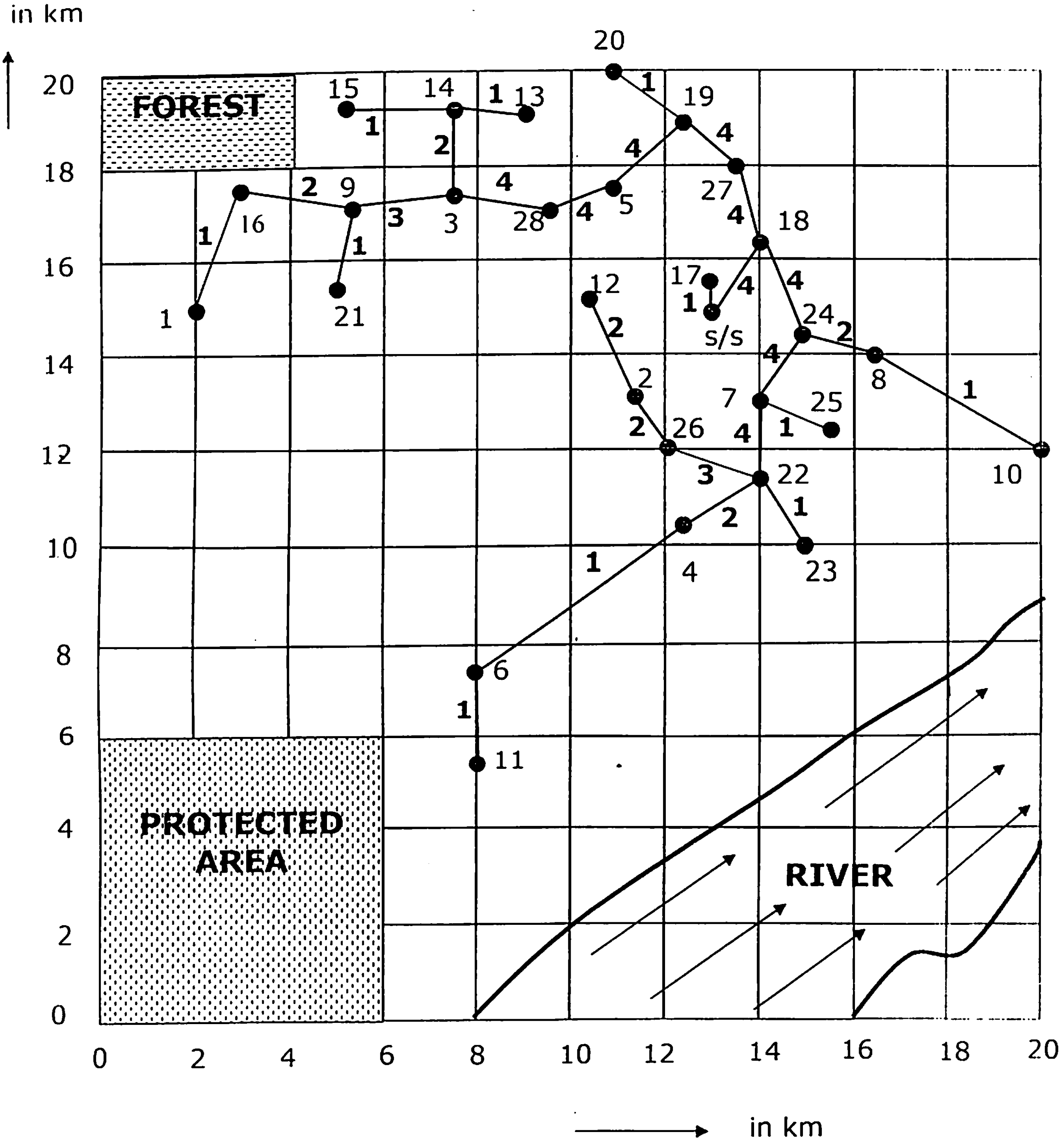


Figure 6.3 Case of Two Feeders

Table 6.7 and Table 6.8 show the load flow results and the computed value of VSI at all nodes respectively for case of three feeders. Table 6.9 shows branch number, sending-end node, receiving-end node, and selected optimal conductor for each branch and length of each branch for case of three feeders. Figure 6.4 shows the connection of all load points to substation (S/S) for case of three feeders. The bold numbers **1,2,3** and **4** show the selected optimal branch conductors where **1**→ SQUIRREL,**2**→ WEASEL, **3**→ RABBIT and **4**→ RACCON respectively.

Table 6.10 shows the comparison of the cases for single feeder, two feeders and three feeders. Utility can select three feeders' case. The kVA rating of the substation is 1169 kVA.

Figure 6.5 and Figure 6.6 show the plot of VSI of the most sensitive node and V_{min} vs TPL and VSI of the most sensitive node and V_{min} vs TQL respectively of the system selected by utility. The critical values of TPL and TQL are 2.8 MW and 2.4 MVAr respectively, beyond which voltage collapse will occur.

6.3 Identification of Substation Location from Given Multiple Locations for Substation

In this case the location of substation is selected from the given multiple locations for the substation corresponding to the minimum planning cost.

Table 6.7 Load Flow Results for the Example having Three Feeders

Node Number	Voltage Magnitude (p.u.)
S/S	1.000000
1	**0.978876**
2	0.984444
3	0.982838
4	0.985916
5	0.987778
6	0.981505
7	0.990100
8	0.993072
9	0.981378
10	0.991870
11	0.980417
12	0.983027
13	0.980152
14	0.981011
15	0.980664
16	0.979609
17	0.999733
18	0.996472
19	0.990963
20	0.990653
21	0.980949
22	0.987687
23	0.986713
24	0.994154
25	0.989249
26	0.985996
27	0.993485
28	0.985572

Table 6.8 Values of VSI for All Nodes of the Example having Three Feeders

Node Number	VSI
1	**0.918143**
2	0.939206
3	0.933086
4	0.944836
5	0.951980
6	0.928000
7	0.960953
8	0.972572
9	0.927564
10	0.967873
11	0.923938
12	0.933814
13	0.922937
14	0.926175
15	0.924869
16	0.920891
17	0.998934
18	0.985937
19	0.964327
20	0.963132
21	0.925944
22	0.951640
23	0.947901
24	0.976754
25	0.957681
26	0.945143
27	0.974175
28	0.943517

Table 6.9 Branch Number, Sending-end Node, Receiving-end Node, Selected Optimal Conductor for Each Branch and Length of Each Branch for Case of Three Feeders for the Example

Branch Number (jj)	Sending-end Node (m1)	Receiving-end Node (m2)	Selected Optimal Branch Conductor	Length of Each Branch(jj) (km)
1	S/S	17	1---->SQUIRREL	0.500000
2	S/S	18	4---->RACCON	1.802776
3	S/S	24	4---->RACCON	2.061553
4	18	27	4---->RACCON	1.581139
5	27	19	4---->RACCON	1.414214
6	24	8	2---->WEASEL	1.581139
7	24	7	4---->RACCON	1.802776
8	7	22	4---->RACCON	1.500000
9	7	25	1---->SQUIRREL	1.581139
10	19	20	1---->SQUIRREL	1.802776
11	22	4	2---->WEASEL	1.802776
12	22	23	1---->SQUIRREL	1.802776
13	22	26	3---->RABBIT	2.061553
14	26	2	2---->WEASEL	1.581139
15	2	12	2---->WEASEL	1.802776
16	19	5	4---->RACCON	2.121320
17	5	28	4---->RACCON	1.581139
18	28	3	4---->RACCON	2.061553
19	3	14	2---->WEASEL	2.000000
20	14	13	1---->SQUIRREL	1.581139
21	14	15	1---->SQUIRREL	2.000000
22	3	9	3---->RABBIT	2.061553
23	9	21	1---->SQUIRREL	1.581139
24	9	16	2---->WEASEL	2.549510
25	16	1	1---->SQUIRREL	2.692582
26	8	10	1---->SQUIRREL	4.472136
27	4	6	1---->SQUIRREL	5.408327
28	6	11	1---->SQUIRREL	2.000000

Table 6.9 Branch Number, Sending-end Node, Receiving-end Node, Selected Optimal Conductor for Each Branch and Length of Each Branch for Case of Three Feeders for the Example

Branch Number (jj)	Sending-end Node (m1)	Receiving-end Node (m2)	Selected Optimal Branch Conductor	Length of Each Branch(jj) (km)
1	S/S	17	1---->SQUIRREL	0.500000
2	S/S	18	4---->RACCON	1.802776
3	S/S	24	4---->RACCON	2.061553
4	18	27	4---->RACCON	1.581139
5	27	19	4---->RACCON	1.414214
6	24	8	2---->WEASEL	1.581139
7	24	7	4---->RACCON	1.802776
8	7	22	4---->RACCON	1.500000
9	7	25	1---->SQUIRREL	1.581139
10	19	20	1---->SQUIRREL	1.802776
11	22	4	2---->WEASEL	1.802776
12	22	23	1---->SQUIRREL	1.802776
13	22	26	3---->RABBIT	2.061553
14	26	2	2---->WEASEL	1.581139
15	2	12	2---->WEASEL	1.802776
16	19	5	4---->RACCON	2.121320
17	5	28	4---->RACCON	1.581139
18	28	3	4---->RACCON	2.061553
19	3	14	2---->WEASEL	2.000000
20	14	13	1---->SQUIRREL	1.581139
21	14	15	1---->SQUIRREL	2.000000
22	3	9	3---->RABBIT	2.061553
23	9	21	1---->SQUIRREL	1.581139
24	9	16	2---->WEASEL	2.549510
25	16	1	1---->SQUIRREL	2.692582
26	8	10	1---->SQUIRREL	4.472136
27	4	6	1---->SQUIRREL	5.408327
28	6	11	1---->SQUIRREL	2.000000

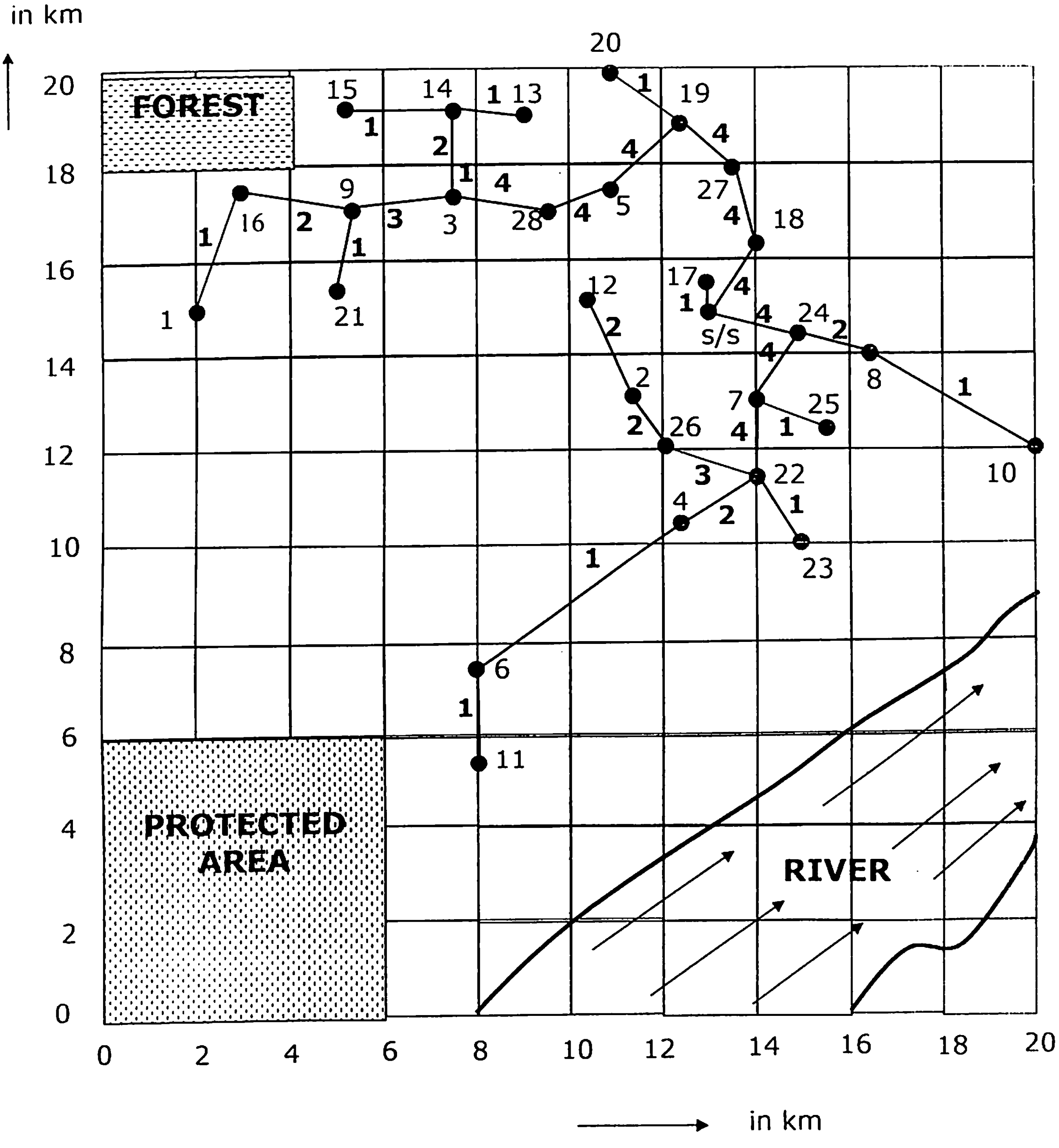


Figure 6.4 Case of Three Feeders

Table 6.10 Comparison of Cases for Single Feeder, Two Feeders and Three Feeders of the Example

Number of Feeder (s)	Real Power Loss (kW)	Reactive Power Loss (kVAr)	Total Feeder Length (km)	Total Cost (Rs)	Highest Sensitive Node	Minimum Voltage
One	18.88	17.33	56.09	141503.67	11	$\|V_{11}\| = 0.970358$
Two	18.25	16.71	56.48	137909.53	11	$\|V_{11}\| = 0.971022$
Three	11.88	10.49	56.30	101083.60	1	$\|V_{1}\| = 0.978876$

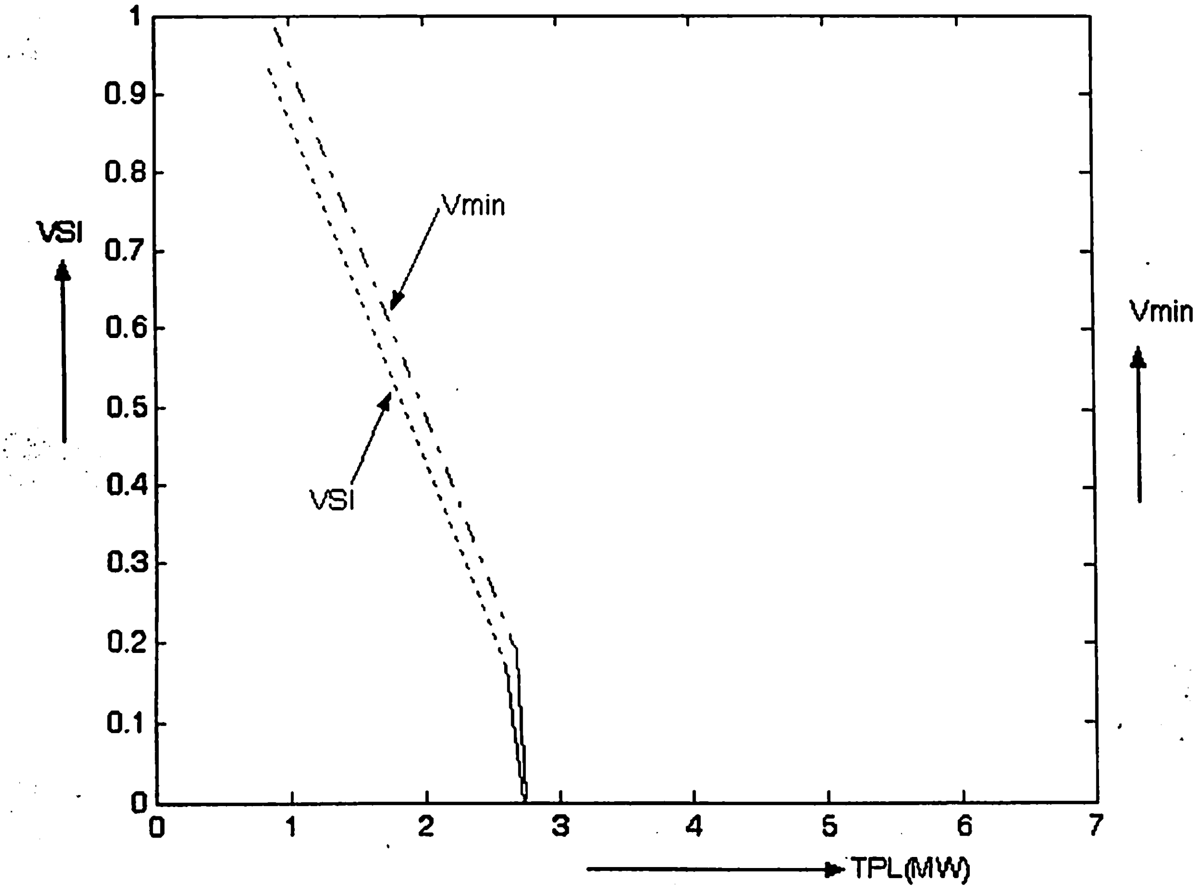


Figure 6.5 Plot of VSI of the Most Sensitive Node and V_{min} vs TPL of the System Selected by Utility

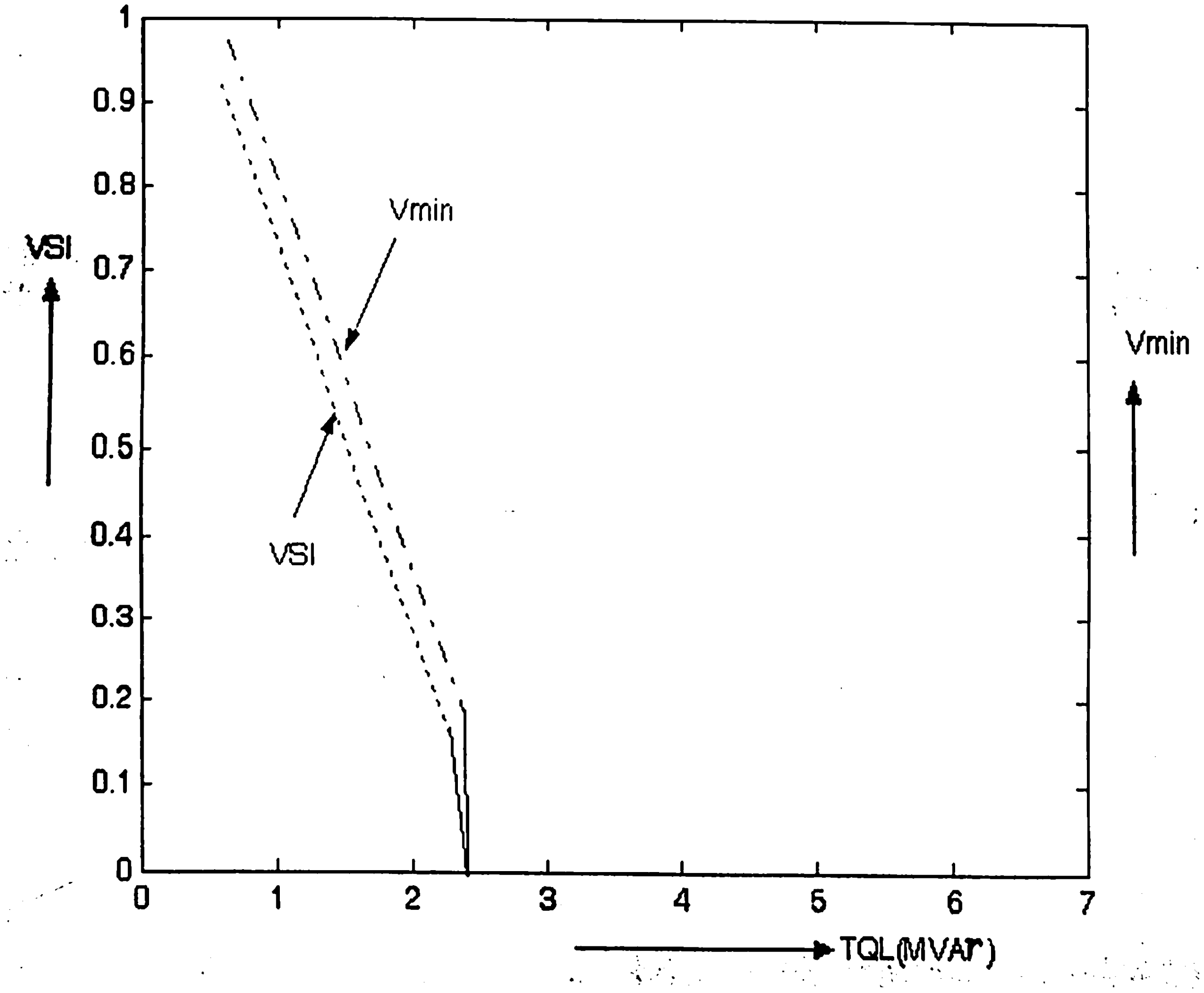


Figure 6.6 Plot of VSI of the Most Sensitive Node and V_{min} vs TQL of the System Selected by Utility

The example of 28 load points shown in Figure 6.1 is redrawn and shown in Figure 6.7 where the available locations for substation are in Cell A(3 , 9), Cell B(1,13), Cell C (19,19) and Cell D(13,7). The connection of load points to substations using knowledge based expert systems and selection of optimal conductors has already been discussed in Chapter-4. The same techniques are used also here.

Table 6.11 compares the cost, real power loss, reactive power loss for one feeder, two feeders and three feeders case for locations of A,B,C and D respectively. The co-ordinate of the substation is taken (19.0, 19.0) because it gives the minimum planning cost.

Table 6.12 and Table 6.13 show the load flow results and the computed value of VSI at all nodes respectively for case of three feeders. Table 6.14 shows branch number, sending-end node, receiving-end node, selected optimal conductor for each branch and length of each branch for case of three feeders. Figure 6.8 shows the connection of all load points to substation (S/S) for case of three feeders. The bold numbers **1,2,3** and **4** show the selected optimal branch conductors where **1**→ SQUIRREL, **2**→ WEASEL, **3**→ RABBIT and **4**→ RACCON respectively. Utility can select three feeders' case and the rating of distribution transformer at the substation is 1169 kVA. Figure 6.9 and Figure 6.10 show the plot of VSI of the most sensitive node and V_{min} vs TPL and VSI of the most sensitive node and V_{min} vs TQL respectively of the system selected by utility.

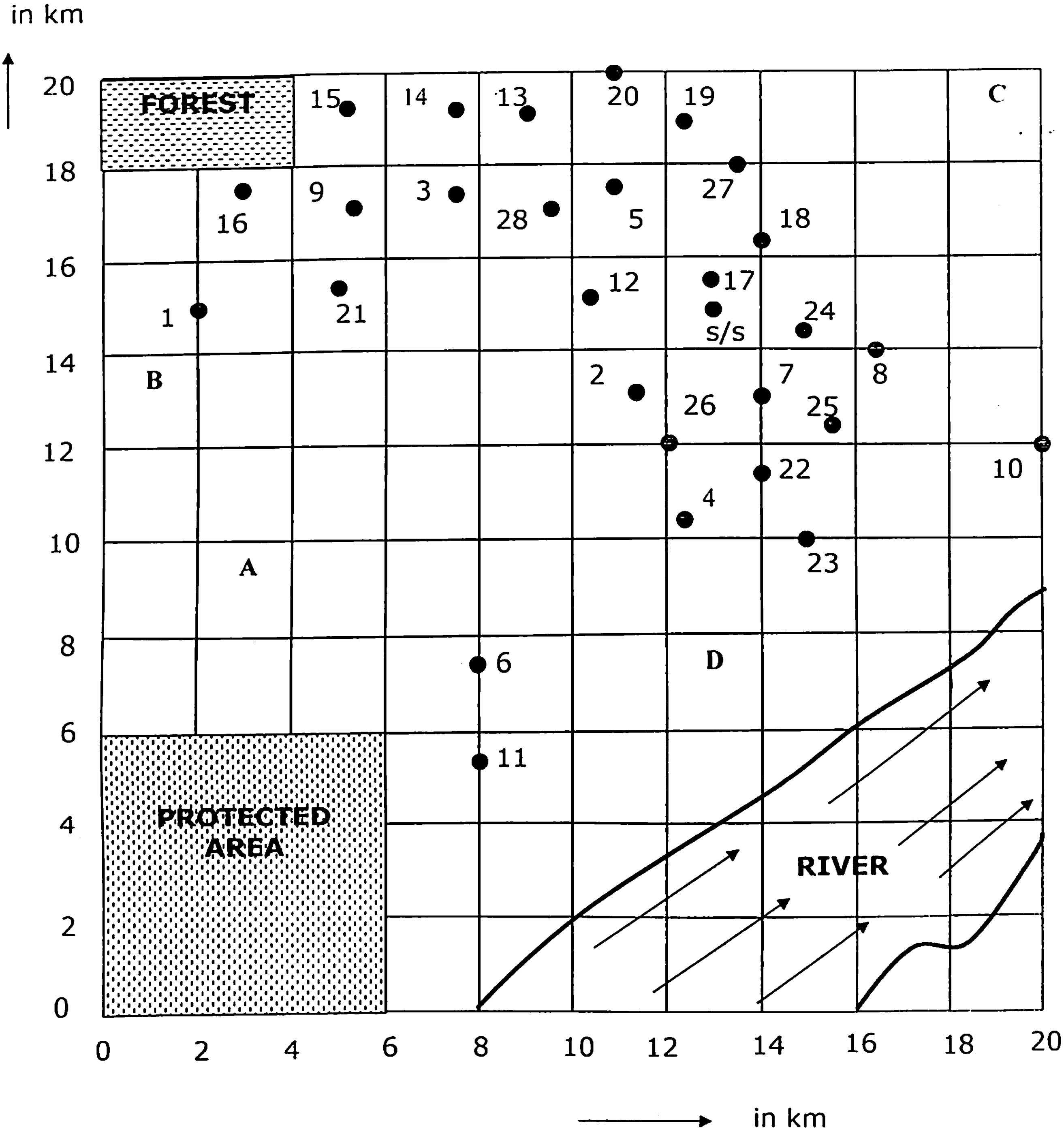


Figure 6.7 Locations for Substations (A, B, C and D)

Table 6.11 Comparison of the Cost for the Cases of Single Feeder, Two Feeders and Three Feeders Case for Locations of Substation in Cell A, B, C and D

Location of S/S in Cell		Cost (Rs)	Real Power Loss (kW)	Reactive Power Loss (kVAr)
A having number of feeder(s)	One	460301.00	68.63	67.13
	Two	443036.93	66.24	64.55
	Three	443170.75	66.05	64.50
B having number of feeder(s)	One	387090.12	56.77	55.43
	Two	353797.34	51.42	50.06
	Three	337112.03	48.50	47.06
C having number of feeder(s)	One	267459.03	37.68	36.24
	Two	165748.92	21.50	19.92
	Three	**154959.62**	**19.65**	**17.91**
D having number of feeder(s)	One	250249.03	35.45	33.95
	Two	239604.40	33.50	32.02
	Three	210008.37	28.23	26.63

Table 6.12 Load Flow Results for the Example having Three Feeders

Node Number	Voltage Magnitude (p.u.)
S/S	1.000000
1	0.974724
2	0.970837
3	0.978703
4	0.972330
5	0.983663
6	0.967857
7	0.976573
8	0.983945
9	0.977236
10	0.982733
11	**0.966754**
12	0.969401
13	0.976005
14	0.976868
15	0.976519
16	0.975460
17	0.995290
18	0.996047
19	0.986862
20	0.986550
21	0.976805
22	0.974127
23	0.973139
24	0.983088
25	0.979836
26	0.972411
27	0.989394
28	0.981448

Table 6.13 Values of VSI for All Nodes of the Example having Three Feeders

Node Number	VSI
1	0.902663
2	0.888348
3	0.917480
4	0.893824
5	0.936216
6	0.877448
7	0.909515
8	0.936811
9	0.912004
10	0.932696
11	**0.873500**
12	0.883105
13	0.907416
14	0.910626
15	0.909331
16	0.905387
17	0.981291
18	0.984245
19	0.948462
20	0.947277
21	0.910398
22	0.900442
23	0.896806
24	0.934048
25	0.921720
26	0.894123
27	0.958026
28	0.927824

Table 6.14 Branch Number, Sending-end Node, Receiving-end Node, Selected Optimal Conductor for Each Branch and Length of Each Branch for Case of Three Feeders for the Example

Branch Number (jj)	Sending-end Node (m1)	Receiving-end Node (m2)	Selected Optimal Branch Conductor	Length of Each Branch(jj) (km)
1	S/S	8	4---->RACCON	5.590170
2	S/S	18	1---->SQUIRREL	5.590170
3	S/S	27	4---->RACCON	5.590170
4	18	17	1---->SQUIRREL	1.414214
5	27	19	4---->RACCON	1.414214
6	8	24	1---->SQUIRREL	1.581139
7	8	25	4---->RACCON	1.802776
8	25	7	4---->RACCON	1.581139
9	7	22	4---->RACCON	1.500000
10	19	20	1---->SQUIRREL	1.802776
11	22	4	2---->WEASEL	1.802776
12	22	23	1---->SQUIRREL	1.802776
13	22	26	3---->RABBIT	2.061553
14	26	2	2---->WEASEL	1.581139
15	2	12	2---->WEASEL	1.802776
16	19	5	4---->RACCON	2.121320
17	5	28	4---->RACCON	1.581139
18	28	3	4---->RACCON	2.061553
19	3	14	2---->WEASEL	2.000000
20	14	13	1---->SQUIRREL	1.581139
21	14	15	1---->SQUIRREL	2.000000
22	3	9	3---->RABBIT	2.061553
23	9	21	1---->SQUIRREL	1.581139
24	9	16	2---->WEASEL	2.549510
25	16	1	1---->SQUIRREL	2.692582
26	8	10	1---->SQUIRREL	4.472136
27	4	6	1---->SQUIRREL	5.408327
28	6	11	1---->SQUIRREL	2.000000

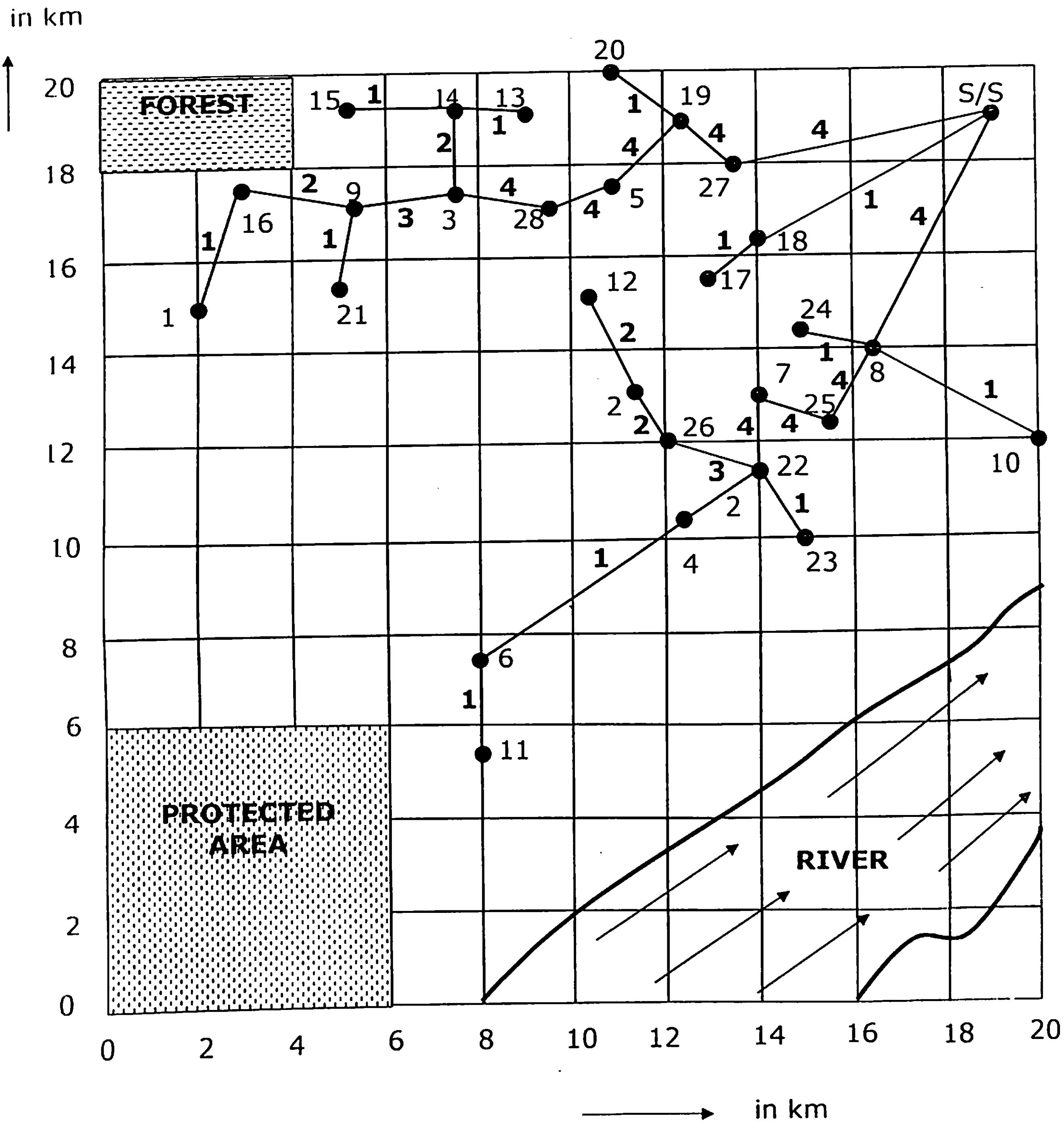


Figure 6.8 Planned System Selected by Utility

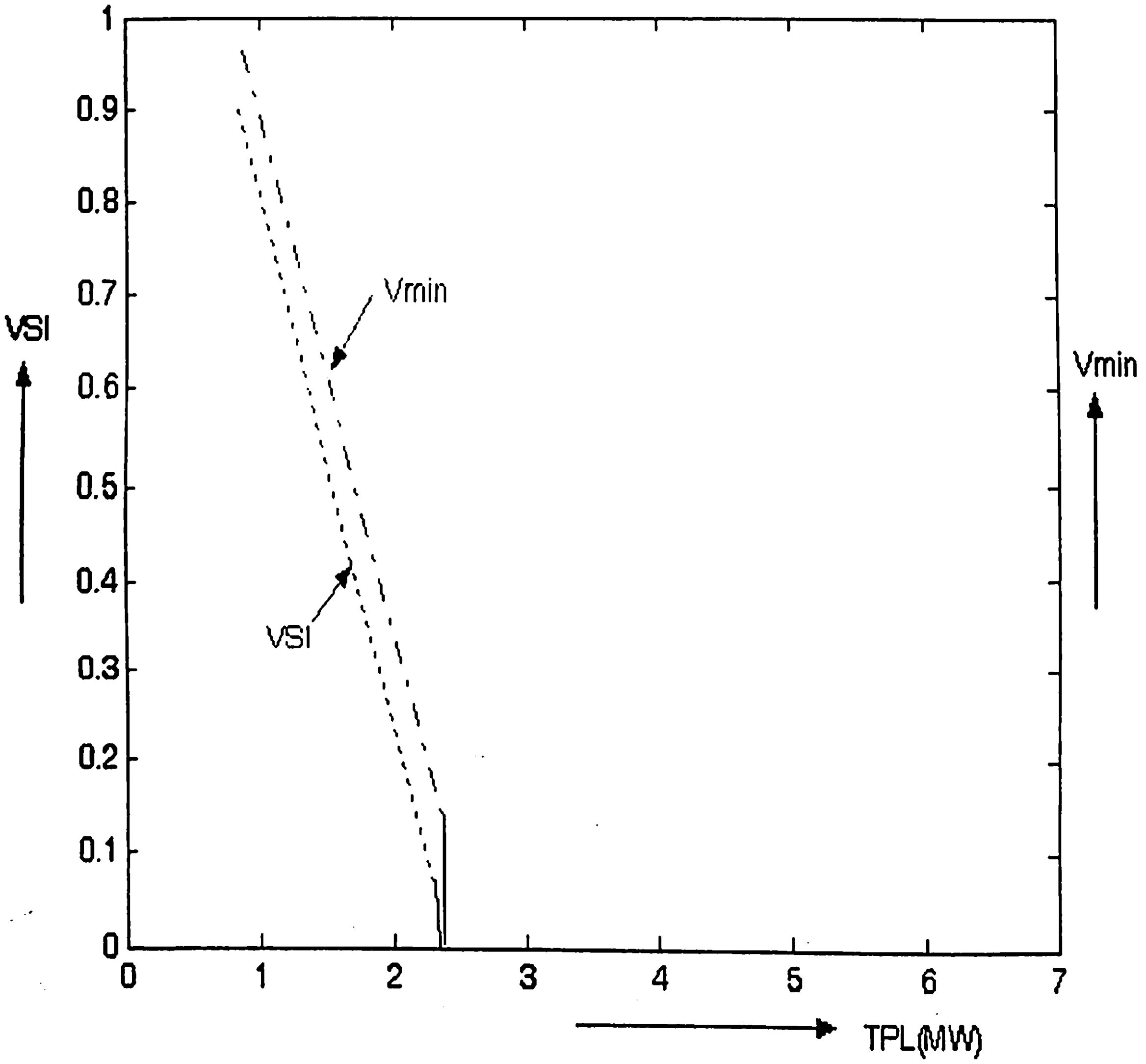


Figure 6.9 Plot of VSI of the Most Sensitive Node and V_{min} vs TPL of the System Selected by Utility

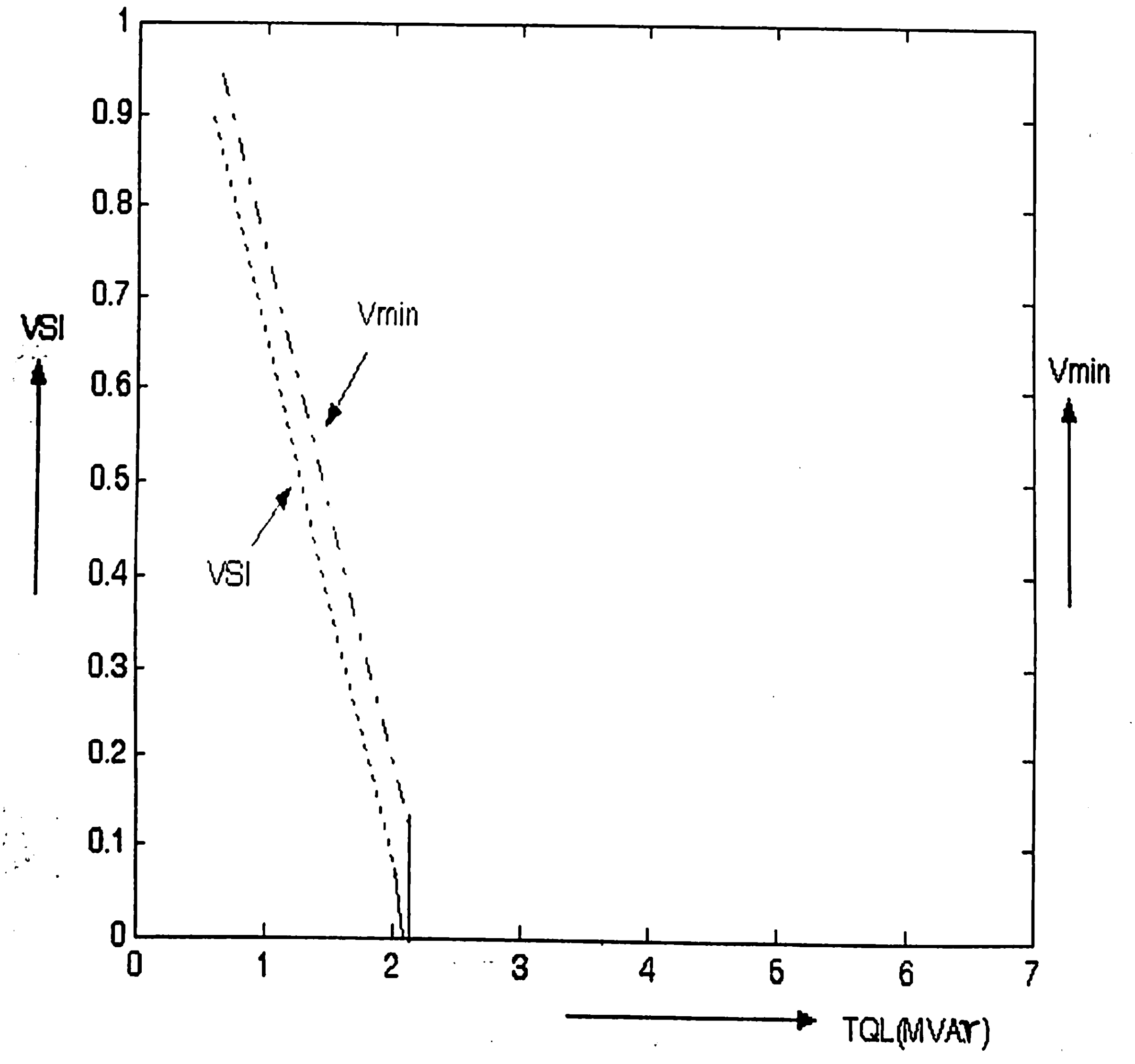


Figure 6.10 Plot of VSI of the Most Sensitive Node and V_{min} vs TQL of the System Selected by Utility

The critical values of TPL and TQL are 2.4 MW and 2.1 MVAr respectively, beyond which the system will actually collapse.

6.4 Summary

In this Chapter two cases are considered. In first case, the near optimum location for the substation has been found out when the exact optimum location cannot be used due to violation of heuristic rules given in Chapter 4. In second case the location for the substation is selected from given multiple locations for substation that gives minimum planning cost. This is very useful in practical cases where the locations for substation are already fixed and the optimum and the near optimum location cannot be used. In both cases the load points are connected in optimum route using the methods of Chen and Hsu (1989), Hsu and Chen (1990) for cases of single feeder, two feeders and three feeders. The optimal branch conductors are selected using the method of Tram and Wall (1988) taking the proposed expression for VSI as one of the constraints and also the most sensitive nodes are identified in all these cases. In both cases the critical values of TPL and TQL of the network selected by utility are computed, beyond which the system will collapse. If alternate algorithms are used for connection of load points in optimum route and selection of optimal branch conductors, the results may be different.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 Summary and Conclusions

The main aim of this chapter is to explore the summary of the significant results obtained in this thesis work and to give the future scope of further research work.

The basics of distribution system, voltage collapse, objectives of the research, scope of the research and organization of the research have been discussed in Chapter 1. The exhaustive literature survey on load flow, voltage stability analysis and planning of electric power distribution system has been presented in Chapter 2.

In Chapter 3, a new expression is derived to compute the VSI of each node of any balanced power distribution network without any assumption. The node having the minimum value of VSI becomes the most sensitive node of this network. To demonstrate the effectiveness of the proposed method three examples 17 node, 29 node and 33 node radial distribution networks have been selected. The most sensitive nodes and their values of VSI in all three cases obtained by the proposed method and by the methods of Jasmon and Lee (1991) and Ranjan *et al.* (2004a) have been compared and also the nodes having the minimum value of voltage and their voltage magnitudes in all the three cases. This comparison shows that the most sensitive nodes identified by the proposed method are the end nodes and also the nodes having the minimum voltage for all the above three cases, which the other two methods do not ensure. The critical values of TPL and TQL for 17 node, 29 node and 33 node radial distribution networks have also been computed by the proposed method and the methods of Jasmon and Lee (1991a) and Ranjan *et al.* (2004a) and the proposed method gives the less critical values of TPL and TQL. This is due to the fact that Jasmon and Lee (1991a) while deriving the expression for VSI had reduced the whole network into its single line equivalent that is valid at the operating point and put the voltage magnitude 1.0 p.u. for all nodes whereas Ranjan *et al.* (2004a) while deriving the expression for VSI had reduced the whole network into its single line equivalent indirectly at the operating point and assumed that the voltage magnitude of sending-end node is equal to that of the receiving-end for all branches that led higher values and unable to identify the proper most sensitive node. The networks are stable at these computed critical values of TPL and TQL and will collapse beyond these values of TPL and TQL.

In Chapter 4, a method is proposed to identify the optimum location of substation using Genetic Algorithm using the proposed expression for VSI in Chapter 3 in fitness function. All the load points are connected in optimum route using heuristic rules proposed by Chen and Hsu (1989) and Hsu and Chen (1990) respectively. For selection of optimal branch conductor the method proposed by Tram and Wall (1988) has been used taking the proposed expression for VSI as one of the constraints. The voltage stability index of each node has been computed using the proposed expression for VSI and the most sensitive node of the network has also been identified. To demonstrate the effectiveness of the proposed method two examples have been selected. The superiority of the proposed method has also been checked by comparing it with the method proposed by Ranjan *et al.* (2002) with the help of 53 load points i.e., Example 1. The identified optimum location for the substation gives the better result compared to that of identified by classical technique. A comparison of the cases of single feeder, two feeders and three feeders have been shown for second example also. Utility can take three feeders' case. The critical values of TPL and TQL of the network selected by utility have also been computed, beyond which the system will collapse. It is important to note that if alternate algorithms are used for connection of load points in optimum route and selection of optimal branch conductors, the results may be different.

In Chapter 5, a method is proposed to identify the optimum location for the substation using Differential Evolution with the help of proposed expression for VSI in Chapter 3. All the load points are connected in optimum route by the methods of Chen and Hsu (1989) and Hsu and

Chen(1990). The selection of optimal branch conductors have been carried out using the method proposed by Tram and Wall (1988) taking the proposed expression for VSI as one of the constraints. The voltage stability index of all nodes has been computed by the proposed expression for VSI. The most sensitive node of the network has also been identified. To demonstrate the effectiveness of the proposed method one example has been selected. The superiority of the proposed method has been demonstrated by comparing it with the method proposed in Chapter 4 using Genetic Algorithm for the same example. This method gives better result compared to the method proposed in Chapter 4. The critical values of TPL and TQL the network selected by utility have also been computed, beyond which the system will collapse. Once again, it is emphasized that if alternate algorithms are used for connection of load points in optimum route and selection of optimal branch conductors, the results may be different.

In Chapter 6, two cases are considered. In first case, the near optimum location for the substation has been found out when the exact optimum location cannot be used due to violation of heuristic rules given in Chapter 4. In second case the location for the substation from given multiple locations for substation is selected which gives minimum planning cost. This is very useful in practical cases where the locations for substation are already fixed and the optimum and the near optimum location cannot be used. In both cases the load points are connected in optimum route using the methods of Chen and Hsu (1989), Hsu and Chen (1990) for cases of single feeder, two feeders and three feeders. The optimal branch conductors are selected using the method of Tram and Wall (1988) taking the proposed expression for VSI as one of the constraints and also the most sensitive nodes are identified in all these cases. In both cases the critical values of TPL and TQL of the network selected by utility are computed, beyond which the system will collapse. If alternate algorithms are used for connection of load points in optimum route and selection of optimal branch conductors, the results may be different.

7.2 Future Scope of Research Work

After carrying extensive investigation in electric power distribution systems, the author has realised that the following guidelines seem to be worth pursuing in electric power distribution systems:

- Fuzzy load flow analysis.
- Fuzzy voltage stability analysis.
- Optimum capacitor placement using Differential Evolution.
- Network reconfiguration using Differential Evolution.
- Optimal conductor selection using Differential Evolution.
- Optimal conductor selection for unbalanced distribution system.
- Voltage stability analysis using other different load modelling.
- Study of distribution system with real data system.

REFERENCES

1. Adams, R.N. and Laughton , M.A. (1974), "Optimal Planning of Power Networks Using Mixed-Integer Programming", Proceedings IEE Part C (GTD), Vol.121, No.2, pp. 139-148.
2. Ajjarapu, V. and Christy, C. (1992), "The Continuation of Power Flow: A Tool for Steady State Voltage Stability", IEEE Transactions on Power Systems, Vol.7, No.1, pp. 416–423.
3. Aoki, K., Ichimori, T., and Kanezashi, M. (1987)," Normal State Optimal Load Allocation in Distribution Systems", IEEE Transactions on Power Delivery, Vol.2, No.1, pp.147–155.
4. Aoki, K., Kuwabara, H., Satoh, T. and Kanezashi, M. (1988), "An Efficient Algorithm for Load Balancing of Transformers and Feeders by Switch Operation in Large Scale Distribution Systems", IEEE Transactions on Power Delivery, Vol.3, No.4, pp. 1865–1872.
5. Aoki, K., Nara, K., Itoh, M. and Kuwabara, H. (1989), "A New Algorithm for Service Restoration in Distribution Systems", IEEE Transactions on Power Delivery, Vol.4, No.3, pp.1832–1839.
6. Aoki, K., Nara, K., Satoh, T., Kitagawa, M. and Yamanaka, K. (1990),"New Approximate Optimization Method for Distribution System Planning", IEEE Transactions on Power Systems, Vol.5, No.1, pp.126–132.

7. Baran, M.E. and Wu, F.F. (1989), "Optimal Sizing of Capacitors Placed on a Radial Distribution System", IEEE Transactions on Power Delivery, Vol.4, No.1, pp.735–743.

8. Baran, M.E. and Wu, F.F. (1989a), "Network Reconfiguration in Distribution Systems for Loss Reduction and Load Balancing", IEEE Transactions on Power Delivery, Vol.4, No.2, pp.1401–1407.

9. Braunder, G. and Zobel , M. (1994), "Knowledge Based Planning of Distribution Networks", IEEE Transactions on Power Systems, Vol.9, No.2, pp.942–948.

10. Brownell, G. and Clark, H. (1989), "Analysis and Solutions for Bulk System Voltage Instability", IEEE Computer Applications in Power, Vol.2, No.3, pp. 31–35.

11. Chakravorty, M. and Das, D. (2001), "Voltage Stability Analysis of Radial Distribution Networks", International Journal of Electrical Power and Energy Systems, Vol.23, No.2, pp.129–135.

12. Chebbo, A.M., Sterling, M.J.H. and Irving, M.R. (1992), "Reactive Power Dispatch Incorporating Voltage Stability", Proceedings IEE Part C (GTD), Vol. 139, No. 3, pp. 253 -260.

13. Chen, J. and Hsu, Y. (1989), "An Expert System for Load Allocation in Distribution Expansion Planning", IEEE Transactions on Power Delivery, Vol.4, No.3, pp.1910–1918.

7. Baran, M.E. and Wu, F.F. (1989), "Optimal Sizing of Capacitors Placed on a Radial Distribution System", IEEE Transactions on Power Delivery, Vol.4, No.1, pp.735-743.

8. Baran, M.E. and Wu, F.F. (1989a), "Network Reconfiguration in Distribution Systems for Loss Reduction and Load Balancing", IEEE Transactions on Power Delivery, Vol.4, No.2, pp.1401-1407.

9. Braunder, G. and Zobel , M. (1994), "Knowledge Based Planning of Distribution Networks", IEEE Transactions on Power Systems, Vol.9, No.2, pp.942-948.

10. Brownell, G. and Clark, H. (1989), "Analysis and Solutions for Bulk System Voltage Instability", IEEE Computer Applications in Power, Vol.2, No.3, pp. 31-35.

11. Chakravorty, M. and Das, D. (2001), "Voltage Stability Analysis of Radial Distribution Networks", International Journal of Electrical Power and Energy Systems, Vol.23, No.2, pp.129-135.

12. Chebbo, A.M., Sterling, M.J.H. and Irving, M.R. (1992), "Reactive Power Dispatch Incorporating Voltage Stability", Proceedings IEE Part C (GTD), Vol. 139, No. 3, pp. 253 -260.

13. Chen, J. and Hsu, Y. (1989), "An Expert System for Load Allocation in Distribution Expansion Planning", IEEE Transactions on Power Delivery, Vol.4, No.3, pp.1910-1918.

14. Chiang, H.D. (1991), "A Decoupled Load Flow Method for Distribution Power Networks: Algorithms Analysis and Convergence Study", International Journal of Electrical Power Energy Systems, Vol.13, No.3, pp.130–138.

15. Civanlar, S., Grainger, J.J. and Lee, S.H. (1988), "Distribution Feeder Reconfiguration for Loss Reduction", IEEE Transactions on Power Delivery, Vol.3, No.3, pp.1217–1223.

16. Crawford, D.M. and Holt, Jr. S.B. (1975), "A Mathematical Optimization Technique for Locating and Sizing Distribution Substations, and Deriving their Optimal Service Areas", IEEE Transactions on Power Apparatus and Systems, Vol.94, No.2, pp.230-235.

17. Custem, T.V. and Mailhot, R. (1997), "Validation of a Fast Voltage Stability Analysis Method on Hydro–Quebec System", IEEE Transactions on Power Systems, Vol. 12, No. 1, pp. 282–292.

18. Das,D., Kothari,D.P. and Kalam, A. (1995), "Simple and Efficient Method for Load Flow Solution of Radial Distribution Networks", International Journal of Electrical Power and Energy Systems, Vol. 17, No.5, pp.335–346.

19. El-Kady, M.A (1984), "Computer-Aided Planning of Distribution Substation and Primary Feeders", IEEE Transactions on Power Apparatus and Systems, Vol.103, No.6, pp. 1183–1189.

20. Fawzi, T.H., Ali,K.F. and El-Sobki, S.M. (1983), "A New Planning Model for Distribution Systems", IEEE Transactions on Power Apparatus and Systems, Vol. 102, No. 9, pp.3010–3017.

21. Gao, B., Morison, G.K. and Kundur, P. (1992), "Voltage Stability Evaluation Using Modal Analysis", IEEE Transactions on Power Systems, Vol.7, No.4, pp.1529 –1542.

22. Ghosh, S. and Das, D. (1999), "Method for Load Flow Solution of Radial Distribution Networks", Proceedings IEE Part C (GTD), Vol. 146, No.6, pp.641–648.

23. Glamocanin, V. (1990), "Optimal Loss Reduction of Distribution Networks", IEEE Transactions on Power Systems, Vol.5, No.3, pp.774 –782.

24. Gonnen, T. (1986), "Electric Power Distribution System Engineering", McGraw Hill, New York.

25. Gonen, T. and Foote, B.L. (1981), "Distribution System Planning Using Mixed Integer Programming", Proceedings IEE Part C (GTD), Vol.128, No.2, pp.70 –79.

26. Gonen, T. and Ramirez-Rosado, I. (1986), "Review of Distribution System Planning Models: a model for optimal multi-stage planning", Proceedings IEE Part C (GTD), Vol.133, No.7, pp.397–408.

27. Goswami, S.K. (1997), "Distribution System Planning Using Branch-Exchange Technique", IEEE Transactions on Power Systems, Vol. 12, No.2, pp. 718 -723.

28. Goswami, S.K. and Basu, S.K. (1991), "Direct Solutions of Distribution Systems", Proceedings IEE Part C (GTD), Vol.138, No.1, pp.78 -88.

29. Gubina, F. and Strmcnik, B. (1997), "A Simple Approach to Voltage Stability Assessment in Radial Networks", IEEE Transactions on Power Systems, Vol.12, No.3, pp.1121 -1128.

30. Hindi, K.S. and Brameller, A. (1977), "Design of Low-Voltage Distribution Networks: A Mathematical Programming Method", Proceedings IEE Part C (GTD), Vol. 124, No.1, pp.54 -58.

31. Holland, J.H.(1975), "Adaptation of Natural and Artificial Systems", University of Michigan Press, Ann Arbor.

32. Hongewi, Dai *et al.* (1997), "Optimal Planning of Distribution Substation Locations Sizes Model and Algorithm", International Journal of Electrical Power and Energy Systems, Vol.18, No.6, pp.353 -357.

33. Hsu, Y. and Chen, J. (1990), "Distribution Planning Using a Knowledge-Based Expert System", IEEE Transactions on Power Delivery, Vol.5, No.3, pp. 1514 -1519.

34. Hsu, Y. and Jwo-Hwu, Y. (1993), "Planning of Distribution Feeder Reconfiguration with Protective Device Coordination", IEEE Transactions on Power Delivery, Vol.8, No.3, pp.1340 -1347.

35. Jasmon, G.B. and Lee, L.H.C.C. (1991), "Stability of Load-Flow Techniques for Distribution System Voltage Stability Analysis", Proceedings IEE Part C (GTD), Vol.138, No.6, pp.479 -484.

36. Jasmon, G.B. and Lee, L.H.C.C. (1991a),"Distribution Network Reduction for Voltage Stability Analysis and Load Flow Calculations", International Journal of Electrical Power and Energy Systems, Vol.13, No.1, pp.9 -13.

37. Kersting, W.H. (1984), "A Method to Teach the Design and Operation of a Distribution System", IEEE Transactions on Power Apparatus and Systems, Vol. 103, No. 7, pp.1945 -1952.

38. Kersting, W.H. and Mendive, D.L. (1976), "An Application of Ladder Theory to the Solution of Three-Phase Radial Load-Flow Problem", IEEE Transactions on Power Apparatus and Systems, Vol.98, No. 7, pp.1061 -1067.

39. Kundur, Prabha (1994), "Power System Stability and Control", McGraw Hill, New York.

40. Leung, L.C. and Khator, S.K. (1995), "Transformer Procurement and Relocation at a Large Electric Utility: A Mixed 0-1 LP Model", IEEE Transactions on Power Systems, Vol.10, No.2, pp.957 -963.

41. Masud, E. (1974), "An Interactive Procedure for Sizing and Timing Distribution Substations-using Optimization Techniques", IEEE Transactions on Power Apparatus and Systems, Vol.93, No.5, pp. 1281 -1286.

42. Merrit, W.C., Taylor, C.H., Burchett, R.C. and Happ, H.H. (1988), "Security Constrained Optimization – a Case Study", IEEE Transactions on Power Systems, Vol.3, No.3, pp.970 -977.

43. Mikic, O.M. (1986), "Mathematical Dynamic Model for Long-term Distribution System Planning", IEEE Transactions on Power Systems, Vol.1, No.1. pp. 34 -40.

44. Nahman, J. *et al.* (1996), "Optimal Planning of Rural Medium Voltage Distribution Networks", International Journal of Electrical Power and Energy Systems, Vol.19, No.8, pp.549 -556.

45. Nara, K., Satoh, T., Kitagawa, M. and Yamanaka, K. (1991), "Multi-Year Expansion Planning for Distribution Systems", IEEE Transactions on Power Systems, Vol.6, No.3, pp. 952 -958.

46. Nara, K., Satoh, T., Kuwabara, H., Aoki, K., Kitagawa, M. and Ishihara, T. (1992) "Distribution Systems Expansion Planning by Multi-Stage Branch Exchange", IEEE Transactions on Power Systems, Vol.7, No.1, pp.208 -214.

47. Nara, K., Kuwabara, H., Kitagawa, M. and Ohtaka, K. (1994), "Algorithm for Expansion Planning in Distribution Systems Taking

Faults into Consideration", IEEE Transactions on Power Systems, Vol.9, No.1, pp.324 -330.

48. Ponnavaikko, M. and Rao , K.S. Prakasa (1981), "Optimal Distribution System Planning", IEEE Transactions on Power Apparatus and Systems, Vol.100, No.6, pp.2969 -2977.

49. Price, K. and Storn, R. (1997), "Differential Evolution- A Simple and Efficient Adaptive Scheme for Global Optimization over Continuous Spaces", Berkely.edu/tr-95 -012.ps.Z.

50. Price, K. and Storn, R. (1997a), "Differential Evolution", Dr. Dobb's J., Issue 264, pp. 18 -24.

51. Quintana, W.H., Temraz, H.K. and Hipel, K.W. (1993), "Two-stage Power System Distribution Planning Algorithm", Proceedings IEE Part C (GTD), Vol.140, No.1, pp. 17-29.

52. Rahman, T.K.A. and Jasmon, G.B. (1995), "A new technique for voltage stability analysis in a power system and improved load flow algorithm for distribution network", International Conference on Energy Management and Power Delivery, Proceedings of EMPD '95, Vol. 2, pp. 21-23.

53. Ramirez-Rasado, I.J. and Gonen, T. (1991), "Pseudodynamic Planning for Expansion of Power Distribution Systems", IEEE Transactions on Power Systems, Vol.6, No.1, pp.245 -254.

54. Ranjan, R., Venkatesh, B. and Das , D. (2002), "A New Algorithm for Power Distribution System Planning", International Journal of Electric Power System Research, Vol. 62, No. 1, pp.55 -65.

55. Ranjan, R. *et al.*(2003), "Optimal Conductor Selection of Radial Distribution Feeders Using Evolutionary Programming", IEEE TENCON Conference on Optimal Operation of Power Systems, pp.456 -459.

56. Ranjan, R. and Das, D. (2004), "Simple and Efficient Computer Algorithm to Solve Radial Distribution Networks", International Journal of Electric Power Components and Systems, Vol. 31, No. 1, pp.95 -107.

57. Ranjan, R., Venkatesh, B. and Das, D. (2004a), "Voltage Stability Analysis of Radial Distribution Networks", International Journal of Electric Power Components and Systems, Vol. 31, No. 2, pp.501-511.

58. Renato, C.G. (1990), "New Method for the Analysis of Distribution Networks", IEEE Transactions on Power Delivery, Vol.5, No.1, pp.9-13.

59. Sarada, A., Khator, S.K. and Leung, L.C. (1995), "Substation Feeder Configuration at a Large Utility", IEEE Computer Applications in Power, Vol.28, No.2, pp.329 -339.

60. Shirmohammadi, D., Hong, H.W., Semlyen, A. and Luo, G.X. (1988), "A Compensation Based Power Flow Method for Weakly Meshed

Distribution and Transmission Network", IEEE Transactions on Power systems, Vol.3, No.2, pp.753 -762.

61. Singh, P. *et al.* (1998), "A New Techniques for Optimal Time Dynamic Distribution Substation and Feeder Planning", International Journal of Electric Power System Research, Vol. 47, No.3, pp. 197–204.

62. Stevens, R.A., *et al.* (1986), "Performance of Conventional Power Flow Routines for Real Time Distribution Automation Application", Proceedings 18th Southeastern Symposium on Systems Theory: IEEE Computer Society, pp.196 -200.

63. Sun, D.I., Farris, D.R., Cote, P.J., Shoults, R.R. and Chen, M.S. (1982), "Optimal Distribution Substation and Primary Feeder Planning via the Fixed Charge Network Formulation", IEEE Transactions on Power Apparatus and Systems, Vol.101, No.3, pp.602–608.

64. Taylor, C.W. (1994), "Power System Voltage Stability", McGraw Hill, New York.

65. Thompson, G.L., and Wall, D.L. (1981), "A Branch and Bound Model for Choosing Optimal Substation Locations", IEEE Transactions on Power Apparatus and Systems, Vol. 100, No.5, pp.2683 -2688.

66. Tram, H.N. and Wall, D.L. (1988), "Optimal Conductor Selection in Planning Radial Distribution Systems", IEEE Transactions on Power Systems, Vol.3, No.1, pp.200–206.

67. Willis, H. Lee and Northcote-Green, J.E.D. (1985), "Comparison of Several Computerized Distribution Planning Methods", IEEE Transactions on Power Apparatus and Systems, Vol.104, No.1, pp.233 -240.

68. Wong, K.P. and Cheung, H.N. (1987), "Artificial Intelligence Approach to Load Allocation in Distribution Substations", Proceedings IEE Part C (GTD), Vol.134, No.5, pp.357 -364.

69. Yeh, E–C, *et al.* (1996), "Improved Distribution System Planning Using Computational Evolution", International Journal of Electric Power System Research, Vol. 11, No. 2, pp. 668 - 674.

APPENDIX A

Table A.1 Line Data of 17 Node Radial Distribution Network

Branch Number	Sending end Node	Receiving end Node	Branch resistance (Ohms)	Branch reactance (Ohms)
1	1	2	0.291088	0.284879
2	2	3	0.413456	0.404637
3	3	4	0.325671	0.318725
4	4	5	1.119759	0.466812
5	5	6	1.121486	0.467532
6	2	7	1.694297	0.479722
7	7	8	0.469290	0.459281
8	8	9	0.211944	0.207423
9	9	10	0.336042	0.328874
10	3	11	0.622088	0.259340
11	11	12	0.670010	0.279318
12	12	13	0.415493	0.280482
13	5	14	0.695517	0.289951
14	14	15	0.474579	0.464456
15	15	16	0.371627	0.250871
16	16	17	1.057550	0.440879

Table A.2 Load Data of 17 Node Radial Distribution Network

Node Number	PL (kW)	QL (kVAR)
1(S/S)	00.00	00.00
2	75.00	66.14
3	47.25	41.67
4	37.50	33.07
5	47.25	41.67
6	75.00	66.14
7	47.25	41.67
8	47.25	41.67
9	37.50	33.07
10	37.50	33.07
11	75.00	66.14
12	75.00	66.14
13	37.50	33.07
14	75.00	66.14
15	75.00	66.14
16	75.00	66.14
17	75.00	66.14

BASE kV = 11 and BASE MVA = 100

APPENDIX B

Table B.1 Line Data of 29 Node Radial Distribution Network

Branch Number	Sending end Node	Receiving end Node	Branch resistance (Ohms)	Branch reactance (Ohms)
1	1	2	0.151116	0.147893
2	2	3	0.427420	0.418330
3	3	4	0.477870	0.467677
4	4	5	0.427420	0.418303
5	5	6	2.050099	0.580464
6	6	7	0.641129	0.627455
7	7	8	0.477870	0.467677
8	8	9	0.623066	0.609777
9	9	10	1.244177	0.518680
10	10	11	1.798056	0.509101
11	11	12	2.274380	0.643967
12	12	13	0.927017	0.625792
13	13	14	1.798056	0.509101
14	14	15	0.675810	0.661396
15	15	16	0.983608	0.410053
16	16	17	1.190166	0.496164
17	17	18	0.453347	0.443678
18	2	19	1.798056	0.509101
19	19	20	1.356999	0.565714
20	20	21	2.050099	0.580464
21	21	22	0.927017	0.625792
22	7	23	1.190166	0.496164
23	23	24	1.356999	0.565714
24	24	25	1.919086	0.800040
25	25	26	3.061977	0.866967
26	9	27	5.085669	1.439954
27	27	28	6.150296	1.741392
28	28	29	2.274380	0.643967

Table B.2 Load Data of 29 Node Radial Distribution Network

Node Number	PL (kW)	QL (kVAR)
1(S/S)	0.0	0.0
2	37.50	33.07
3	12.00	10.58
4	18.75	16.54
5	37.50	33.07
6	12.00	10.58
7	18.75	16.53
8	12.00	10.58
9	47.25	41.67
10	37.50	33.07
11	37.50	33.07
12	12.00	10.58
13	12.00	10.58
14	18.75	16.53
15	37.50	33.07
16	47.25	41.67
17	75.00	66.14
18	37.50	33.07
19	37.50	33.07
20	37.50	33.07
21	37.50	33.07
22	18.75	16.53
23	18.75	16.53
24	75.00	66.14
25	47.25	41.67
26	18.75	16.53
27	18.75	16.53
28	18.75	16.53
29	37.50	33.07

BASE kV = 11 and BASE MVA = 100

APPENDIX C

Table C.1 Line Data of 33 Node Radial Distribution Network

Branch Number	Sending end Node	Receiving end Node	Branch resistance (Ohms)	Branch reactance (Ohms)
1	1	2	0.0922	0.0470
2	2	3	0.4930	0.2511
3	3	4	0.3660	0.1864
4	4	5	0.3811	0.1941
5	5	6	0.8190	0.7070
6	6	7	0.1872	0.6188
7	7	8	0.7114	0.2351
8	8	9	1.0300	0.7400
9	9	10	1.0040	0.7400
10	10	11	0.1996	0.0650
11	11	12	0.3744	0.1238
12	12	13	1.4680	1.1550
13	13	14	0.5416	0.7129
14	14	15	0.5910	0.5260
15	15	16	0.7463	0.5450
16	16	17	1.2890	1.7210
17	17	18	0.7320	0.5740
18	2	19	0.1640	0.1565
19	19	20	1.5042	1.3554
20	20	21	0.4095	0.4784
21	21	22	0.7089	0.9373
22	3	23	0.4512	0.3083
23	23	24	0.8980	0.7091
24	24	25	0.8960	0.7011
25	6	26	0.2030	0.1034
26	26	27	0.2842	0.1447
27	27	28	1.0590	0.9337
28	28	29	0.8042	0.7006
29	29	30	0.5075	0.2585
30	30	31	0.9744	0.9630
31	31	32	0.3105	0.3619
32	32	33	0.3410	0.5302

Taken from Baran and Wu(1989a)

Table C.2 Load Data of 33 Node Radial Distribution Network

Node Number	PL (kW)	QL (kVAR)
1(S/S)	0.0	0.0
2	100.0	60.0
3	90.0	40.0
4	120.0	80.0
5	60.0	30.0
6	60.0	20.0
7	200.0	100.0
8	200.0	100.0
9	60.0	20.0
10	60.0	20.0
11	45.0	30.0
12	60.0	35.0
13	60.0	35.0
14	120.0	80.0
15	60.0	10.0
16	60.0	20.0
17	60.0	20.0
18	90.0	40.0
19	90.0	40.0
20	90.0	40.0
21	90.0	40.0
22	90.0	40.0
23	90.0	50.0
24	420.0	200.0
25	420.0	200.0
26	60.0	25.0
27	60.0	25.0
28	60.0	20.0
29	120.0	70.0
30	200.0	600.0
31	150.0	70.0
32	210.0	100.0
33	60.0	40.0

Taken from Baran and Wu(1989a)
BASE kV = 12.66 and BASE MVA = 100

APPENDIX D

Table D.1 Data for Conductors

Type of Conductor	Area of cross section (mm^2)	Resistance (Ω/km)	Reactance (Ω/km)	Maximum Current carrying capacity(Amp)	Cost of conductor (Rs/km)
Squirrel	12.90	1.3760	0.3896	70.0	2880
Weasel	19.35	0.9810	0.3797	100.0	4338
Rabbit	32.26	0.5441	0.3673	148.0	7306
Raccon	48.39	0.3657	0.3579	200.0	10950

Taken From Ranjan et al.(2003)

APPENDIX E

Table E.1 Co-ordinate and Load kVA of each of 53 Load Points

Node Numbers	Co-ordinates		Load kVA
	X (km)	Y (km)	
S/S	-	-	-
1	1.00	2.00	25.0
2	2.00	15.0	25.0
3	3.00	4.00	25.0
4	4.00	12.0	50.0
5	5.00	11.5	63.0
6	6.00	10.0	63.0
7	7.00	7.00	50.0
8	1.50	5.50	25.0
9	11.5	13.5	16.0
10	7.50	17.5	16.0
11	8.50	15.5	25.0
12	12.5	10.5	50.0
13	11.0	17.5	63.0
14	8.00	7.50	63.0
15	11.0	6.00	25.0
16	5.50	5.50	16.0
17	3.50	8.50	16.0
18	13.0	8.00	16.0
19	14.0	13.0	63.0
20	16.5	14.0	25.0
21	5.5	17.0	25.0
22	20.5	12.0	50.0
23	8.00	9.00	100.0
24	5.00	7.00	100.0
25	8.00	5.50	100.0
26	10.5	8.00	50.0
27	10.5	15.0	50.0
28	9.00	19.0	25.0
29	7.50	19.5	63.0
30	5.50	19.5	63.0
31	3.00	17.5	25.0
32	13.0	15.5	50.0
33	14.0	16.5	50.0
34	12.5	19.0	25.0
35	11.0	20.0	25.0
36	5.00	15.5	50.0

			Continued
37	2.00	10.5	50.0
38	3.00	3.50	63.0
39	6.00	4.00	25.0
40	9.00	4.50	25.0
41	14.0	11.5	50.0
42	15.0	10.0	50.0
43	15.0	14.5	25.0
44	15.5	12.5	25.0
45	12.0	12.0	63.0
46	14.5	7.50	63.0
47	13.5	6.00	25.0
48	13.0	4.50	16.0
49	13.5	18.0	16.0
50	4.00	5.00	25.0
51	9.50	6.50	16.0
52	9.50	17.0	25.0
53	12.0	2.50	50.0

Taken From Ranjan et al. (2002)
BASE kV = 11 and BASE MVA = 100

APPENDIX F

Table F.1 Co-ordinate and Load kVA of each of 16 Load Points

Node Number	Co-ordinates		Load kVA
	X (km)	Y (km)	
S/S	-	-	-
1	13.5	11.4	50.00
2	12.8	12.5	63.00
3	14.3	13.2	100.0
4	11.0	12.5	63.00
5	9.50	11.5	63.00
6	11.8	10.8	100.0
7	13.5	9.50	100.0
8	13.5	8.50	100.0
9	11.8	8.50	100.0
10	16.0	12.4	63.00
11	16.6	13.0	50.00
12	17.5	14.0	50.00
13	16.5	14.4	100.0
14	17.5	15.0	100.0
15	19.0	14.5	100.0
16	18.5	13.5	50.00

BASE kV = 11 and BASE MVA = 100

APPENDIX G

Table G.1 Co-ordinate and Load kVA of each of 28 Load Points

Node Numbers	Co-ordinates		Load kVA
	X (km)	Y (km)	
S/S	-	-	-
1	2.0	15.0	25.0
2	11.5	13.5	25.0
3	7.5	17.5	63.0
4	12.5	10.5	50.0
5	11.0	17.5	25.0
6	8.0	7.5	25.0
7	14.0	13.0	100.0
8	16.5	14.0	63.0
9	5.5	17.0	16.0
10	20.5	12.0	25.0
11	8.0	5.5	50.0
12	10.5	15.0	100.0
13	9.0	19.0	50.0
14	7.5	19.5	50.0
15	5.5	19.5	16.0
16	3.0	17.5	63.0
17	13.0	15.5	50.0
18	14.0	16.5	16.0
19	12.5	19.0	50.0
20	11.0	20.0	16.0
21	5.0	15.5	25.0
22	14.0	11.5	50.0
23	15.0	10.0	50.0
24	15.0	14.5	50.0
25	15.5	12.5	50.0
26	12.0	12.0	25.0
27	13.5	18.0	25.0
28	9.5	17.0	16.0

BASE kV = 11 and BASE MVA = 100

APPENDIX H

LIST OF PUBLICATIONS

1. Ghosh, S. and Bansal, H.O. (2002), "An Approach for Inverse Load Flow Technique for Determining the Rating of Distribution Transformer", Proceedings of National Conference on Application of Evaluation Strategies to Power Signal Processing and Control, REC, Rourkela, 14-15 Feb, P.P.- 47-50.
2. Ghosh, S., Partheeban, M., Bannerjee, M., Saha, A. and Bansal, H.O. (2004), "A method to find the optimum position of substation using genetic algorithm," Proceedings of IEEE-PEECON (Feb.19) -HCE - Chennai, pp.114–115.
3. Ghosh, S. and Bansal, H.O. (2004), "A novel method for voltage sensitivity analysis of radial distribution networks," Proceedings of IEEE–PEECON (Feb.19)–HCE–Chennai, pp.116–118.
4. Ghosh, S., SenGupta, S. and Bansal, H.O. (2005), "An Efficient Algorithm for Determining the Rating of Distribution Transformers", Published in IEE International Conference, PETISCON, Kolkata.

APPENDIX I

BRIEF BIOGRAPHY OF CANDIDATE

Hari Om Bansal has been awarded B.E. (Electrical Engineering) and M.E.(Power Systems) from Engineering College, Kota and Malaviya Regional Engineering College, Jaipur in 1998 and 2000 respectively. He is a life member of Indian Society of Technical Education. He has served as a Lecturer in Mody College of Engineering & Technology, Lakshmangarh. He has published papers in National and International Conferences. His area of interest is Electric Power Distribution System. Currently he is serving as Lecturer in BITS, Pilani.

BRIEF BIOGRAPHY OF SUPERVISOR

Dr. Smarajit Ghosh has been awarded B.Sc. (Phy. Hons.), B.Tech. (Electrical Engineering), M.Tech. (Electrical Machines and Power Systems) from Calcutta University in 1991, 1994, 1996 respectively and finally Ph.D. from I.I.T., Kharagpur in 2000. He has already served as a Management Trainee in NICCO Cables, Calcutta and as a Lecturer in R.E.C., Durgapur. He is sole author of Basic Electrical and Electronics Engineering, Programming in C and Network Theory: Analysis and Synthesis all from Prentice Hall of India, Control System Engineering: Theory and Applications, Control Systems (JNTU) and Electrical Machines all from Pearson Education. He has published several papers in International and National Journals and Conferences. His areas of interest are Electric Power Distribution Systems and Soft Computing. Currently he is working as Assistant Professor in BITS, Pilani.