ESTIMATION OF COMMERCIAL LOSSES IN POWER DISTRIBUTION NETWORK

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree of

MASTER OF TECHNOLOGY

in

ELECTRICAL ENGINEERING

(With Specialization in System Engineering and Operations Research)

By

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CANDIDATE'S DECLARATION

I hereby declare that the work, which is being presented in this dissertation entitled **"ESTIMATION OF COMMERCIAL LOSSES IN POWER DISTRIBUTION NETWORK"** in the partial fulfillment of the requirement for the award of the degree of **Master of Technology in Electrical Engineering** with specialization in **System Engineering and Operations Research,** submitted in the **Department of Electrical Engineering, Indian Institute of Technology Roorkee,** Roorkee, is an authentic record of my own work carried out during July 2005 to June 2006 under the supervision of **Prof. Hari Om Gupta,** Professor, Department of Electrical Engineering, I. I. T Roorkee.

I have not submitted the matter embodied in this dissertation for award of any other degree.

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CERTIFICATE

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

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Abstract

Transmission and Distribution losses in India are much higher than those in any developed country. Out of these, the losses in distribution sector are very large. Commercial losses constitute the major part of losses in the distribution system. Estimation of these losses is of major importance which requires optimal placement of metering devices. In this thesis, the research work is done in the area of this meter placement problem. A 41-bus 33 kV system is considered for the analysis in the entire thesis.

In the present thesis work, the meter placement problem is handled using genetic algorithms. The meter placement thus obtained, balances between the financial constraint and Observability of the network. Numerical Observability technique is used to find the Observability of the network for each and every combination of meters obtained for meter placement.

The meter placement problem is found to have some disadvantages, hence a new algorithm is developed which overcomes the disadvantages of the former. This algorithm divides the basic structure of the network in to number of sub-laterals, processes them separately and again combine them to form the original structure. More constraints are imposed to refine the meter structure. The original method and the proposed method are compared in the aspect of faster convergence, search space, cost of the algorithms and size of matrices used.

The meters thus obtained will monitor the different areas of the network. The commercial losses are estimated with the help of these monitoring meters. The commercials losses and Technical losses of the 41-bus, 33 KV system are compared. Load flow analysis is done by Forward/Backward sweep method.

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CHAPTER-1
INTRODUCTION

1.1 GENERAL

Electric power distribution is a vital link between utility and the consumer, thus playing a very important role in the entire power system network. Hence it is imperative to exercise utmost caution in planning the system with losses as low as possible and a better quality supply to the consumers. In the context of chronic power shortage and ever increasing prices of fuel, it assumes greater importance.

Transmission and Distribution losses in India are much higher than those in any developed country. The losses can be as high as 35-40% or even more. Out of this Transmission and Distribution losses, the loss in the Distribution sector is very large.

There are several reasons for this high amount of losses such as

I. Improper Planning of the entire distribution system
II. Long feeders with very high LT:HT ratio
III. Feeders highly loaded and improper conductor configuration
IV. Commercial losses etc.

There are several reasons for commercial loss and it is a purely non-technical loss consisting of theft, pilferage and billing inaccuracies. Other losses are technical in nature and there is always a scope for system improvement by minimizing these losses. Proper estimation of technical loss is the only way to estimate the commercial loss occurring in the system.

Accurate monitoring of power system operation has become one of the most important functions in today's deregulated power markets. State estimators are the essential tools of choice in the implementation of this function. Whether, a new state estimator is put in to service or an existing one is being upgraded, placing new meters for improving or maintaining reliability of measurement systems is of great concern. Determination of the best possible combination of meters of monitoring a given power system is referred to as the optimal meter placement problem.

1.1.1 State Estimation & Observability analysis

During real-time power system monitoring, state estimation is responsible for providing a complete and reliable database in an energy management system. The State estimation correctly identifies and removes the redundant and bad data. The determination of system topology and Observability analysis are a part of state estimation.

Data redundancy is crucial for the success of state estimation. Adequate redundancy levels efficiently processes bad data and also to achieve good and reliable estimates, even in the case of temporary data loss. Data redundancy can be evaluated considering the number, type and topological distribution of metering devices. The highly redundant metering systems are not desirable due to financial constraints.

The particular meter arrangement is said to be observable if and only if by these meter readings, we can estimate the state of the entire power network or in other words, if the Gain matrix is nonsingular, then this particular meter arrangement is observable. Planning metering systems for power system monitoring is a complex task, not only due to the number of combinations available, but also to the need of establishing a trade-off between state estimation performance and metering system costs.

1.1.2 Genetic Algorithms:

A genetic algorithm is a search technique used to find approximate solutions to optimization and search problems. Genetic algorithms are a particular class of evolutionary algorithms that use techniques inspired by evolutionary biology such as natural selection, inheritance, mutation and crossover.

The evolution starts from a population of completely random individuals and happens in generations. In each generation, the fitness of the whole population is evaluated, multiple individuals are stochastically selected from the current population (based on fitness), modified to form a new population, which becomes current in the next iteration of the algorithm. After a finite number of iterations, we can check the solution (encoding is done if necessary).

1.2 Objective of the work:

The research work is done in the area of the optimal placement of meters in the power distribution network. Previously, during the encoding part of power distribution network, the entire network is taken at a time for the search using genetic algorithm, which is time taking and search procedure is laborious. A New method is developed to increase the speed of the algorithm and reduce the search samples by splitting the network in to number of sub-networks and rebuilding the same.

Using this meter placement, the commercial losses are estimated and compared with the total technical losses. The area having high commercial losses is found out.

1.2.1 Organization of the work:

- Finding the network model of the power distribution network by power balance equations.
- State estimation process to find the observability of the network for the particular arrangement of meters.
- Load flow analysis of the network.
- Applying Genetic algorithm to the problem for the best meter placement to maintain network observability.
- Splitting the whole network in to number of sub-networks and to find the meter placements.
- A case is considered where we can re-build the spitted network.
- Further reduction of redundant meters, where financial constraint matters.
- Comparison of the previous method and the proposed method of meter placements.
- Estimation of commercial losses in the network using the revenue loss data at each load and to find the area which is having high commercial losses.

1.3 Literature review:

The literature reveals that the state estimation is a powerful tool for the on-line studies and research is mainly concentrated on meter placement problem. Many authors used different ways for meter placement problem, some by genetic algorithms, some on tabu search techniques etc..,

Julio cesar stacchini de souza [1] developed a technique for the optimal placement of monitoring devices by using genetic algorithms, he used the observability test, cost of meters in the fitness function, the model takes in to account different topologies the network may experiment. He has taken the topology of the entire metering setup in one chromosome.

Ashwani kumar [2] used genetic algorithm based meter placement for static estimation of harmonic sources in a power system. The encoding technique and generation of random numbers are well explained in this paper. If in a power system network, any single branch outage/ or loss of measurement is taken[3], then the meter setup must maintain Observability. This concept is implemented by Amany El- Zonkoly [3], but is confirmed to transmission only.

Milton Brown [4] included a new concept called, critical measurements and sets [4] which come in to picture when redundant meters are placed in the network. Data redundancy is very important when there is a failure in some measurements and for reliability purposes.

The state estimation is applied to distribution systems in the paper by C. N. Lu [5]. In this paper, a three phase distribution system state estimation algorithm is presented. A current based formulation is included and compared with other formulations. Power system state estimation was introduced by Schweppe et al. [6] in 1969. The basics of state estimation and Observability analysis is given in this paper [6].

The real-time modeling of power networks is concentrated in the paper by clements [7]. A. The formulations of network equations, power balance equations, measurement model is included in his paper. This measurement model is a key player in finding the Observability of the network.

An efficient load flow technique is discussed in papers [8] and [10], the forward/backward sweep technique is termed as the best method in these papers, the convergence of this load flow method is given in [9] by E. Bompard.

Forward/backward method for ill-conditioned and weakly meshed networks are given in [10], the bus numbering scheme also given.

Mesut E. Baran in his paper [12], identifies the data requirements for real-time monitoring and control of distribution systems. It points out that in addition to the data acquisition on switches, a method is given, an accurate estimation of data needed for feeder automation functions, a meter placement procedure is given for this purpose.

Monticelli in his book [11] discussed the numerical Observability technique, formulation of network model. The topological Observability is given in the paper [13] , which is calculated by different graph techniques and again Genetic algorithm techniques are used to solve the meter placement problem.

During the Observability analysis, the Jacobian matrices and Gain matrices are calculated, the structure of jacobian matrices and Observability analysis using these matrices are given in papers [15] and [16]. In [15], the pseudo-measurements sets are found out, which makes the un-observable part in to observable one. Gaussian elimination method is used on gain matrix for observability analysis. In [16], as the jacobian matrices for big networks are large, they are split in to small matrices and processed separately,.

Goldberg [14], serves are the basic book for the reference of the genetic algorithms, different crossover techniques, mutation techniques are given in this book.

The technical and commercial losses of Gujarat Electricity regulatory commission are estimated by power systems group [17], vadodara. The commercial losses reduction techniques are given. In this paper, the commercial losses are further divided in to several types and are estimated separately. [17]

Gives different techniques to reduce the commercial losses by good metering setup.

For a big power network, to find whether it is numerically observable or not, is a big task. For these type of networks, a method is given in [18]. [19] States the observability analysis of models the selected substations at physical level. Different cases are given in [19] with the status of circuit breakers (open/closed). Tabu search technique is used instead of genetic algorithms in [21].

The different types of commercial and technical losses, their characteristics and reduction are given in [20] and [22], in [20], a UB electric distribution share holding company is taken as case-study for the analysis of commercial and technical losses. Using intelligent metering systems, the commercial losses can be reduced, which automatically improves the revenue [23].

1.4 Organization of the thesis:

This dissertation is organized into nine chapters.

Chapter 2 details the need of state estimation in power systems, different measurements, the state equation and the WLSE theory.

Chapter 3 details different techniques to find Observability of the network, its role in state estimation and numerical Observability is studied.

Chapter 4 details the different tools of genetic algorithms.

Chapter 5 gives the Forward/Backward sweep method of load flow analysis.

Chapter 6 A meter placement technique is applied to 41-Bus, 33 KV system and the results are analyzed.

Chapter 7 A new algorithm is developed and applied to the same bus structure, the results are analyzed and the two methods are compared on the basis of t their performance.

Chapter 8 using the meter placement in the previous chapters and revenue data, the commercial losses are estimated in the network and the area of high commercial losses is shown. The results are analyzed and technical and commercial losses are compared.

Chapter 9 Conclusions and Scope for future work.

Chapter – 2

State Estimation in Power Systems

2.1 Introduction:

Modern electric power systems are enormous in scale, typically spanning continents, and provide services for hundreds of millions of customers. These systems consist of numerous interconnected networks that contain various types of generators and consumers of electrical energy, which are also interconnected by high voltage equipment such as transmission lines and transformers. Each of these networks is operated and maintained by companies who are responsible for the consistently secure and economic operation of their network, as well as for the reliability of the larger power system.

Prior to this, power system operators working at the control centers had only a minimal amount of information and controls available to achieve these objectives. The only information received was that which is essential to control the real-time network's basic operation, such as system frequency, breaker statuses, and a minimal set of active power measurements.

In 1969 Fred Schweppe introduced the idea of using the redundant number of measurements, made available by the supervisory control and data acquisition (SCADA) system to statistically determine the state of the network. His proposition, the state estimator, was eventually accepted and serves as a basis for static state estimation.

The state estimator plays the essential role of a purifier, creating a complete and reliable database for security monitoring, security analysis and the various controls of a power system. The state estimator thus employs statistical methods to act as a tunable filter between the field data measurements and security and control functions.

The fundamental equation for the problem of power system state estimation (SE) can be formulated as

$$Z = Hx + e \qquad (2.1)$$

Where

- 'x' is the n vector of true states (unknown).
- 'Z' is the m vector of measurements (known).
- 'H' is the m x n Jacobian matrix.
- 'H x' is the m vector of linear functions linking measurements to states.
- 'e' is the m vector of random errors.
- 'm' is the number of measurements.
- 'n' is the number of state variables.

2.2 Measurements:

Non-availability of measurements may create condition of unobservability and therefore it is important to maintain sufficient redundancy. This leads to the following classification of measurements.

- ***Telemetered measurements***: On-line telemetered bus voltage magnitudes, active and reactive power flows, active and reactive injections, subject to noise or error in metering, communication system etc. They are assigned weightings in inverse proportion of their variance.

- ***Pseudo measurements*** are the guesses in respect of generation or substation loads based on historical data and are assigned least weightings. It is used in the event of missing data or bad data.

The State estimator provides estimates of the state variables based on a combination of measurements and pseudo-measurements of the following types.

2.2.1 Different Measurements:

1. Voltage magnitude V_k at bus k.
2. Voltage angle θ_k at bus k.
3. Active Power
   a) Branch flow P_{km} in branch km.
   b) Branch-group flow ΣP_{km} in the designated group of branches.
   c) Bus injection P_k into bus k.
4. Reactive Power
   a) Branch flow Q_{km} in branch km.
   b) Branch-group flow ΣQ_{km} in the designated group of branches.
   c) Bus injection Q_k into bus k.
5. Current magnitude flow $|I_{km}|$ in branch km, and injection $|I_k|$ at bus k.
6. Magnitude of turns ratio t_{km} in transformer km.
7. Angle of turns ratio φ_{km} in transformer km.

2.3: Weighted Least Square Estimation (WLSE) Theory:

It is often desirable to put different weightings on the different components of measurements since some of the measurements may be more reliable and accurate than the others and should be given more importance. If a single parameter x, is estimated using Nm measurements, the WLSE problem can be described as:

$$\min J(x) = \sum_{i=1}^{Nm} \frac{\left[z_i^{meas} - h_i(x)\right]^2}{\sigma_i^2} \tag{2.2}$$

where

σ_i =variance for the ith measurement

J(x) =measurement residual

Nm=number of independent measurements

z_i^{meas} = i^{th} measured quantity

If Ns unknown parameters are to be estimated using Nm measurements, the estimation problem can be described as:

$$\min\ J(x_1, x_2, \ldots, x_{Ns}) = \sum_{i=1}^{Nm} \frac{\left[z_i^{meas} - h_i(x_1, x_2, \ldots x_{Ns})\right]^2}{\sigma_i^2} \tag{2.3}$$

2.3.1 Matrix Formulation:

If functions $h_i(x_1, x_2, \ldots x_{Ns})$ are *linear functions* then

$$h_i(x_1, x_2, \ldots x_{Ns}) = h_i(x) = h_{i1}x_1 + h_{i2}x_2 + \ldots\ldots + h_{iNs}x_{Ns} \tag{2.4}$$

$$h(x) = \begin{bmatrix} h_1(x) \\ h_2(x) \\ \\ h_{Ns}(x) \end{bmatrix} = [H]x \tag{2.5}$$

Where, [H] is an (Nm x Ns) matrix containing the coefficient of the linear functions $h_i(x)$.

Placing the measurements in a vector form:

$$Z^{meas} = \begin{bmatrix} z_1^{meas} \\ z_2^{meas} \\ \vdots \\ z_{Nm}^{meas} \end{bmatrix} \tag{2.6}$$

Eqn. (2.3) may be written in a very compact form as:

$$\min J(x) = \left[z^{meas} - f(x)\right]^T \left[R^{-1}\right]\left[z^{meas} - f(x)\right] \tag{2.7}$$

$$\text{Where } [R] = \begin{bmatrix} \sigma_1^2 & & & \\ & \sigma_2^2 & & \\ & & \ddots & \\ & & & \sigma_{Ns}^2 \end{bmatrix}$$

[R] is called covariance matrix of measurement errors.

The Gain matrix is defined as G = $H^T R^{-1} H$

When Ns=Nm, the state estimation is

$$X^{est} = [H]^{-1} Z^{meas} \tag{2.8}$$

In power system state estimation, underdetermined problems (i.e., where Ns>Nm) are solved by adding pseudo measurements to the measurement set to give a completely determined (Ns=Nm) or over determined (Ns<Nm) problem.

State estimation is an excellent, reliable and accurate online study. Load flow studies done based on state estimation are more accurate than the routine offline load-flow techniques. The meter placement problem is the heart of state estimation. If we want an accurate state estimation, the meter placement must be accurate and redundant. Observability analysis is studied in the next chapter.

Chapter – 3

Observability Analysis

3.1 Introduction:

Observability analysis is necessary to examine whether the relationship between measurement allocation and power system configuration is appropriate. Every time when a system configuration is changed for some reasons, a topological Observability test should be executed prior to performing the state estimation to check one-to-one correspondence between measurements and buses. If this is not the case, Observability analysis methods can provide the minimum set of additional measurements needed to restore Observability. Hence an efficient implementation of the Observability test is a crucial step in achieving a satisfactory performance for the entire state estimation process and whole real-time monitoring and control of power systems.

Observability analysis has so far been accomplished with the help of either topological or numerical approaches. The topological approach makes use of the graph theory and determines network Observability strictly based on the type and location of measurements. It does not use any floating point arithmetic and is implemented independent of the state estimation itself. Numerical approaches are based on the measurement Jacobian and the associated gain matrix.

3.2 Network Observability:

Observability analysis may be divided into two categories: numerical and topological Observability.

3.2.1: Topological Observability:

Topological Observability algorithms, which use information about the network topology and measurement, were developed in order to avoid the rather difficult task of numerical computation of the rank of the measurement Jacobian matrix. Such algorithms have been widely used in the state estimator Observability programs.

In the case of networks containing only line flow measurements in which real and reactive measurements occur in pairs, the topological condition for Observability is that there exists at least one bus voltage magnitude measurement and that a spanning tree of the entire network can be built using only measured lines. Finding such a tree can be done using one of the well-known tree search methods such as breadth-first or depth-first search.

For an N-bus network with only bus injection measurements, the determination of Observability is even simpler; there must be at least one bus voltage measurement and at least N-1 bus injection measurements.

The measurement model for state estimator is

$$z = h(x) + e \tag{3.1}$$

Where

z represents all measurements, including power injection, power flow and bus voltage magnitude measurements,

e is the measurement noise vector,

x is the state vector composed of the phase angles and magnitudes of the voltages at network buses,

$h(.)$ Stands for the nonlinear measurement functions relating measurements with state variables.

The above measurement model is approximated by a linear plus a constant term model

$$\Delta z = [H]\Delta x + c + e \tag{3.2}$$

where

$$H = \begin{bmatrix} H_\theta & 0 \\ 0 & H_v \end{bmatrix} \tag{3.3}$$

"An N-bus power network is observable with respect to a given measurement set M if and only if the rank of the gain matrix H is equal to 2N-1.

3.2.2: Numerical Observability:

The numerical Observability is based on the calculation of Jacobian matrix, state estimation Gain matrix and performing different tests on gain matrix to analyze Observability of the network. Prior to the analysis of Numerical Observability, a network model should be formed for the power system network under consideration by power balance equations. Using Measurement model, the Observability can be analyzed.

The measurement model for state estimator is

$$z = h(x) + e$$

$$h(x) = \begin{bmatrix} h_1(x) \\ h_2(x) \\ \vdots \\ h_{Ns}(x) \end{bmatrix} = [H]x \tag{3.4}$$

Placing the measurements in a vector form:

$$Z^{meas} = \begin{bmatrix} z_1^{meas} \\ z_2^{meas} \\ \vdots \\ z_{Nm}^{meas} \end{bmatrix} \tag{3.5}$$

Eqn. (3.3) may be written in a very compact form as:

$$\min J(x) = \left[z^{meas} - f(x)\right]^T \left[R^{-1}\right]\left[z^{meas} - f(x)\right] \tag{3.6}$$

[R] is called covariance matrix of measurement errors.

The State estimation Gain Matrix 'G' is defined as follows

$$G = H^T R^{-1} H. \tag{3.7}$$

A system is said to be observable if the gain matrix G is non-singular. A singular matrix will have its rank equal to its highest order.

The numerical Observability algorithms are new and are starting to be implemented at some control centers. They have the virtue of being conceptually simple and of employing numerical routines that are already needed for computation of state estimation. Topological algorithms on the other hand require additional non numerical routines that may be rather complex but generally run faster than numerical tests.

3.3 Analysis of Numerical Observability by a Case-study:

In the present dissertation work, the numerical Observability is used to determine the Observability of the given network. First a simple two bus system is considered for analysis, with three alternative metering systems in figures 3.1, 3.2, 3.3 . as a case study.

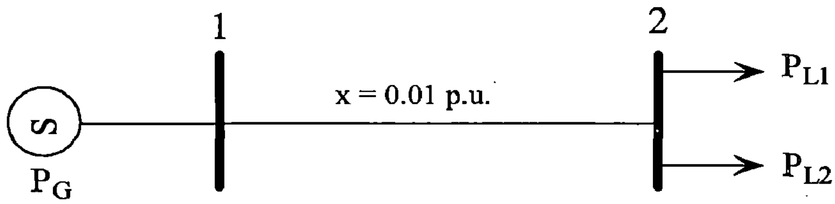


Figure 3. 1 Sample three bus system taken for Observability analysis

- **Problem Variables:**

The problem variables of any network model can be branch power flows, bus power loads and generations, bus voltage angles. The problem variables for the specified network model in fig () are

P_G, P_{L1}, P_{L2}, P_{12}, and θ_2 ($\theta_1 = 0^0$).

Let n_v be the number of problem variables then for the specified network, $n_v = 5$.

- **Network Model:**

There are three network equations for this system. Two equations determine the active power balance at the two buses; and the other equation relates the active power flow in the line to the bus voltage angles. Let number of network equations be n_e, for the specified model in fig(), $n_e = 3$

$$P_G - P_{12} = 0$$
$$P_{L1} - P_{L2} + P_{12} = 0$$
$$P_{12} + 100\,\theta_2 = 0$$

- **State Variables:**

For a network model with n_v problem variables and n_e network equations, the total network can be solved if and only if (n_v-n_e) variables are known. Hence for any of (n_v-n_e) number of problem variables can be selected as state variables. The value (n_v-n_e) is called the degree of freedom of this network model.

In the specified case, there are five variables and three equations. For solving the above model, we have to know the values of minimum of two variables in advance. Hence two out of five variables are selected as state variables. For instance Θ_2 and P_{L2} are taken as state variables.

- **Measurement Model:**

The measurement model describes the measurement system by establishing the relationships between the measured variables and the state variables. State estimation is based on the set of measurements (both telemetered data and pseudo-measurements).

Measurements are divided in to two categories: measurements of state variables and the measurements of dependent variables. Both types of measurements are represented in the measurement model: the former is trivial, whereas for the latter, network model equations are used to write the measured variables in terms of the state variables. The number of degrees of freedom of the measurement model is the difference between the number of states and the rank of the model.

3.3.1 Metering system1:

An under-determined system of linear equations is always not observable by the available measurements. To make the system observable, the pseudo-measurements are taken in to account.

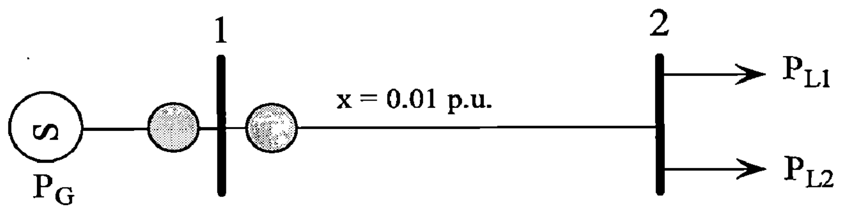


Figure 3. 2 metering system of type1

By the meter placement in fig b, the measurement model can be calculated as

$$-100\theta_2 = P_G^{meas}$$
$$-100\theta_2 = P_{12}^{meas}$$

These equations can be written in matrix form as below

$$\begin{pmatrix} -100 & 0 \\ -100 & 0 \end{pmatrix} \begin{pmatrix} \theta_2 \\ P_{L2} \end{pmatrix} = \begin{pmatrix} P_G^{meas} \\ P_{12}^{meas} \end{pmatrix} \qquad (3.8)$$

In this under-determined set of equations, the Jacobian Matrix is singular, which means that state variables cannot be determined from the measurement model. Hence the total system is un-observable.

The pseudo-measurements can be taken in to account to make this system observable but the state that is estimated with these measurements are erroneous and hence these systems are not desirable. In this metering sytem-1, only state P_G is observable; state P_{L1} is un-observable and state P_{L2} is indeterminate.

3.3.2 Metering system 2:

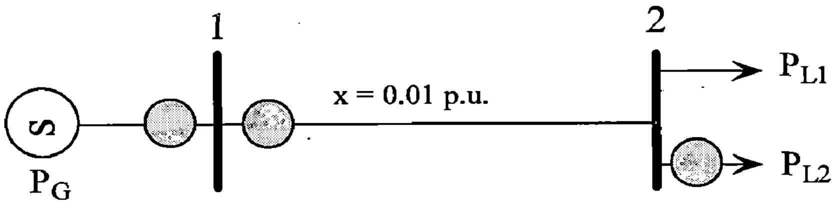


Figure 3. 3 Metering system 2 for Observability analysis

In the Metering system-2, an additional meter is placed at load2, the measurement model and the Jacobian matrix are

$$\begin{pmatrix} 100 & -1 \\ -100 & 0 \\ -100 & 0 \end{pmatrix} \begin{pmatrix} \theta_2 \\ P_{L2} \end{pmatrix} = \begin{pmatrix} P_{L2}^{meas} \\ P_G^{meas} \\ P_{12}^{meas} \end{pmatrix} \tag{3.9}$$

The System is Observable as the state variables can be determined from the metering systems. In this metering system, both the states P_G and P_{L1} are observable and the state P_{L2} is determinate.

3.3.3 Metering system 3:

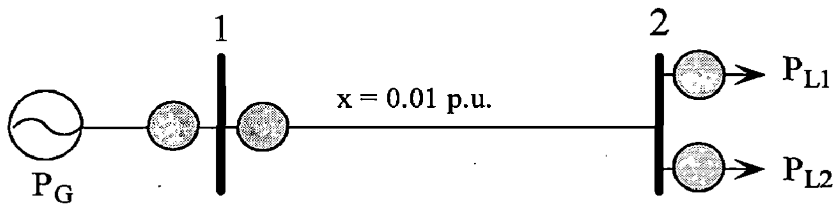


Figure 3. 4 Metering System 3 for Observability analysis

The redundant meter placements are those which are having more meters placed than the number of state variables (n_v-n_e). There are many advantages of having these types of systems which produces redundant measurement of data.

- Due to the redundant measurements, the problem of detection, identification and elimination of bad data can be eliminated.
- The system can withstand a temporary loss of measurements without compromising the quality of the estimated values.
- Metering errors can be taken in to account only in the redundant metering systems

The only disadvantage of redundant metering systems is the cost of meters. Hence the meter placement problems are optimization problems which balance the cost of the meters and network observability and some other factors.

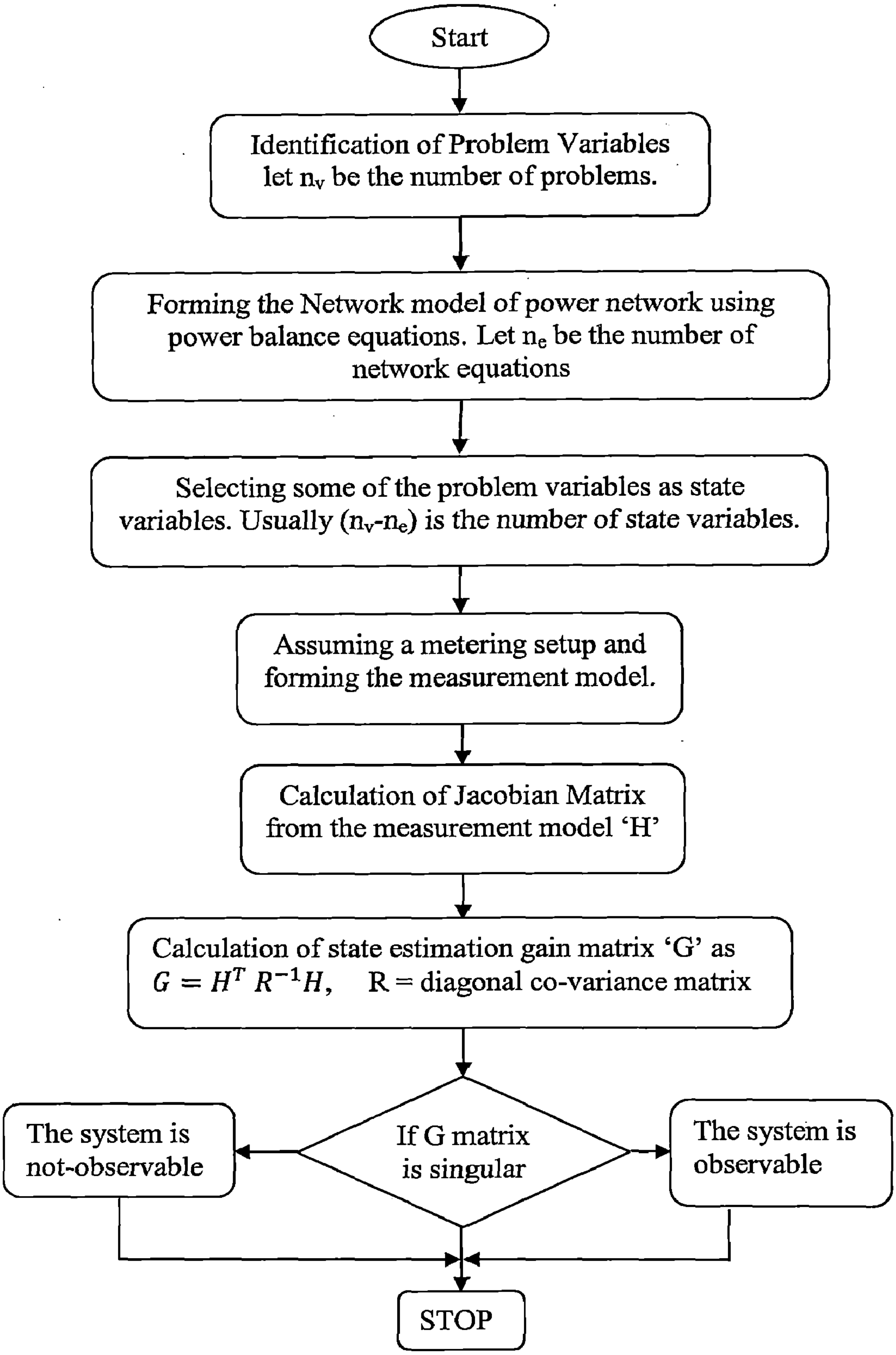
In the metering system-3, one more meter is added at first load, the measurement model and the Jacobian matrix are shown below.

$$\begin{pmatrix} 0 & 1 \\ 100 & -1 \\ -100 & 0 \\ -100 & 0 \end{pmatrix} \begin{pmatrix} \theta_2 \\ P_{L2} \end{pmatrix} = \begin{pmatrix} P_{L1}^{meas} \\ P_{L2}^{meas} \\ P_{G}^{meas} \\ P_{12}^{meas} \end{pmatrix} \qquad (3.10)$$

The System is Observable as the state variables can be determined from the metering systems. In this metering system, both the states P_G and P_{L1} are observable and the state P_{L2} is determinate.

This system has also an over-determined system of equations, hence more desirable for system reliability but compromising on the cost of the meters.

3.4 Flow chart for Observability analysis for the given power network:



CHAPTER - 4
GENETIC ALGORITHMS

4.1 INTRODUCTION:

Genetic algorithms are search algorithms based on the mechanics of natural selection and natural genetics. They combine survival of the fittest among string structures known as population with a randomized structure to form a search algorithm which resemblances the genetic nature of the human being. In every generation, a new set of artificial creatures (strings) are created using bits and pieces of the fittest of the old. From all the parents and children in the mating pool, the fittest is again selected, so that after every iteration, the performance is improved. This algorithm is computationally simple yet powerful in its search for improvement.

The GA maintains a set of possible solutions (population) represented as a string of typically, binary numbers (0/1). New strings are produced in each and every generation by the repetition of a two-step cycle.

1. First step involves first decoding each individual string and assessing its ability to solve the problem. Each string is assigned fitness values, depending on how well it is performed in an environment.

2. In the second stage, the fittest string is preferentially chosen for recombination, which involves the selection of two strings, and the switching of the segments this is called crossover.

Another genetic operator is mutation. It is used to maintain genetic diversity within a small population of strings. There is a small probability that any bit in a string will be flipped from '0' to '1'. This prevents certain bits from becoming fixed at a specific value due to every string in the population having the same value, often causing premature convergence to a non-optimal solution.

4.2 Tools of Genetic algorithm:

1. **Chromosome:**

   In biological terms, a chromosome means a DNA which carries genetic information in cells. Similarly in artificial chromosome (i.e. chromosome used in genetic algorithms), each element is a competitor for the final solution which carries the fitness related to the fitness function (objective function). The chromosome can be of any type (decimal, binary, octal etc..,) The chromosome format used in this thesis is a binary format and is generally represented as (16 bit chromosome)

   $$1011010100101010 \qquad (4.1)$$

2. **Population:**

   In genetic algorithms, the processing is not done on a single chromosome, but on a set of chromosomes, which is called population. The population is updated at every iteration, where the population of the current iteration has children which are better in fitness than the population in the previous iteration.

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Prof. & Head,

EBD

Enclosed please find herewith 3 copies of dissertation submitted by Shri/Ms. N. Naresh Sai for the degree of M.Tech./M.Arch./ M.U.R.P./M. Phil. in the field of SBOR Ele (Batch 2004-05) for further necessary action at your end please.

Copies of dissertation of above student have been checked and found correct.

Prof H.O. Gupta

Encl : As Above

SP
22 June 06

For ASSTT. REGISTRAR (ACD.)

General form of population is

$$\text{Population} = \begin{bmatrix} Cromosome1 \\ Cromosome2 \\ . \\ . \\ cromosome'n' \end{bmatrix}$$

Where 'n' is the population size (pop size).

4. Crossover rate:

In the mating pool, different chromosomes are selected for crossover based on some selection criteria. Crossover rate is the rate at which the number of chromosomes that are selected for crossover over the total number of chromosomes present in the mating pool.

$$Crossover\ rate = \frac{Number\ of\ cromosomes\ selected\ for\ crossover}{Total\ number\ of\ cromosomes\ in\ the\ matingpool} \quad (4.2)$$

4. Mutation rate:

To avoid some abnormal conditions which shows direct effect on the convergence of the algorithm, we will mutate the chromosomes, based on mutation rate. Mutation rate is the number of chromosomes that are selected for mutation over the number of chromosomes present in the mating pool.

$$Mutation\ rate = \frac{Number\ of\ cromosomes\ selected\ for\ Mutation}{Total\ number\ of\ cromosomes\ in\ the\ matingpool} \quad (4.3)$$

4.3 Genetic Representation:

4.3.1 Encoding:

Representing or encoding the problem in hand when applying GA is a vital task. Genetic representation of a chromosome is called encoding. There are a few ways of encoding the chromosomes, such as integer, real-valued but one of the most popular ways is binary encoding (bit string), because it is a simpler string to operate.

For binary encoding each chromosome is constructed by stringing binary representations of vector components. The length of each chromosome depends on the vector dimension and the desired accuracy. A sample binary representation is shown here.

$$S = 1010101111101011 \qquad (4.4)$$

An 'n' bit string can represent integers from 0 to 2^n-1 i.e. 2^n integers.
The main advantage of binary encoding is that it maximizes for greater sampling of the solution space. The other kinds of encoding include octal encoding, hexadecimal encoding etc..,

4.3.2 Decoding:

In order to retrieve original information from the chromosome, it must be decoded to its original format. If a chromosome (S) in binary format is considered, the decoding value of the binary string is

$$\sum_{k=0}^{k=n-1} 2^k S_k \qquad (4.5)$$

The original value of X, the integer is

$$X = X_L + \frac{(X_U - X_L)}{(2^n - 1)} \text{ x decoded value of the string} \qquad (4.6)$$

4.4 A simple genetic algorithm:

Genetic algorithm has got a simple structure, basically consisting of three operators.

1. Reproduction/Selection.
2. Crossover.
3. Mutation.

The primary step prior to the start of genetic algorithm is the initialization of the tools of the GA (population, crossover rate etc...). The next step is reproduction.

4.4.1 Reproduction:

Reproduction is the first operator applied on population. Reproduction is a process in which individual strings are copied according to their objective function values, *f*. Chromosomes are selected from the population to be parents to crossover and produce offspring. Strings with higher value of fitness have more probability to be selected from the mating pool. Hence this process is also called selection.

4.4.2 Roulette wheel selection:

This selection procedure is so called because it works in a way that is analogous to a roulette wheel. Each individual in a population is allocated a share of a wheel, the size of the share being in proportion to the individual's fitness.

A pointer is spun (a random number generated) and the individual to which it points is selected. This continues until the pre-requisite number of individuals has been selected. An individual's probability of selection is thus related to its fitness ensuring that fitter individuals are more likely to leave offspring.

First the fitness values are then calculated using the fitness function for each chromosome V_i (i=1....pop size). The total fitness of the population is given by

$$F = \sum_{i=1}^{pop\ size} fitnessfun(V_i) \qquad (4.7)$$

The probability of selection for each chromosome V_i (i=1... pop size) is

$$P_i = \frac{\text{fitnessfun}(V_i)}{F} \qquad (4.8)$$

And the cumulative probability is

$$Q_i = \sum_{j=1}^{i} P_j \qquad (4.9)$$

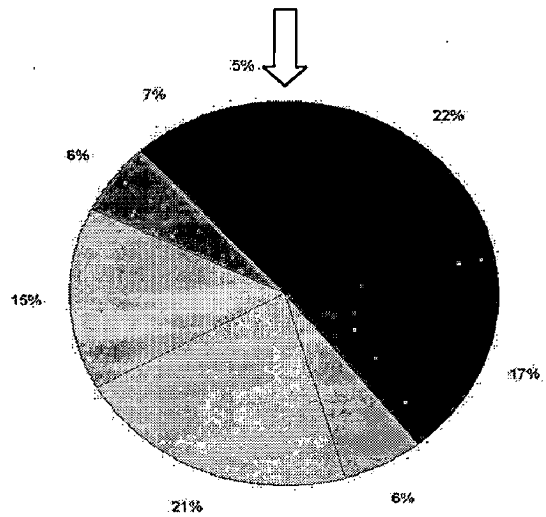


Figure 4. 1 Roulette wheel technique for selection process

A roulette wheel is constructed with the cumulative probabilities of all the chromosomes. A chromosome with greater fitness function will have more probability and hence will be selected number of times to the mating pool. The selection process is based on spinning the roulette wheel pop size times, each time selecting a single chromosome for the mating pool.

In the Simulation of Roulette wheel, a random number is generated between 0 and 1 and the chromosome is selected such that the generated random number is in the arc of the cumulative probabilities.

4.4.3 Crossover Algorithms:

Crossover is a process where two chromosomes are mixed in different means to produce two different off-springs. After the process of reproduction/selection, the parents in the mating pool are selected for crossover. The selection of parents is purely based on random techniques and the number of parents selected for crossover is decided by crossover rate which is defined before the genetic algorithm.

4.4.3.1 Single-point crossover:

The most basic crossover algorithm is Single Point Crossover.

Parent 1: **1 0 0**$_{1}$**1 1 1 0 1**

Parent 2: **1 1 0**$_{1}$**0 1 0 0 1**

⇩

Child1 = **1 0 0 0 1 0 0 1**

Child2 = **1 1 0 1 1 1 0 1**

A random number is generated which indexes the bits along the string and the strings are swapped over at this index to form two new off-springs.

4.4.3.2 Multi-point crossover:

Multipoint crossover algorithms extend simple crossover by selecting multiple crossover points and swapping the part of the two chromosomes between these two random numbers.

Parent 1: **1 0 0_1 1 1 1_1 0 1**

Parent 2: **1 1 0_1 0 1 0_1 0 0**

⇩

Child1 = **1 0 0 0 1 0 0 0**

Child2 = 1 **1 0 1 1 1 0 1**

4.4.3.3 Uniform Crossover:

In this type of crossover, random numbers of 1s and 0s of the same length as the parent strings is generated. If a bit in the mask is 1 then the corresponding bit in the first child will come from the first parent and the second parent will contribute that bit to the second offspring. If the mask bit is 0 the first parent contributes to the second child and the second parent to the first child.

Random: **0 0 1 1 0 1** 0 1

Parent 1: **1 0 0 1 1 1 0 1**

Parent 2: **1 1 0 0 1 0 0 0**

⇩

Child1 = **1 1 0 1 1 1 0 1**

Child2 = 1 **0 0 0 1 0 0 0**

4.4.4 Mutation Process:

Mutation is a process in which a bit is taken from a chromosome at random and flip that bit from '0' to '1' or vice-versa. The selection of chromosome from the mating pool is also random. Mutation is done mainly to deal two special cases.

1. If all the chromosomes in the mating pool are equal, the crossover produces children which are identically equal to the parents. Due to this, the convergence is never achieved.
2. If bits of all the chromosomes are either zeros or ones, mutation helps to get convergence.

To simulate mutation, two random numbers are required, one for selection a particular chromosome in the mating pool and second one is to select a particular bit in the chromosome to flip that bit.

Before mutation = **1 1 0 1 1 1 0 1**

After mutation = **1 1 0 0 1 1 0 1**

At the end of the two processes, crossover and mutation, the population is updated with the new population, the update must be in such a manner that the new population must have good finesses when compared to old population.

4.5 Flow Chart for the Genetic Algorithm:

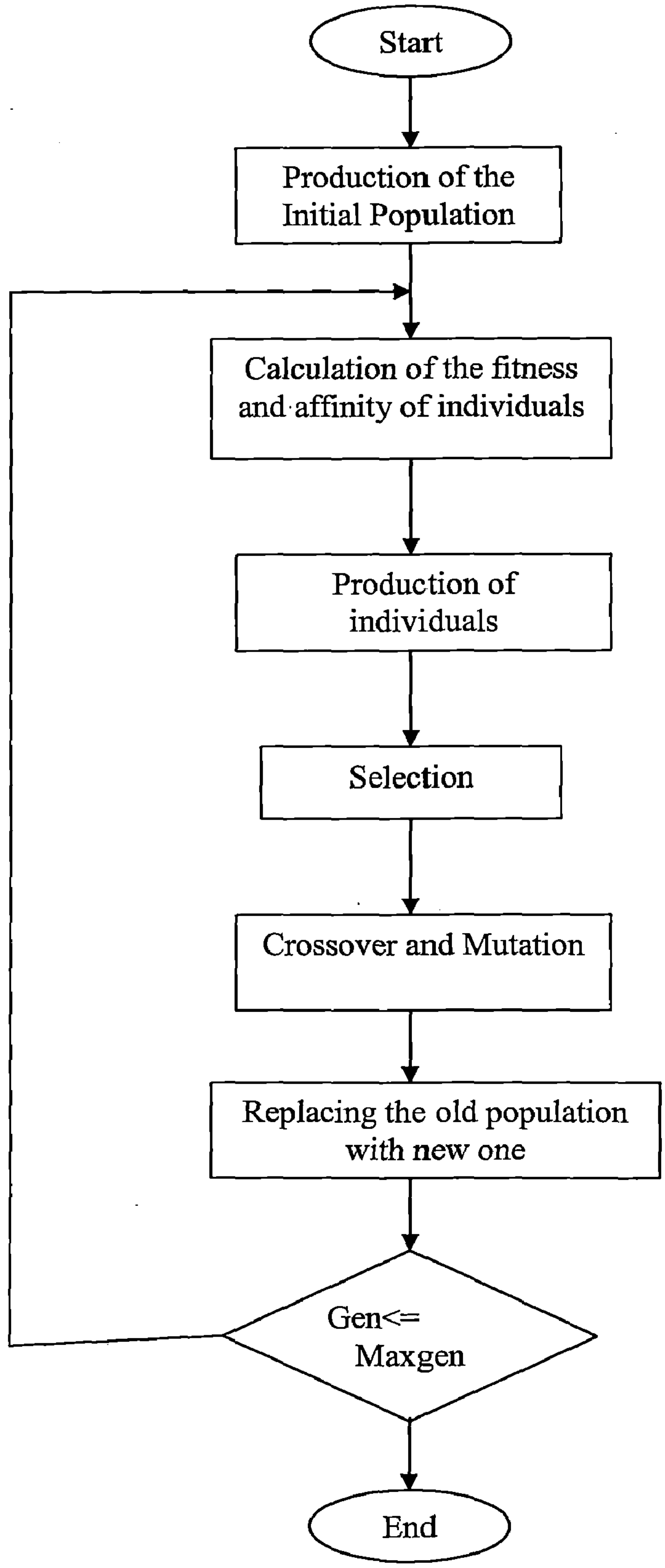


figure 4. 2 Flow chart of working of Genetic Algorithm

CHAPTER-5

LOAD FLOW ANALYSIS

5.1 Introduction:

The distribution systems are structurally weakly meshed but are typically operated with a radial structure. The computational methods for the load-flow analysis of radial distribution systems adopt either the same algorithms used in the transmission systems analysis or dedicated methods which exploit the radial structure of the network.

The computational methods can be grouped into two basic classes. The first class includes the direct methods, defined using the basic circuit laws. The Forward/Backward sweep and other methods based on the calculation of the node equivalents belong to this class.

The other class is composed of methods which require the derivatives of the network equations. The Newton-Raphson method and its modifications belong to this class. The fast-decoupled load-flow method which is widely used in the transmission networks is less effective in the analysis of distribution networks with low $\frac{X}{R}$ Ratios

5.2 Forward /backward sweep method:

The general algorithm consists of two basic steps, backward sweep and forward sweep, which are repeated until convergence is achieved the backward sweep is primarily a current or power flow summation with possible voltage updates the forward sweep is primarily a voltage drop calculation with possible current or power flow updates. Regardless of its topology, the distribution network is first converted in to a radial network.

5.2.1 Algorithm:

Voltage at substation is known and assuming a flat voltage profile of 1.0 p.u. at the other buses following are the steps involved in obtaining the load flow solution.

Step1:

Nodal current calculation:

The nodal current injection $I_i^{(k)}$, at network node i is calculated as

$I_i^{(k)} = (S_i / V_i^{(k-1)})^* - Y_i V_i^{(K-1)}$ i= 1,2, ...,n ......(5.1) Where

$V_i^{(k-1)}$ Is the voltage at node i calculate during (k-1) I th iteration

S_i is the specified power injection at node i

Yi is the sum of all shunt elements at node i

Step 2:

Backward sweep:

Starting from the branches in the last layer and moving towards the branches connected to the root node. The current in branch L, is calculated as

$J_{L2}^{(k)} = -I_{L2}^{(k)} + \sum$ (currents in branches emanating from node L2) . (5.2)

L=b, b-1 1

Where $I_{l2}^{(k)}$ is the current injection at node L2.

Step3:

Forward sweep:

Nodal voltages are updated in a forward sweep starting from branches in the first layer toward those in the last. For each branch, L, the voltage at node L2 is calculated using the up dated voltage at node L1 and the branch current calculated in the preceding backward sweep

$V_{12}^{k} = V_{L1}^{k} - Z_L J_L^{k}$ L= 1, 2........ b .... (5.3)

Where Z_L is the series impedance of branch L

Step 4:

Convergence criteria:

Compute the loads at all the buses with calculated current injections in step 1 and voltages in step 3 and compare with specified loads and if the difference is within the pre-specified tolerance then the load flow is converged otherwise repeat above steps still convergence is achieved.

$S_i^k = V_i^k (I_i^k)^* - Y_i \left|V_i^k\right|^2$

$\Delta P_i^k = Re[S_i^k - S_i]$ .... (5.4)

$\Delta Q_i^k = Im[S_i^k - S_i]$

5.3 Flow chart for Forward/backward sweep method:

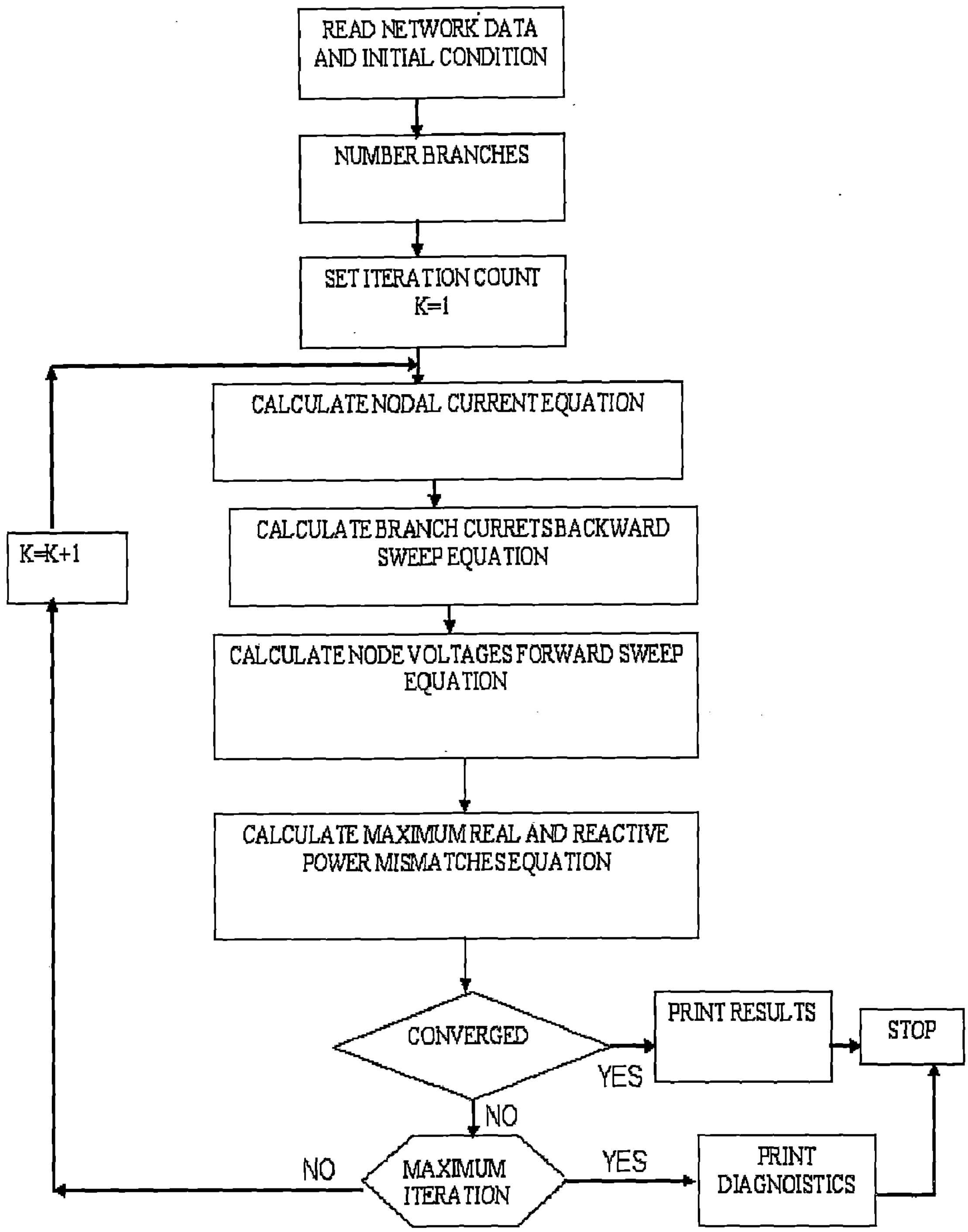


Figure 5. 1 Flow Chart for Forward/Backward Sweep Method of Load flow Analysis

5.4 Bus Structure Used for the Entire analysis:

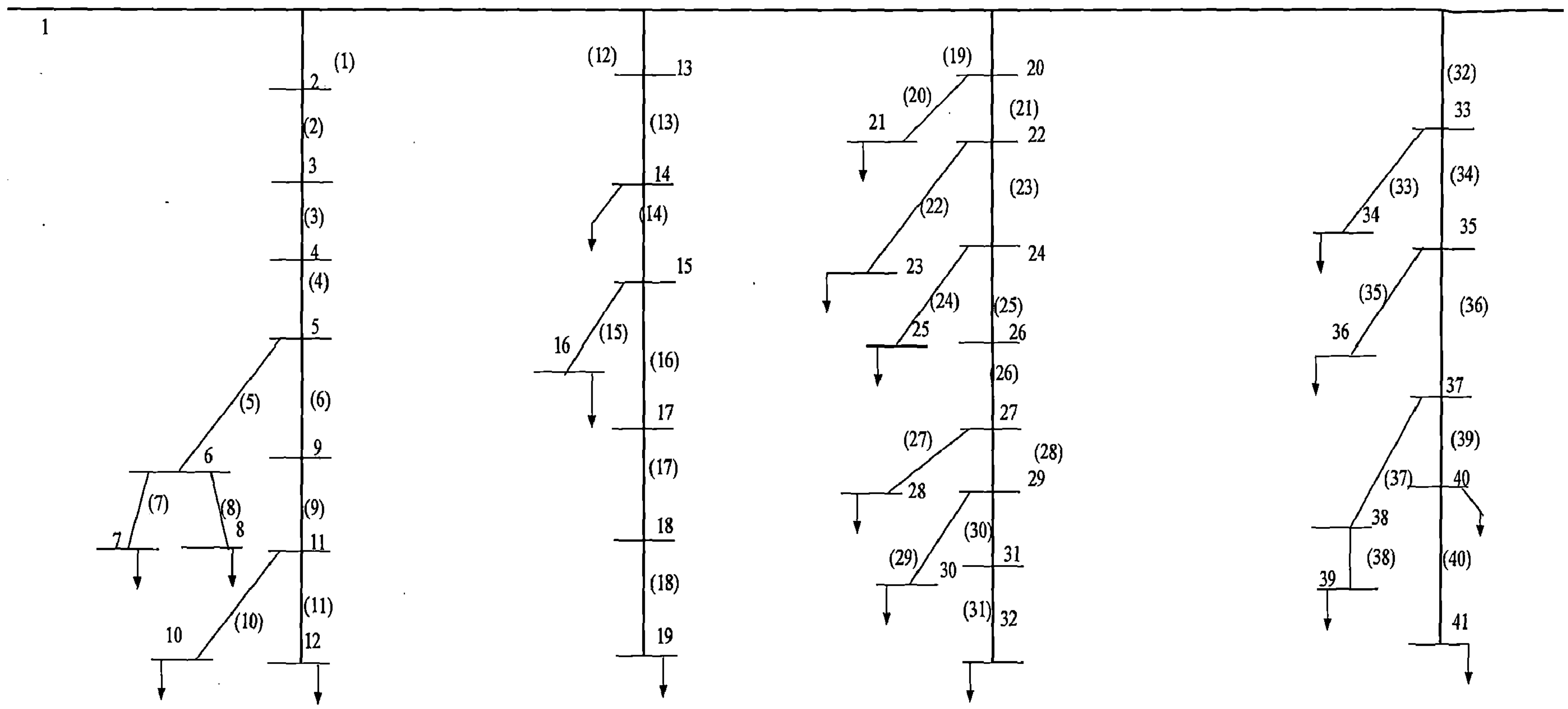


figure 5. 2 Bus structure used for the entire analysis

N : Bus Number

(N): Branch Number

5.4.1 Bus data:

Branch no	Connections		Resistance in Ohm	Reactance in Ohm	Length in Km
	From	To			
1	1	2	0.5499	0.582	1.5
2	2	3	3.2553	3.4461	8.88
3	3	4	2.4636	2.6079	6.72
4	4	5	0.528	0.5589	1.44
5	5	6	0.066	0.0699	0.18
6	5	9	0.6159	0.6519	1.68
7	6	7	0.264	0.2793	0.72
8	6	8	0.8799	0.9315	2.4
9	9	10	0.4398	0.4656	1.2
10	9	11	2.4636	2.6079	6.72
11	11	12	1.0449	1.1061	2.85
12	1	13	0.5499	0.582	1.5
13	13	14	3.2553	3.4461	8.88
14	14	15	2.5515	2.7099	6.96
15	15	16	1.0577	1.1175	2.88
16	15	17	1.1439	1.2108	3.12
17	17	18	0.528	0.5589	1.44
18	18	19	0.264	0.2793	0.72
19	1	20	2.3535	2.4915	6.42
20	20	21	2.0895	2.2119	5.69
21	20	22	0.231	0.2445	0.63
22	22	23	0.165	0.1746	0.45
23	22	24	0.231	0.2445	0.63
24	24	25	0.3849	0.4074	1.05
25	24	26	0.6708	0.7101	1.83
26	26	27	0.5499	0.582	1.5
27	27	28	0.462	0.486	1.26
28	27	29	1.0998	1.1643	3.0
29	29	30	.3849	0.4074	1.05
30	29	31	0.3849	0.4074	1.05
31	31	32	0.33	0.3492	0.9
32	1	33	2.0895	2.2119	5.69
33	33	34	0.462	0.489	1.26
34	33	35	0.5499	0.582	1.5
35	35	36	0.033	0.0348	0.9
36	35	37	0.6159	0.6519	1.68
37	37	38	0	0	0
38	37	40	1.0998	1.1643	3.3
39	38	39	0.0219	0.0234	0.0597
40	40	41	3.8493	4.0746	10.5

Table 5. 1 Bus Data For 41-Bus 33 KV system

5.4.2 Bus loading:

Bus no	Active power in KW	Reactive power in KVAr
2	0	0
3	0	0
4	0	0
5	0	0
6	0	0
7	597	60
8	6268	626
9	0	0
10	117	12
11	0	0
12	100	10
13	0	0
14	8109	811
15	0	0
16	249	25
17	0	0
18	0	0
19	289	29
20	0	0
21	4975	498
22	0	0
23	503	50
24	0	0
25	351	35
26	0	0
27	0	0
28	4975	498
29	0	0
30	784	78
31	0	0
32	131	13
33	0	0
34	386	39
35	0	0
36	146	15
37	0	0
38	0	0
39	103	10
40	4975	498
41	4975	498

Table 5. 2 Bus loading For 41-Bus 33 KV system

CHAPTER-6

Meter Placement Problem

6.1 INTRODUCTION:

Meter placement problem can be defined as "Optimal placement of measuring devices along the power system network which optimizes different criteria and satisfying some pre-defined constraints". In the present work, the optimizing criterion is the cost of meters, cost of remote terminals and the Observability of the power system network due to the particular meter arrangement.

To determine the Observability of the network due to the particular meter arrangement, the network modeling, Jacobian matrix calculation, State estimation gain matrix calculations are necessary.

Necessity for the placement of meters:

- Modern electric power systems are enormous in scale and provide services for hundreds of millions of consumers. The reliability, security and economic operation of these networks are highly desirable. To achieve these objectives, the monitoring of the whole power system network is the first step to be completed.

  Previously, the power system operators working at the control centers had only a minimal amount of information and controls available to achieve these objectives.

  Optimal meter placement plays a key role in achieving these objectives.

- For online load-flow studies, the state estimation is a powerful and accurate tool which requires meter placement along the network as a first step. Redundant measurements are always desirable for the reliability of the network Observability.

- For estimation of different losses such as technical and commercial losses, meter placement is necessary.

6.2 Optimal placement of monitoring devices:

The 41-bus system is considered for the meter placement problem and a series of steps are followed for meter placement.

- Formation of Network Model.
- Observability analysis using state estimation process.
- Application of Genetic algorithm to the model.

6.3 Network Model:

For the network model, the network variables are determined. A series of power balance equations are written and state variables are selected according to the required criteria. The procedure to form the network model of a given bus system is explained in chapter3 with the help of a small example.

6.3.1 Problem Variables:

The problem variables of the 41-bus system is as follows

- The first type of variables will be the active power at the bus 'i'

Where i = 1 to 41

$P_1, P_2, P_3 \ldots P_{40}, P_{41}$ ------> 41 variables.

- The second type of variables will be the active power flow between the buses

$P_{(1,2)}, P_{(2,3)}, P_{(3,4)} \ldots P_{(40,41)}$ ------> 40 variables.

- The third type of variables will be the power angle (Θ) at each bus except at bus 1 where Θ at bus 1 is assumed to be 0^o.

$\Theta_2, \Theta_3, \Theta_4 \ldots \Theta_{40}, \Theta_{41}$ ------> 40 variables.

The total number of variables of the model (n_v) is 41+40+40 = 121 variables.

6.3.2 Power balance equations:

The P-Θ (active power-angle) model is used for balance equations.

1 $P_1 - P_{(1,2)} - P_{(1,13)} - P_{(1,20)} - P_{(1,33)} = 0$

2 $P_2 - P_{(2,3)} + P_{(1,2)} = 0$

3 $P_3 + P_{(2,3)} - P_{(3,4)} = 0$

4 $P_4 + P_{(3,4)} - P_{(4,5)} = 0$

5 $P_5 + P_{(4,5)} - P_{(5,6)} - P_{(5,9)} = 0$

6 $P_6 + P_{(5,6)} - P_{(6,7)} - P_{(6,8)} = 0$

7 $P_7 + P_{(6,7)} = 0$

8 $P_8 + P_{(6,8)} = 0$

9 $P_9 + P_{(5,9)} - P_{(9,10)} - P_{(9,11)} = 0$

10 $P_{10} + P_{(9,10)} = 0$

11 $P_{11} + P_{(9,11)} - P_{(11,12)} = 0$

12 $P_{12} + P_{(11,12)} = 0$

13 $P_{13} + P_{(1,13)} - P_{(13,14)} = 0$

14 $P_{14} + P_{(13,14)} - P_{(14,15)} = 0$

15 $P_{15} + P_{(14,15)} - P_{(15,16)} - P_{(15,17)} = 0$

16 $P_{16} + P_{(15,16)} = 0$

17 $P_{17} + P_{(15,17)} - P_{(17,18)} = 0$

18 $P_{18} + P_{(17,18)} - P_{(18,19)} = 0$

19 $P_{19} + P_{(18,19)} = 0$

20 $P_{20} + P_{(1,20)} - P_{(20,21)} - P_{(1,20)} - P_{(20,22)} = 0$

21 $P_{21} + P_{(20,21)} = 0$

22 $P_{22} + P_{(20,22)} - P_{(22,23)} - P_{(22,24)} = 0$

23 $P_{23} + P_{(22,23)} = 0$

24 $P_{24} + P_{(22,24)} - P_{(24,25)} - P_{(24,26)} = 0$

25 $P_{25} + P_{(24,25)} = 0$

26 $P_{26} + P_{(24,26)} - P_{(26,27)} = 0$

27 $P_{27} + P_{(26,27)} - P_{(27,28)} - P_{(27,29)} = 0$

28 $P_{28} + P_{(27,28)} = 0$

29 $P_{29} + P_{(27,29)} - P_{(29,30)} - P_{(29,31)} = 0$

30 $P_{30} + P_{(29,30)} = 0$

31 $P_{31} + P_{(29,31)} - P_{(31,32)} = 0$

32 $P_{32} + P_{(31,32)} = 0$

33 $P_{33} + P_{(1,33)} - P_{(33,34)} - P_{(33,35)} = 0$

34 $P_{34} + P_{(33,34)} = 0$

35 $P_{35} + P_{(33,35)} - P_{(35,36)} - P_{(35,37)} = 0$

36 $P_{36} + P_{(35,36)} = 0$

37 $P_{37} + P_{(35,37)} - P_{(37,38)} - P_{(37,40)} = 0$

38 $P_{38} + P_{(37,38)} - P_{(38,39)} = 0$

39 $P_{39} + P_{(38,39)} = 0$

40 $P_{40} + P_{(37,40)} - P_{(40,41)} = 0$

41 $P_{41} + P_{(40,41)} = 0$

42 $P_{(1,2)} + 49.5\ (\Theta_2) = 0$

43 $P_{(2,3)} + 8.36(\Theta_3 - \Theta_2) = 0$

44 $P_{(3,4)} + 11.05(6. - \Theta_3) = 0$

45 $P_{(4,5)} + 51.55(\Theta_5 - 6.) = 0$

46 $P_{(5,6)} + 416.67(\Theta_6 - \Theta_5) = 0$

47 $P_{(5,9)} + 46.25(\Theta_9 - \Theta_5) = 0$

48 $P_{(6,7)} + 103.09(\Theta_7 - \Theta_6) = 0$

49 $P_{(6,8)} + 30.96(\Theta_8 - \Theta_6) = 0$

50 $P_{(9,10)} + 61.73(\Theta_{10} - \Theta_9) = 0$

51 $P_{(9,11)} + 11.05(\Theta_{11} - \Theta_9) = 0$

52 $P_{(11,12)} + 26.04(\Theta_{12} - \Theta_{11}) = 0$

53 $P_{(1,13)} + 49.5(\Theta_{13}) = 0$

54 $P_{(13,14)} + 8.36(\Theta_{14} - \Theta_{13}) = 0$

55 $P_{(14,15)} + 10.67(\Theta_{15} - \Theta_{14}) = 0$

56 $P_{(15,16)} + 25.77(\Theta_{16} - \Theta_{15}) = 0$

57 $P_{(15,17)} + 23.81(\Theta_{17} - \Theta_{15}) = 0$

58 $P_{(17,18)} + 51.55(\Theta_{18} - \Theta_{17}) = 0$

59 $P_{(18,19)} + 103.09(\Theta_{19} - \Theta_{18}) = 0$

60 $P_{(1,20)} + 11.57(\Theta_{20}) = 0$

61 $P_{(20,21)} + 13.04(\Theta_{21} - \Theta_{20}) = 0$

62 $P_{(20,22)} + 117.65(\Theta_{22} - \Theta_{20}) = 0$

63 $P_{(22,23)} + 163.93(\Theta_{23} - \Theta_{22}) = 0$

64 $P_{(22,24)} + 117.65(\Theta_{24} - \Theta_{22}) = 0$

65 $P_{(24,25)} + 70.92(\Theta_{25} - \Theta_{24}) = 0$

66 $P_{(24,26)} + 40.62(\Theta_{26} - \Theta_{24}) = 0$

67 $P_{(26,27)} + 49.5(\Theta_{27} - \Theta_{26}) = 0$

68 $P_{(27,28)} + 58.82(\Theta_{28} - \Theta_{27}) = 0$

69 $P_{(27,29)} + 26.75(\Theta_{29} - \Theta_{27}) = 0$

70 $P_{(29,30)} + 70.92(\Theta_{30} - \Theta_{29}) = 0$

71 $P_{(29,31)} + 70.92(\Theta_{31} - \Theta_{29}) = 0$

72 $P_{(31,32)} + 82.64(\Theta_{32} - \Theta_{31}) = 0$

73 $P_{(1,33)} + 13.04(\Theta_{33} - \Theta_{1}) = 0$

74 $P_{(33,34)} + 58.82(\Theta_{34} - \Theta_{33}) = 0$

75 $P_{(33,35)} + 49.5(\Theta_{35} - \Theta_{33}) = 0$

76 $P_{(35,36)} + 833.33(\Theta_{36} - \Theta_{35}) = 0$

77 $P_{(35,37)} + 46.25(\Theta_{37} - \Theta_{35}) = 0$

78 $P_{(37,38)} + \frac{1}{\varepsilon}(\Theta_{38} - \Theta_{37}) = 0$

79 $P_{(37,40)} + 29.75(\Theta_{40} - \Theta_{37}) = 0$

80 $P_{(38,39)} + 1250(\Theta_{39} - \Theta_{38}) = 0$

81 $P_{(40,41)} + 7.07(\Theta_{41} - \Theta_{40}) = 0$

There are 81 network equations ($n_e = 81$).

6.3.3 Selection of state variables:

For a system with n_v problem variables and n_e independent equations, the number of state variables are (n_v-n_e). Hence for the considered problem of 41-bus system, the number of network equations are 81, while the number of problem variables are 121 hence the number of state variables that must be selected are 121-40 = 40 (n_s=40). These state variables may be any of these 121 variables.

The state variables selected for the problem under study are active power flow between the buses.

$P_{(1,2)}$, $P_{(2,3)}$, $P_{(3,4)}$ ... $P_{(40,41)}$ ------> 40 state variables.

6.4 Measurement model:

In this problem, two types of meters are taken in to account. One type of meter measures the power at the bus and the other type measures the power between the buses. For every configurations of meters, the jacobian matrix and state estimation gain matrix is calculated and an Observability test is done on this meter configuration. Once this test is over, the next meter configuration is randomly generated and solved by means of genetic algorithm.

6.4.1 Encoding:

In the genetic algorithm, a set of chromosomes are generated each of length 81 binary digits, each at a time is taken for processing. The bit '1' means that a meter is present at that location and '0' is that the meter is not present.

The encoding of the chromosome for a sample 3 bus system is shown for simplicity. The concept is analogous to the 41-bus system. In the system under study, each chromosome has 81 bits, the first 41bits denotes the meters to measure active power at the bus and the second 40 bits denotes the meters which measures the active power flow between the buses.

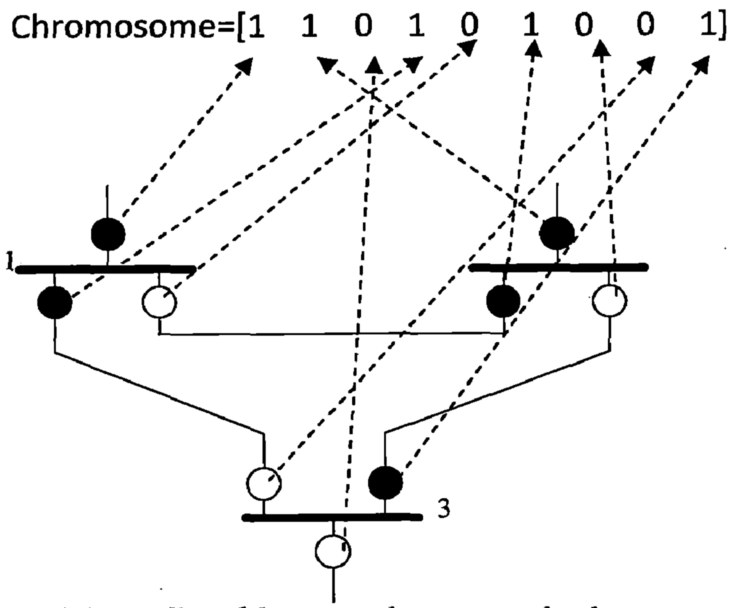


Figure 6. 1 Encoding of the meter placement to the chromosome

6.4.2 Error Co-Variance Matrix & Weight Matrix:

A diagonal variance matrix is a square matrix in which all the elements other than the diagonal matrix are zeros and the diagonal elements are non-zeros with values that are quite small. The diagonal elements signify the error of the measured value with the original value.

The order of the variance matrix is equal to the number of meters in the chromosome. The weight matrix(W) used in weighted least squares method is the matrix with the same order of variance matrix but its diagonal matrix inversed.

The more the variance, the less the weight for that measurement and vice versa. In this problem, the variance matrix is taken as 0.02 for all the measurements and hence the diagonal matrix will have all elements equal to 500

Suppose any chromosome has 40 meters then the weight matrix will be

$$V = \begin{bmatrix} 0.02 & 0 & 0 & 0 & 0 \\ 0 & 0.02 & 0 & 0 & 0 \\ 0 & 0 & . & 0 & 0 \\ 0 & 0 & 0 & . & 0 \\ 0 & 0 & 0 & 0 & 0.02 \end{bmatrix} \quad \text{and}$$

$$W = \begin{bmatrix} 500 & 0 & 0 & 0 & 0 \\ 0 & 500 & 0 & 0 & 0 \\ 0 & 0 & . & 0 & 0 \\ 0 & 0 & 0 & . & 0 \\ 0 & 0 & 0 & 0 & 500 \end{bmatrix}$$

V is the variance matrix of the order 40 x 40
W is the weight matrix with the order 40 x 40

6.4.3 Jacobian Matrix:

Jacobian matrix is that matrix which relates the measurement matrix with the state variable matrix. It is the key player in finding the Observability of a particular chromosome. For the present 41-bus system with a chromosome having 40 meters, the jacobian matrix is calculated as follows.

Consider the state estimate equation

$$\begin{bmatrix} P_1^{meas} \\ P_2^{meas} \\ . \\ . \\ P_n^{meas} \\ --- \\ P_{(1,2)}^{meas} \\ P_{(2,3)}^{meas} \\ . \\ . \\ P_{(a,b)}^{meas} \end{bmatrix}_{40x1} = [H]_{40x40} \begin{bmatrix} P_{(1,2)} \\ P_{(2,3)} \\ P_{(3,4)} \\ . \\ . \\ . \\ P_{(39,40)} \\ P_{(40,41)} \end{bmatrix}_{40x1} + [e]_{40x1}$$

Here 'H' is the Jacobian matrix and is calculated by assuming 'e' vector as zero. The network equations are written in the matrix format, which serves as lookup table to form the jacobian matrix. The Jacobian matrix for 40 meters is not shown here because of lack of space and is shown in next chapter for lesser number of meters.

6.4.4 State estimation gain matrix:

$$G = [H]_{40x40}{}^{T} \begin{bmatrix} 500 & 0 & 0 & 0 & 0 \\ 0 & 500 & 0 & 0 & 0 \\ 0 & 0 & . & 0 & 0 \\ 0 & 0 & 0 & . & 0 \\ 0 & 0 & 0 & 0 & 500 \end{bmatrix}_{40x40} [H]_{40x40}$$

The size of the state estimation gain matrix is also 40 X 40 and is not shown here due to lack of space and is shown in next chapter for lesser number of meters. The chromosome taken for analysis is observable as the corresponding gain matrix G is non-singular.

6.5 Application of Genetic Algorithms:

In the current work, the Genetic Algorithms are used to solve the meter placement problem; the genetic algorithm loops round the state estimation, Observability analysis of each and every chromosome, calculates its fitness at each and every iteration and participates in the competition in the mating pool. The chromosomes that win the competition will participate in the next iteration.

6.5.1 Objective function:

The objective function for this problem consists of three parts.

1) Cost of the meters
2) Cost of the remote terminal units.
3) The Observability of the chromosome.

The objective function is thus

$Minimize\ F = n\ x\ cost\ per\ meter + n\ x\ cost\ of\ RTU\ per\ meter + P_{obs}\ x\ Obs$

Where

Obs = 1 if the system is observable, else obs=0.

'n' is the number of meters.

$P_{obs} = 10^6$ (applicable when system is not observable)

6.5.2 Parameters of the algorithm:

Cost per meter = Rs. 100.

Cost of Remote Terminal Units = Rs. 2000.

Penalty factor for non-observable chromosomes (P_{obs}) = 10^6.

Crossover type = Two point crossover.

Selection type = Roulette wheel technique.

Weight matrix = Diagonal square matrix with diagonal elements equal to 500

Stopping criteria = based on number of iterations.

These parameters are also applicable for the six genetic algorithms in the next chapter.

Observations:

The number of meters obtained as the optimal solution = 40.

The size of Gain matrix and Jacobian Matrix are 40 x 40.

6.5.3 Convergence of Genetic Algorithm for The meter Placement Problem:

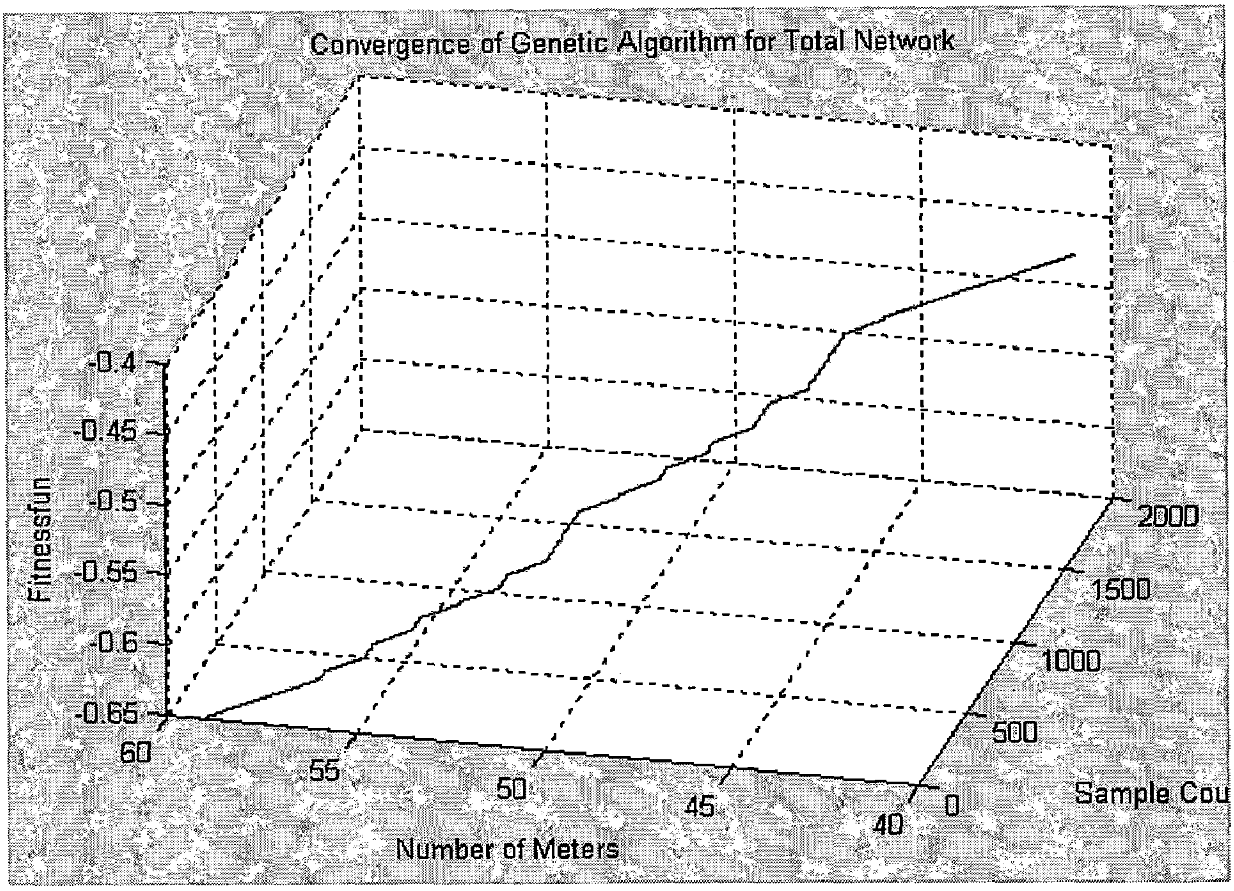
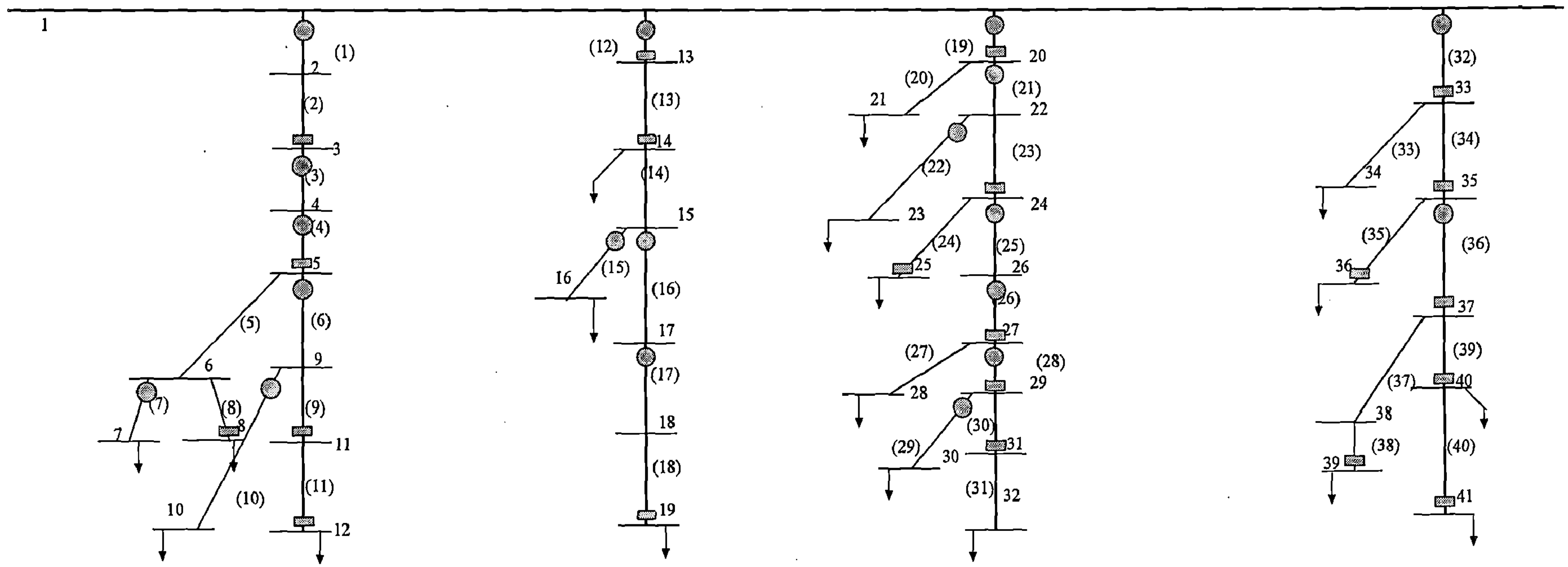


Figure 6. 2 Convergence of Genetic Algorithm for the whole network

6.5.4 The Meter arrangement after the implementation of the Meter Placement Problem:



N : Bus Number

(N): Branch Number

Number of state variables: 40

Number of Meters: 40

System Status: Observable.

CHAPTER-7

A New Algorithm for Meter Placement Problem

7.1 Introduction:

There are many disadvantages in the meter placement algorithm that is solved in the previous chapter, they are

- The search space is very large. The length of the chromosome in the previous model is 81 and the format is binary. Hence number of combinations of meters in the search space is 2^{81}.
- The Order of Jacobian matrix (H) and State estimation gain matrix (G) is very large. For a 40 meter chromosome their order is 40 x40, the operations on these matrices are time taking.
- The time of execution of the program range from 1.5 hours and more.
- The cost of the algorithm is huge as both the execution time is more and memory required to store these big matrices are also large.

7.2 Overview of the New model:

The model in this chapter is formed to overcome the disadvantages of the algorithm in the previous chapter. The procedure for the proposed algorithm is as follows

- The power system network is split in to 'n' laterals and each lateral is solved separately for optimal meter placement. They are solved in such a manner that each lateral is independent of the other n-1 laterals.
- These small laterals are again rebuilt in to the original network, after the meter placement problem is over.

- New constraints are added to further decrease the number of meters, keeping the Observability un-disturbed.

7.3 Applying the Algorithm to the network:

The 41-bus system is divided into 4 laterals (n=4) , and genetic algorithm is applied separately to all the four laterals.

Lateral 1:

Lateral 1 is the 12 bus system, with four loads at bus 7,8,10 and 12.

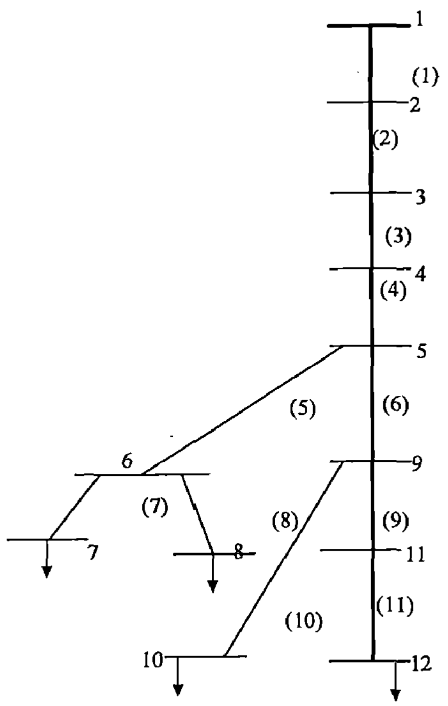


Figure 7. 1 Lateral-1 selected for the algorithm

7.3.1 Problem variables:

The problem variables of the 12-bus system is as follows

- The first type of variables will be the active power at the bus 'i' where i = 1 to 41

$P_1, P_2, P_3 \ldots P_{11}, P_{12}$ ------> 12 variables.

- The second type of variables will be the active power flow between the buses

  $P_{(1,2)}, P_{(2,3)}, P_{(3,4)} \ldots P_{(11,12)}$ ------> 11 variables.

- The third type of variables will be the power angle (Θ) at each bus except at bus 1 where Θ at bus 1 is assumed to be 0^o.

  $\Theta_2, \Theta_3, \Theta_4 \ldots \Theta_{11}, \Theta_{12}$ --- - -- > 11 variables.

The total number of variables of the model (n_v) is 12+11+11 = 34 variables.

7.3.2 Power balance equations:

The P-Θ (active power-angle) model is used for balance equations.

- ➢ $P_1 - P_{(1,2)} = 0$ and equations from 2 to 12. --- > 12 equations
- ➢ Equations from 42 to 52 --- > 11 equations

There are 23 network equations ($n_e = 23$).

7.3.3 Network Model in matrix form:

```
NM=[ 1 0 0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0 0 0 0 0 0
     0 1 0 0 0 0 0 0 0 0 0 0 1 -1 0 0 0 0 0 0 0 0 0
     0 0 1 0 0 0 0 0 0 0 0 0 0 1 -1 0 0 0 0 0 0 0 0
     0 0 0 1 0 0 0 0 0 0 0 0 0 0 1 -1 0 0 0 0 0 0 0
     0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 1 -1 -1 0 0 0 0 0
     0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 -1 -1 0 0 0
     0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0
     0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0
     0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 1 0 0 -1 -1 0
     0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 1 0 0
     0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 1 -1
     0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 1]
```

7.3.4 Selection of state variables:

For the considered problem of 12-bus system, the number of network equations are 23, while the number of problem variables are 34 hence the number of state variables that must be selected are 34-23 = 11 (n_s=11). These state variables may be any of these 34 variables.

The state variables selected for the problem under study are active power flow between the buses.

$P_{(1,2)}$, $P_{(2,3)}$, $P_{(3,4)}$ ... $P_{(11,12)}$ ------> 11 state variables.

$$X = \begin{bmatrix} P_{(1,2)} \\ P_{(2,3)} \\ P_{(3,4)} \\ \cdot \\ \cdot \\ \cdot \\ P_{(9,11)} \\ P_{(9,12)} \end{bmatrix}$$

The size of X is 11 x 1 and is called state variable matrix.

7.3.5 Measurement model:

Let us consider 11 meters are placed randomly in the network then the measurement matrix will be.

$$Z = \begin{bmatrix} P_1^{meas} \\ P_2^{meas} \\ \cdot \\ \cdot \\ P_n^{meas} \\ --- \\ P_{(1,2)}^{meas} \\ P_{(2,3)}^{meas} \\ \cdot \\ \cdot \\ P_{(a,b)}^{meas} \end{bmatrix}$$

The size of Z is 11 x 1 and is called measurement matrix.

7.3.6 Error Co-Variance Matrix & Weight Matrix:

In this problem, the variance matrix is taken as 0.02 for all the measurements and hence the diagonal matrix will have all elements equal to 500

Suppose any chromosome has 11 meters then the weight matrix will be

$$V = \begin{bmatrix} 0.02 & 0 & 0 & 0 & 0 \\ 0 & 0.02 & 0 & 0 & 0 \\ 0 & 0 & . & 0 & 0 \\ 0 & 0 & 0 & . & 0 \\ 0 & 0 & 0 & 0 & 0.02 \end{bmatrix} \quad \text{and} \quad W = \begin{bmatrix} 500 & 0 & 0 & 0 & 0 \\ 0 & 500 & 0 & 0 & 0 \\ 0 & 0 & . & 0 & 0 \\ 0 & 0 & 0 & . & 0 \\ 0 & 0 & 0 & 0 & 500 \end{bmatrix}$$

V is the variance matrix of the order 11 x 11

W is the weight matrix with the order 11 x 11

7.3.7 Jacobian Matrix:

For the present 12-bus system with a chromosome having 11 meters, the jacobian matrix is

$$Jacobian = \begin{bmatrix} 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

7.3.8 State estimation gain matrix:

The size of the gain matrix is also 11 X 11. The chromosome taken for analysis is observable as the corresponding gain matrix G is non-singular.

Gain Matrix =

[0.0020	0	0	0	0	0	0	0	0	0	0
0	0.0040	-0.0020	0	0	0	0	0	0	0	0
0	-0.0020	0.0040	-0.0020	0	0	0	0	0	0	0
0	0	-0.0020	0.0040	-0.0020	-0.0020	0	0	0	0	0
0	0	0	-0.0020	0.0020	0.0020	0	0	0	0	0
0	0	0	-0.0020	0.0020	0.0040	0	0	0	0	0
0	0	0	0	0	0	0.0020	0	0	0	0
0	0	0	0	0	0	0	0.0020	0	0	0
0	0	0	0	0	0	0	0	0.0020	0	0
0	0	0	0	0	0	0	0	0	0.0040	-0.0020
0	0	0	0	0	0	0	0	0	-0.0020	0.0020]

The gain matrix for the considered case is non-singular, hence the 11 meter arrangement is observable.

7.3.9 Results for Lateral 1:

The meter configuration after the genetic algorithm for Lateral 1 is shown

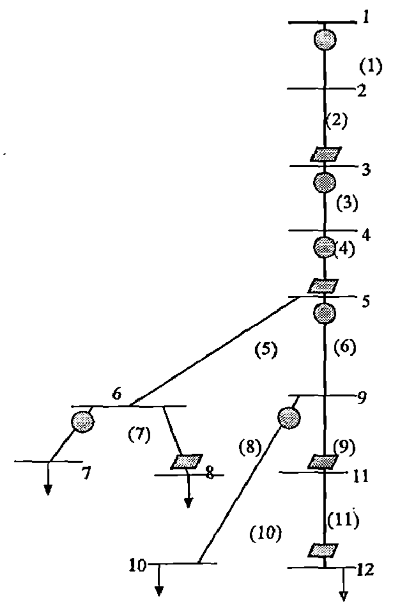


Figure 7. 2 The Meter placement of lateral-1 by genetic algorithm

7.3.10 Convergence of Genetic Algorithm for Lateral 1:

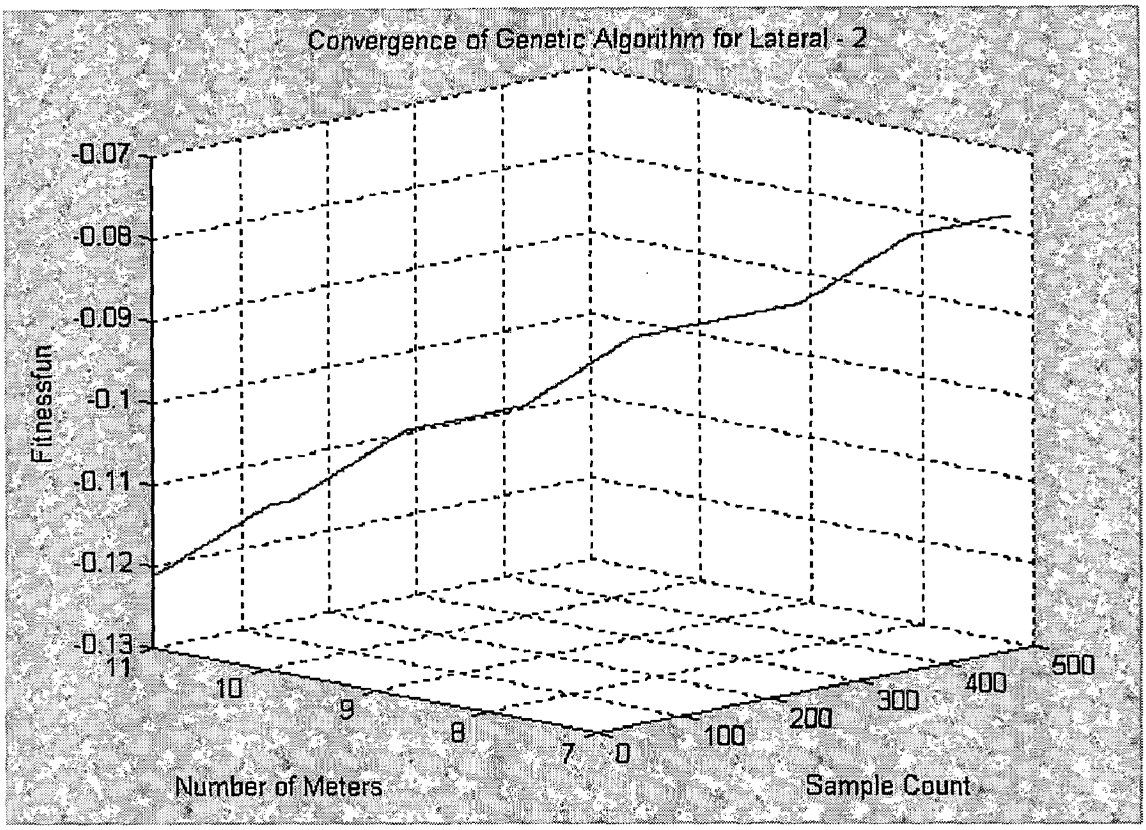


Figure 7. 3 Convergence of Genetic Algorithm for Lateral-1

7.4 Lateral 2:

The second part of the network, is selected for processing and is shown in the Figure

7.4.1 Problem variables:

The problem variables of the 8-bus system is as follows

- The first type of variables will be the active power at the bus 'i' where i = 1 to 41

------ > 8 variables.

- The second type of variables will be the active power flow between the buses

  $P_{(1,13)}$, $P_{(13,14)}$, $P_{(14,15)}$ ... $P_{(18,19)}$ ------> 7 variables.

- The third type of variables will be the power angle (Θ) at each bus except at bus 1 where Θ at bus 1 is assumed to be 0^o.

  Θ_{13}, Θ_{14}, Θ_{15} ... Θ_{18}, Θ_{19} ------> 7 variables.

The total number of variables of the model (n_v) is 8+7+7 = 22 variables.

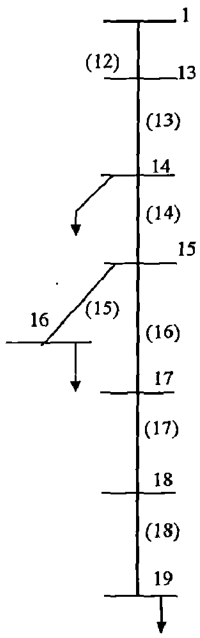


Figure 7. 4 Lateral-2 selected for the Alorithm

7.4.2 Power balance equations:

The P-Θ (active power-angle) model is used for balance equations.

- ➢ $P_1 - P_{(1,13)} = 0$ and equations from 14 to 20. --- > 8 equations
- ➢ Equations from 53 to 59 --- > 7 equations

There are 15 network equations (n_e = 15).

7.4.3 Network Model in matrix form:

NM = [1 0 0 0 0 0 0 0 0 -1 0 0 0 0 0
0 1 0 0 0 0 0 0 1 -1 0 0 0 0 0
0 0 1 0 0 0 0 0 0 1 -1 0 0 0 0
0 0 0 1 0 0 0 0 0 0 1 -1 -1 0 0
0 0 0 0 1 0 0 0 0 0 0 1 0 0 0
0 0 0 0 0 1 0 0 0 0 0 0 1 -1 0
0 0 0 0 0 0 1 0 0 0 0 0 0 1 -1
0 0 0 0 0 0 0 1 0 0 0 0 0 0 1]

7.4.4 Selection of state variables:

For the considered problem of 8-bus system, the number of network equations are 15, while the number of problem variables are 22 hence the number of state variables that must be selected are 22-15 = 7 (n_s=7). These state variables may be any of these 22 variables.

The state variables selected for the problem under study are active power flow between the buses.

$P_{(1,13)}$, $P_{(13,14)}$, $P_{(14,15)}$ ... $P_{(18,19)}$ ------ > 7 state variables.

X = The size of X is 7 x 1 and is called state variable matrix.

7.4.5 Measurement model:

Let us consider 7 meters are placed randomly in the network then the measurement matrix will be.

$$Z = \begin{bmatrix} P_1^{meas} \\ P_2^{meas} \\ \cdot \\ \cdot \\ P_n^{meas} \\ --- \\ P_{(1,2)}^{meas} \\ P_{(2,3)}^{meas} \\ \cdot \\ \cdot \\ P_{(a,b)}^{meas} \end{bmatrix}$$

The size of Z is 7 x 1 and is called measurement matrix.

7.4.6 Jacobian Matrix:

For the present 8-bus system with a chromosome having 7 meters, the jacobian matrix is

Jacobian = [-1 1 0 0 0 0 0
0 0 -1 1 1 0 0
0 0 0 0 -1 1 0
0 0 0 0 0 0 -1
1 0 0 0 0 0 0
0 0 0 1 0 0 0
0 0 0 0 1 0 0]

7.4.7 State estimation gain matrix:

The size of the gain matrix is also 7 X 7. The chromosome taken for analysis is observable as the corresponding gain matrix G is non-singular.

The gain matrix for the considered case is non-singular, hence the 7 meter arrangement is observable.

Gain matrix =

[0.0040	-0.0020	0	0	0	0	0
-0.0020	0.0020	0	0	0	0	0
0	0	0.0020	-0.0020	-0.0020	0	0
0	0	-0.0020	0.0040	0.0020	0	0
0	0	-0.0020	0.0020	0.0060	-0.0020	0
0	0	0	0	-0.0020	0.0020	0
0	0	0	0	0	0	0.0020]

7.4.8 Results for Lateral 2:

The meter configuration after the genetic algorithm for Lateral 2 is shown

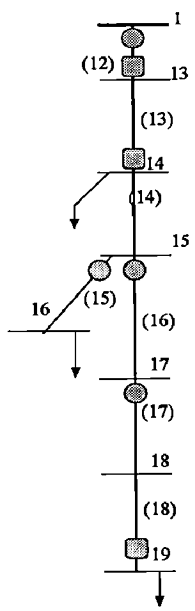


Figure 7. 5 Meter placement for Lateral-2 after Genetic Algorithm

1. The convergence of the algorithm started from 20 meters and end up with 7 meters.

2. The size of the Jacobian matrix and the gain matrix regarding the output chromosome is 7X7.
3. The total number of samples of observable chromosomes in the search space of the genetic algorithm is 500.

7.4.9 Convergence of Genetic Algorithm for Lateral-2:

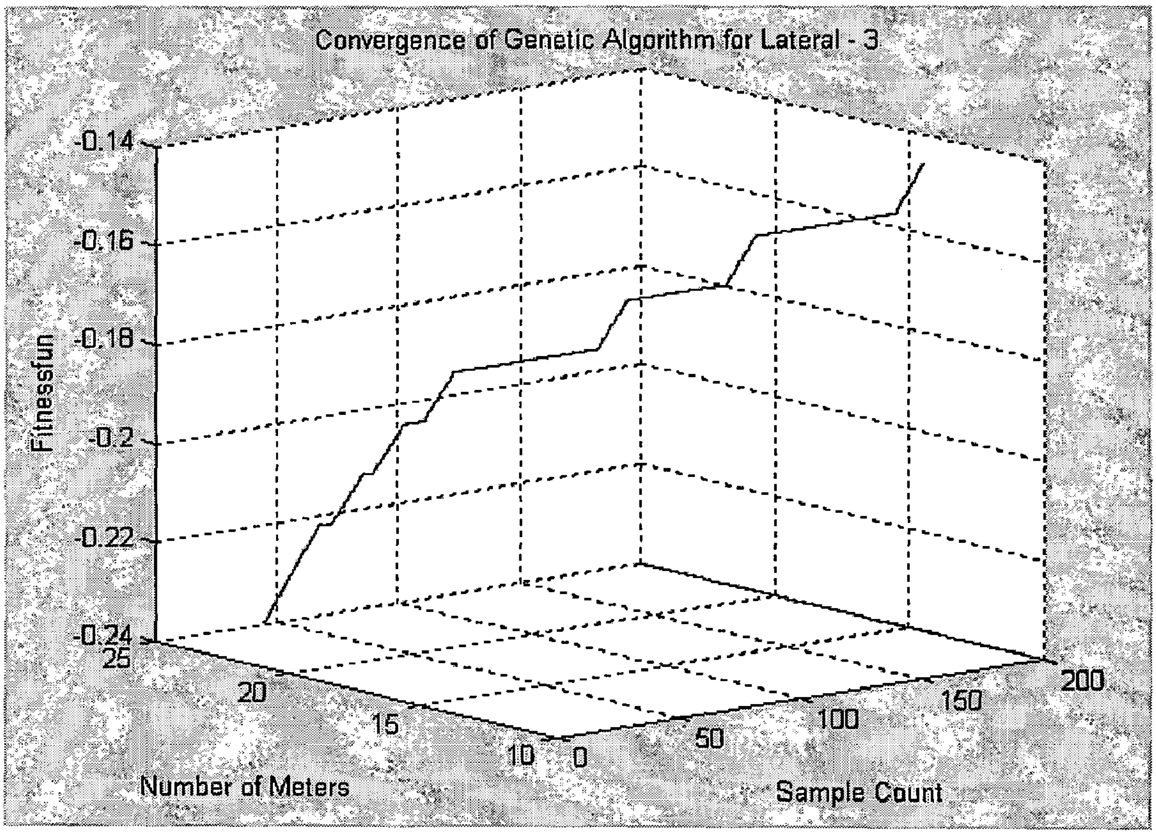


Figure 7. 6 Convergence of Genetic Algorithm for Lateral 2

7.5 Lateral 3:

The Lateral-3 selected for the algorithm is shown in figure 7.7

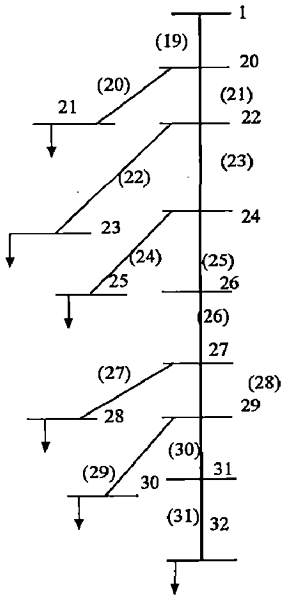


Figure 7. 7 Lateral-3 selected for the algorithm

7.5.1 Problem variables:

The problem variables of the 14-bus system is as follows

- The first type of variables will be the active power at the bus 'i' where i = 1 to 41

  $P_1, P_{20}, P_{21} \ldots P_{31}, P_{32}$ ------ > 14 variables.

- The second type of variables will be the active power flow between the buses

  $P_{(1,13)}, P_{(13,14)}, P_{(14,15)} \ldots P_{(18,19)}$ ------ > 13 variables.

- The third type of variables will be the power angle (Θ) at each bus except at bus 1 where Θ at bus 1 is assumed to be 0^o.

$\Theta_{20}, \Theta_{21}, \Theta_{22} \ldots \Theta_{31}, \Theta_{32}$ ------> 13 variables.

The total number of variables of the model (n_v) is 14+13+13 = 40 variables.

7.5.2 Power balance equations:

The P-Θ (active power-angle) model is used for balance equations.

$P_1 - P_{(1,20)} = 0$ and equations from 21 to 33. --- > 14 equations

Equations from 60 to 72 --- > 13 equations

There are 27 network equations ($n_e = 27$).

7.5.3 Network Model in matrix form:

```
NM=[1 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0 0 0 0 0 0 0 0
    0 1 0 0 0 0 0 0 0 0 0 0 0 0 1 -1 -1 0 0 0 0 0 0 0 0 0 0
    0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0
    0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 1 -1 -1 0 0 0 0 0 0 0 0
    0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0
    0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 1 -1 -1 0 0 0 0 0 0
    0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0
    0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 1 -1 0 0 0 0 0
    0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 1 -1 -1 0 0 0
    0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0
    0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 1 -1 -1 0
    0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0
    0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 1 -1
    0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 1]
```

7.5.4 Selection of state variables:

For the considered problem of 14-bus system, the number of network equations are 27, while the number of problem variables are 40 hence the number of state variables that must be selected are 40-27 = 7 (n_s=13). These state variables may be any of these 40 variables.

The state variables selected for the problem under study are active power flow between the buses.

$P_{(1,20)}$, $P_{(20,21)}$, $P_{(21,22)}$ ... $P_{(31,32)}$ ------ > 13 state variables.

X = The size of X is 13 x 1 and is called state variable matrix.

7.5.5 Measurement model:

Let us consider 13 meters are placed randomly in the network then the measurement matrix will be.

The size of Z is 13 x 1 and is called measurement matrix.

7.5.6 Jacobian Matrix:

For the present 14-bus system with a chromosome having 13 meters, the jacobian matrix is

$$\text{Jacobian} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

7.5.7 State estimation gain matrix:

The size of the gain matrix is also 13 X 13. The chromosome taken for analysis is observable as the corresponding gain matrix G is non-singular. Hence the arrangement is observable.

7.5.8 Results for Lateral 3:

1. The convergence of the algorithm started from 20 meters and end up with 13 meters.
2. The size of the Jacobian matrix and the gain matrix regarding the output chromosome is 13X13.
3. The total number of samples of observable chromosomes in the search space of the genetic algorithm is 500.

The meter configuration after the genetic algorithm for Lateral 3 is shown

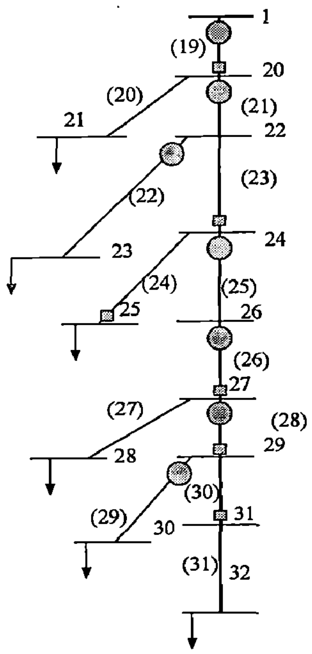


Figure 7. 8 Meter Configuration after Genetic Algorithm for Lateral 3

7.5.9 Convergence of Genetic Algorithm for Lateral-3:

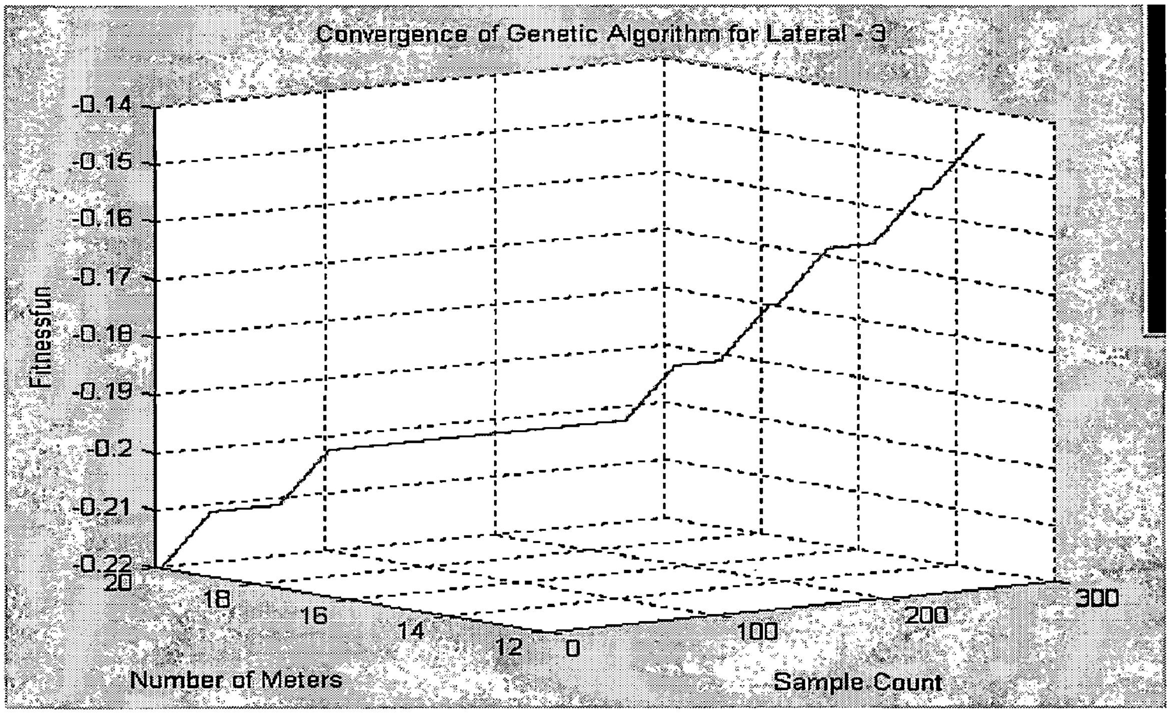


Figure 7. 9 Convergence of Genetic Algorithm for Lateral 3

7.6 Lateral 4:

The meter configuration after the genetic algorithm for Lateral 4 is shown in the figure 7.10

7.6.1 Problem variables:

The problem variables of the 10-bus system is as follows

- The first type of variables will be the active power at the bus 'i' where i = 1 to 41

------ > 10 variables.

- The second type of variables will be the active power flow between the buses

$P_{(1,33)}$, $P_{(33,34)}$, $P_{(34,35)}$ ... $P_{(40,41)}$ ------> 9 variables.

- The third type of variables will be the power angle (Θ) at each bus except at bus 1 where Θ at bus 1 is assumed to be 0^o.

Θ_{33}, Θ_{31}, Θ_{32} ... Θ_{40}, Θ_{41} ---- -- -> 9 variables.

The total number of variables of the model (n_v) is 10+9+9 = 28 variables.

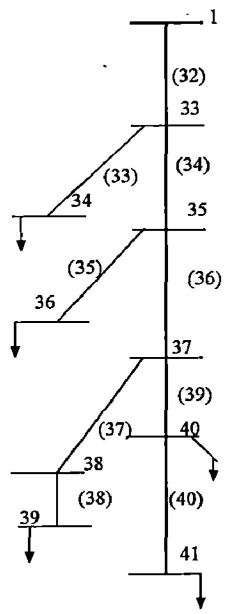


Figure 7. 10 Lateral 4 selected for the algorithm

7.6.2 Power balance equations:

The P-Θ (active power-angle) model is used for balance equations.

- $P_1 - P_{(1,33)} = 0$ and equations from 34 to 42. --- > 10 equations
- Equations from 73 to 81 --- > 9 equations

There are 19 network equations ($n_e = 19$).

7.6.3 Network Model in matrix form:

NM = [1 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0 0 0 0
0 1 0 0 0 0 0 0 0 0 1 -1 -1 0 0 0 0 0 0
0 0 1 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0
0 0 0 1 0 0 0 0 0 0 0 0 1 -1 -1 0 0 0 0
0 0 0 0 1 0 0 0 0 0 0 0 0 1 0 0 0 0 0
0 0 0 0 0 1 0 0 0 0 0 0 0 0 1 -1 -1 0 0
0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 1 0 -1 0
0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 1 0
0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 1 0 -1
0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 1]

7.6.4 Selection of state variables:

For the considered problem of 10-bus system, the number of network equations are 19, while the number of problem variables are 28 hence the number of state variables that must be selected are 28-19 = 7 (n_s=9). These state variables may be any of these 28 variables.

The state variables selected for the problem under study are active power flow between the buses.

$P_{(1,33)}$, $P_{(33,34)}$, $P_{(33,35)}$ ... $P_{(40,41)}$ ------ > 9 state variables.

X = The size of X is 9 x 1 and is called state variable matrix.

7.6.5 Measurement model:

Let us consider 9 meters are placed randomly in the network then the measurement matrix will be a 9X1 matrix with measurements given by the meters.

7.6.6 Jacobian Matrix:

For the present 14-bus system with a chromosome having 13 meters, the jacobian matrix is

Jacobian = [

1	0	0	0	0	0	0	0	0
-1	1	1	0	0	0	0	0	0
0	0	0	0	-1	1	1	0	0
0	0	0	0	0	0	0	-1	0
0	0	0	0	0	0	0	0	-1
0	1	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0	0
0	0	0	0	1	0	0	0	0
0	0	0	0	0	0	1	0	0]

7.6.7 State estimation gain matrix:

The size of the gain matrix is also 9 X 9. The chromosome taken for analysis is observable as the corresponding gain matrix G is non-singular. Hence the arrangement is observable.

Gain matrix:

[0.0040	-0.0020	-0.0020	0	0	0	0	0	0
-0.0020	0.0040	0.0020	0	0	0	0	0	0
-0.0020	0.0020	0.0020	0	0	0	0	0	0
0	0	0	0.0020	0	0	0	0	0
0	0	0	0	0.0040	-0.0020	-0.0020	0	0
0	0	0	0	-0.0020	0.0020	0.0020	0	0
0	0	0	0	-0.0020	0.0020	0.0040	0	0
0	0	0	0	0	0	0	0.0020	0
0	0	0	0	0	0	0	0	0.0020]

7.6.8 Results for Lateral 4:

1. The convergence of the algorithm started from 15 meters and end up with 9 meters.
2. The size of the Jacobian matrix and the gain matrix regarding the output chromosome is 9X9.

3. The total number of samples of observable chromosomes in the search space of the genetic algorithm is 500.

The meter configuration after the genetic algorithm for Lateral 3 is shown

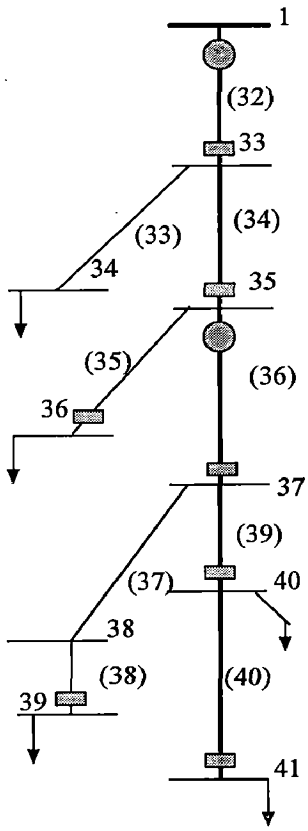


Figure 7. 11 Meter Placement after Genetic Algorithm for Lateral-4

7.6.9 Convergence of Genetic Algorithm for Lateral 4:

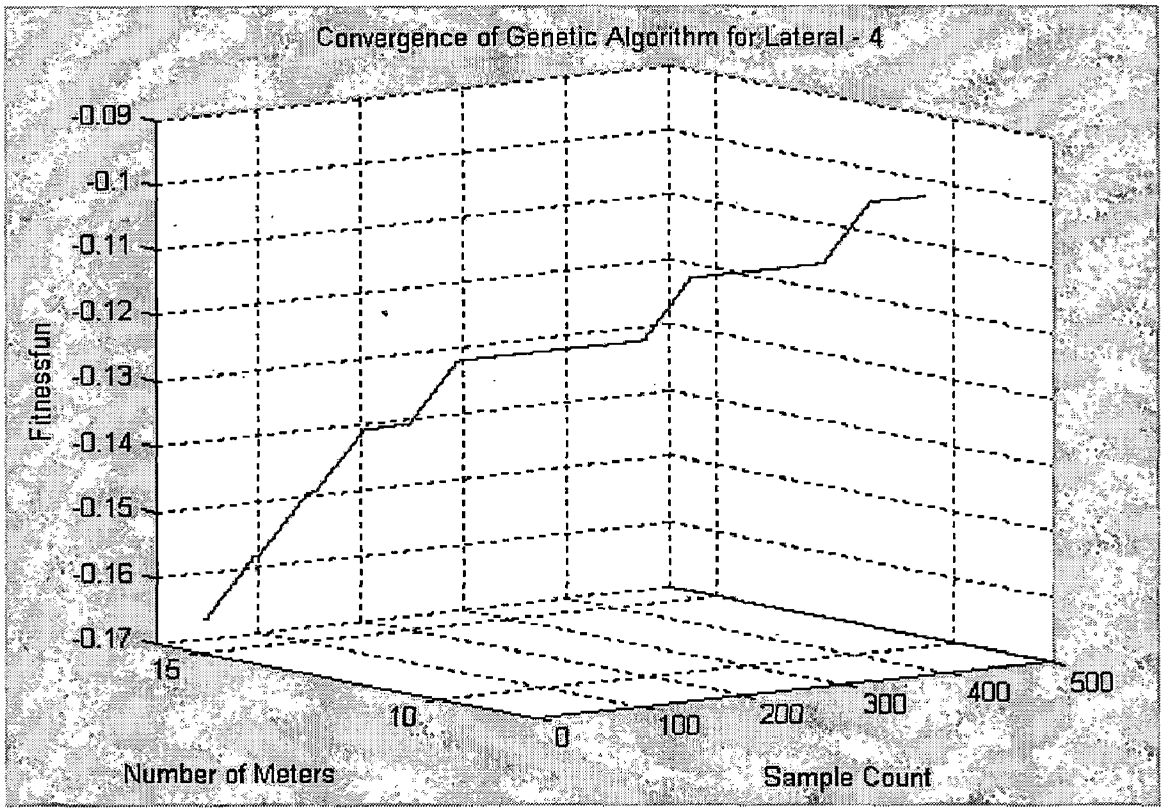


Figure 7. 12 Convergence of Genetic Algorithm for Lateral-4

7.7 Removing redundant meters from the network:

The Redundant measurements are always desirable for more reliability and accuracy, but the main disadvantage is that they are costly. For those who prefer the financial constraint than the reliability constraint, some extra constraints are added at each step to reduce the number of meters and also which maintains Observability with the error in accepted tolerance.

If we consider the figure (7.13), some sets of meters, show almost the same readings, for example, the meters between buses 1 and 20, meter between 20 and 22, show the same readings, with some acceptable error(error is the loss which is small when compared to the power flowing through the buses) .

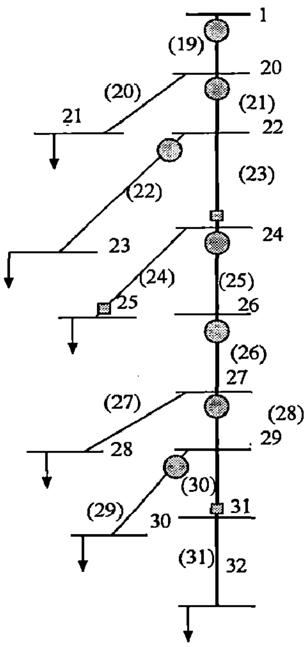


Figure 7. 13 Network with meters are taken to check the algorithm

7.7.1 Algorithm for removing meters:

Step 1: K←0, i←1 (i = bus index)

Step 2: If any meter encountered between i and (i+1)th bus then k←1.

Step 3: if k=0 goto step 5

Step 4: If any more meters encountered between i and (i+1)th bus then remove the meters.

Step 5: if all meters are scanned between i and (i+1)th bus, i is incremented to the next bus. Else go to step 2.

Step 6: if any branch or load is taken from bus i, k← 0 else k←1 and go to step 2

Step 7: if all the buses are traced, return to the called procedure.

The solution after reduction of meters is shown in the figure(7.14)

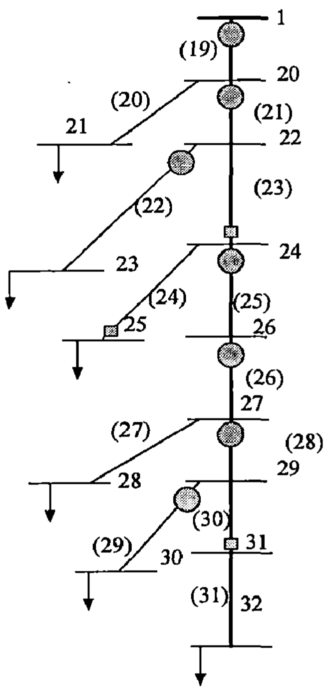


Figure 7. 14 Metering Placement after the number of reduction of meters.

For this case, Number of meters reduced = 3. The same algorithm is applied to the solution of the new method, we get the meter placement as shown in the figure 7.15. The number of meters reduced is 20, financially a good solution and also the accuracy is also with in limits.

7.7.2 The meter placement after the application of the Constraint to reduce meters:

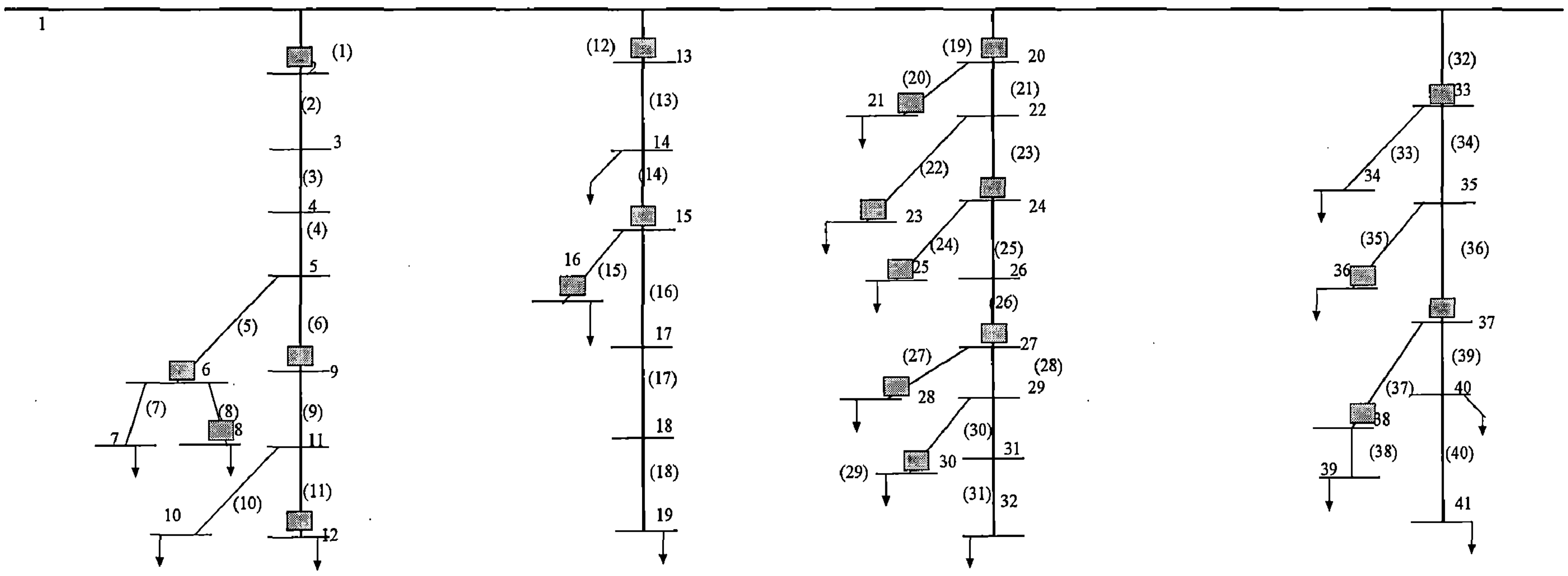


figure 7. 15 Meter placement of the bus after the application of the constraints

N : Bus Number

(N): Branch Number

Number of meters: 20

Number of load measuring meters: 10

Number of monitoring meters: 10

Number of meters reduced: 20

System Status: Observable (with reduced accuracy)

7.8 Rebuilding the different laterals to form Original network:

For analysis purpose, a lateral is divided in to two sub-laterals, the meter setup is calculated with the help of genetic algorithms and applying this algorithm to re-build the original network.

7.8.1 Algorithm:

Step1: Attach the first lateral with the second lateral.

Step 2: At the meeting bus, verify whether there is any load or branch connected to it.

Step 3: if there is any load or branch at that bus, k←1

Step 4: If k = 1 then apply algorithm 7.7.1.

Step 5: else keep the meter placement as it is.

Step 6: stop.

The lateral-3 taken for the test of algorithm in figure 7.7

The lateral 3 in figure (7.7) is divided in to two parts.

7.8.2 Lateral 3, first part:

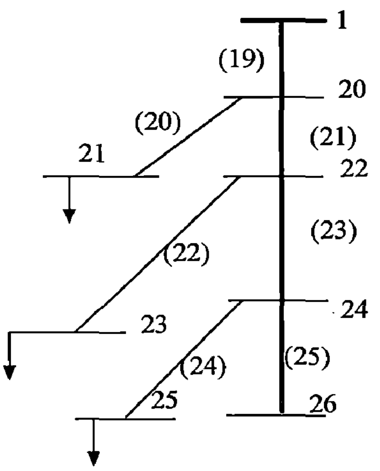


Figure 7. 16 (a) Lateral-3 first part

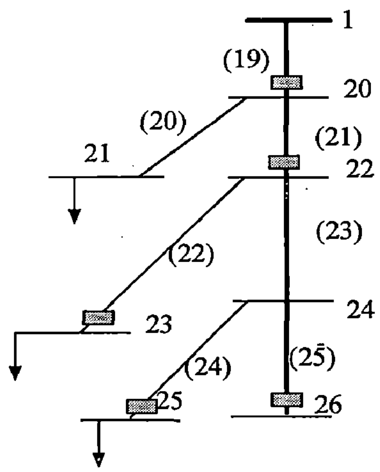


Figure 7. 16 (b) meter placement

7.8.3 Convergence of Genetic algorithm for Lateral-3 first part:

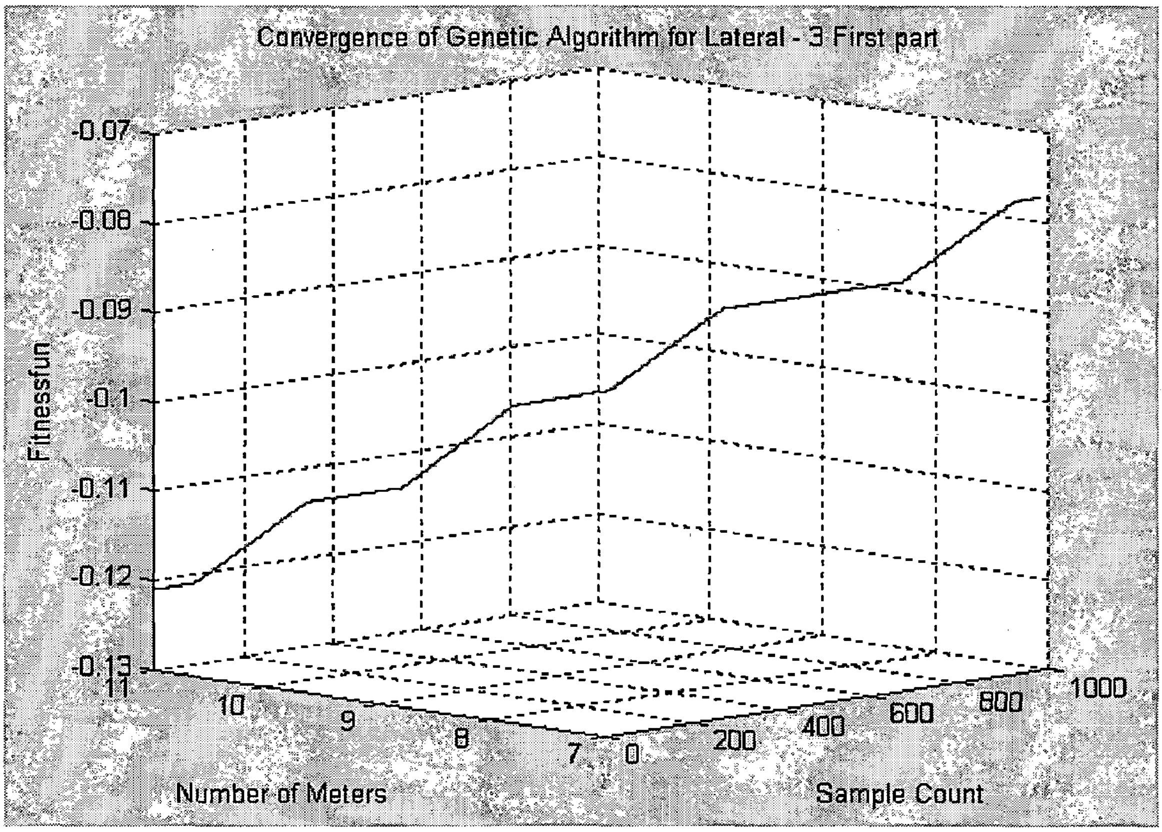


Figure 7. 17 Convergence of Genetic Algorithm for Lateral 3 first part

7.8.4 Lateral 3, Second Part:

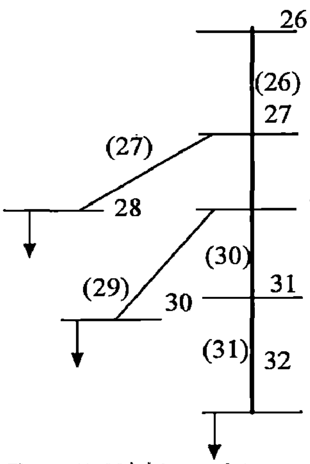


Figure 7. 18(a) Lateral-3 second part

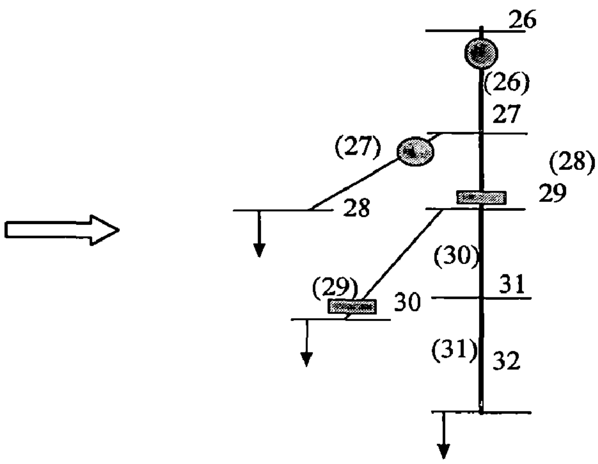


Figure 7. 18(b) meter placement

7.8.5 Convergence of Genetic algorithm for Lateral-3 second part:

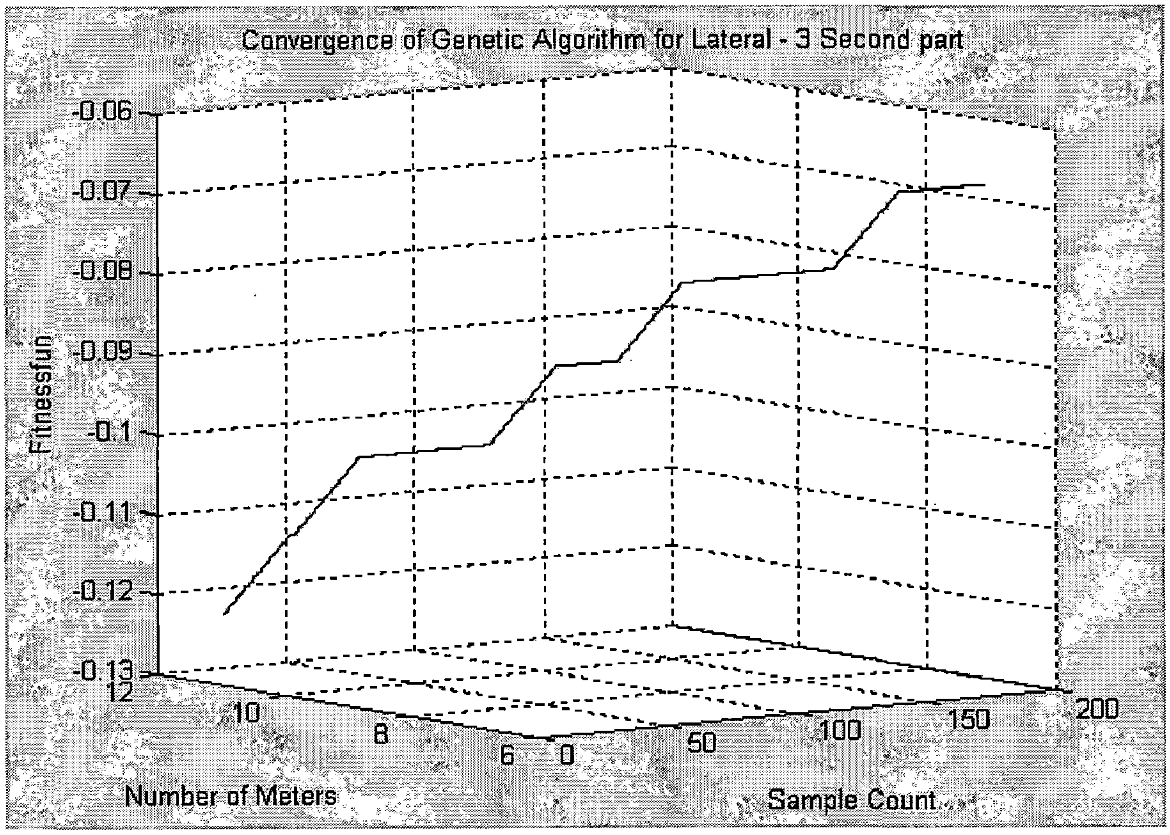


Figure 7. 19 Convergence of Genetic Algorithm for Lateral-3 second part.

7.8.6 Re-build the laterals:

For analysis, the lateral 3 first part and lateral 3 second part are attached to each other and the algorithm 7.8.1 is applied to the two parts, we get the whole part as in figure 7.17. The overall concept of the algorithm is to reduce the redundant meters that will appear after rejoining the two networks. After joining, if some meters are found to be redundant, the first meter encountered will be kept as it is and the remaining placements are removed. They will take the same reading as the previous meter.

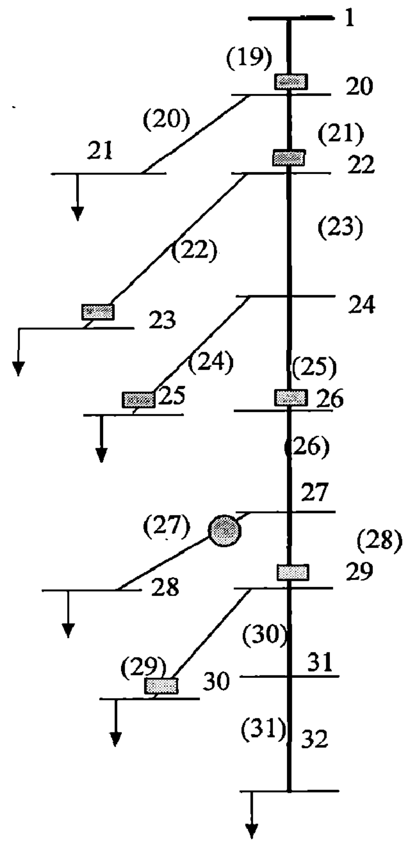


Figure 7. 20 Final figure after re-bulding the laterals

7.9 Comparison between the two methods in chapter 6 and chapter 7:

1. Search Space:

In the previous meter placement problem, the length of the chromosome is 81. Hence the search space has 2^{81} Combinations of the chromosomes to be searched.

In the proposed method, the total network is split in to four parts and the lengths of the chromosomes for the four laterals are 23,15,27,19 respectively. Hence the search space is $2^{23} + 2^{15} + 2^{27} + 2^{19}$.

The ratio

$$\frac{Search\ Space\ of\ the\ previous\ model}{Search\ Space\ in\ the\ Proposed\ m} = 1.6889\ x\ 10^6$$

Hence a large reduction in search space is attained in the proposed model.

2. **Size of Matrices:**

In the Previous algorithm, the size of Jacobian and Gain matrices are large. For example, if a chromosome of 40 meters is taken, the size of Jacobian matrix is 40 x 40 and the size of gain matrix is also 40 x 40, hence difficult to do operations on these matrices.

In the proposed algorithm, the size of jacobian and gain matrices are less, for example, the chromosome of 11 meters is taken, the size of jacobian matrix and gain matrices are 11 x 11. Hence operations on these matrices are quite simple.

3. **Time of execution:**

The Previous method takes around 1.5 hours and more, for the execution but the proposed method has four programs each takes around 2-6 minutes, hence very faster.

4. **Cost of the Algorithm:**

The Cost of the Algorithm is defined as the product of time taken to execute the algorithm and the memory taken by that algorithm.

In previous method, as the Size of Jacobian and Gain matrices are very high, the memory required to store these matrices are also high. As the search space is more, the time of exection is also high. Hence the cost of the algorithm is also more.

In this new method, The size of Jacobian and Gain matrices are less and the search space is very less when compared to the previous algorithm, hence the cost of the algorithm is also very low.

CHAPTER-8

Estimation of Commercial Losses

8.1 Introduction:

Sub-Transmission and Distribution systems constitute the link between electricity utilities and consumers, their revenue realization segment. For consumers, it represents the face of the utility. Efficient functioning of this segment of the utility is essential to sustain the growth of power sector and the economy. The present situation is characterized by unacceptably high losses (both technical and commercial), poor quality and reliability of supply, billing, revenue collection, frequent interruptions in supply and consumer dissatisfaction etc..,

The all-India T & D Losses, which were about 15% till 1966-67, increased gradually and is 24.79% (1997-98). During the last few years some of utilities variously estimated the losses in the range over 30% to 50% much higher than the preceding years. T & D losses in developed countries are around 7-8% only. Taking into consideration the Indian conditions such as rural areas, nature of loads, system configuration etc. the reasonable permissible (technical) energy losses should be 10-15% in different states.

The commercial losses, which are also called non-technical losses, form the major component of overall losses in the distribution system. Commercial losses can occur due to many reasons

- Power theft is the major cause for Commercial losses, due to this, the billing and revenue collections are very poor leading to combined state utility financial losses.
- Defective (slow) meters, stuck up/burnt meters etc.
- Absence of adequate metering at the rural level.
- Improper planning and monitoring of distribution networks.
- In efficient management.

And many more reasons for the huge commercial losses at distribution level. Proper estimation of commercial losses and finding the area of the network which has high commercial losses is a key task to improve the efficiency.

8.2 Estimation of Commercial losses:

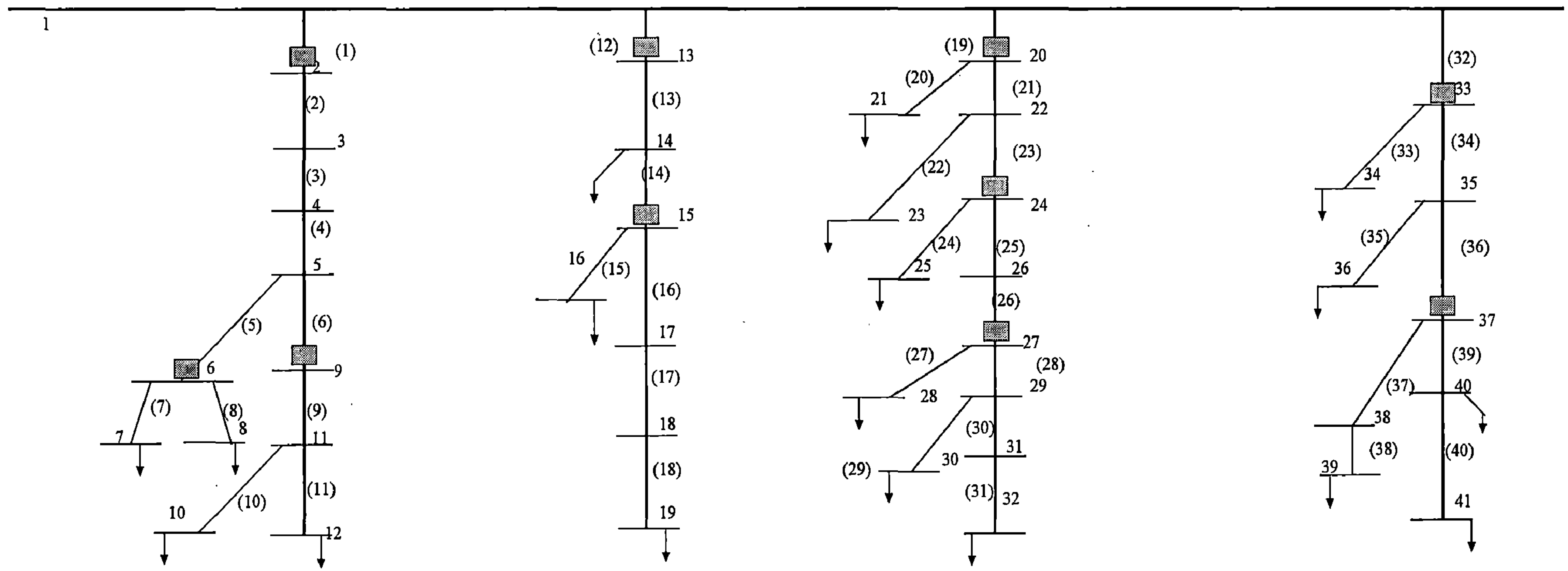
The basic step in the estimation of commercial losses is the proper estimation of technical losses. The online or offline load flow studies are needed to attain this task. Generally, the online load flow is done by state estimation and offline load flow is done using different load flow methods available. Forward/backward sweep method of load flow is used in the current work for the estimation of technical losses.

8.2.1 Monitoring Devices:

Different monitoring devices are placed along the network to monitor the voltages, powers and losses continuously along the network. The placement of monitoring devices is done in the previous chapter. Some devices are just used to monitor the load, and these meters are removed and those meters which monitor the network are taken in to consideration in evaluating the commercial losses.

For the entire network, a total of 10 meters is used as monitoring devices, each device will monitor one area hence a total of 10 areas are monitored in the whole network. After estimating the commercial losses, the area with highest commercial losses is shown so that more concentration is done on that area to decrease the loss in that area.

8.2.1.1 The meter placement for the estimation of commercial losses in the network:



Number of monitoring meters: 10

N : Bus Number

(N): Branch Number

8.2.2 Revenue data:

Each load is assigned a value of loss of revenue to attain this process. This percentage contains both the technical loss and commercial losses.

Load Connected to be bus	Loss of revenue (%)
7	15
8	25
10	22
12	10
14	13
16	12
19	15
21	11
23	18
25	20
28	18
30	10
32	20
34	15
36	18
39	9
40	24
41	9

Table 8. 1 Revenue data at each and every load

8.2.3 Algorithm to estimate commercial losses:

Step 1: Revenue collected at each load is calculated through loss of revenue in the table 8.1. Assuming Rs. 2 per kwh.

Step 2: Scan from each meter to the end of the lateral sum up all the revenue collected at each bus to get revenue collected per meter.

Step 3: Using the online/offline load flow studies, the meter reading is calculated and the revenue that must be collected per meter is calculated

Step 4: The difference between the values calculated in step 2 and step 3 gives the total loss of revenue per area.

Step 5: The technical losses is calculated per area and the difference between the total losses and the technical losses, gives the commercial losses per area.

8.2.4 Results for the Estimation of commercial losses:

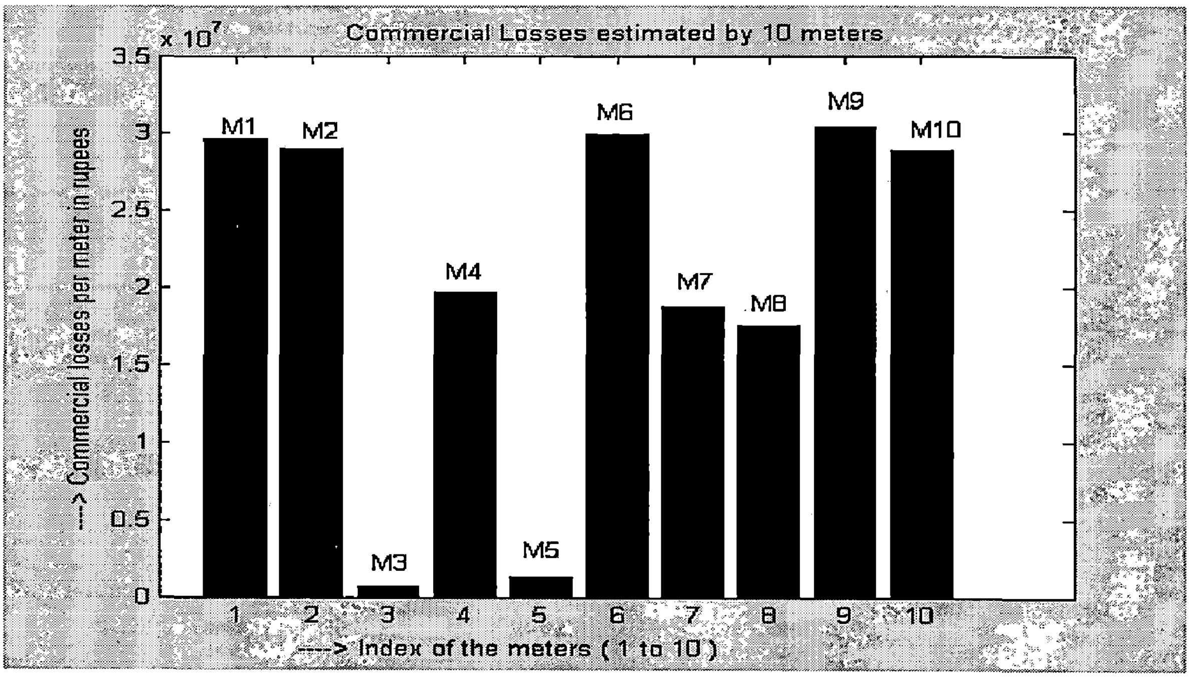


Figure 8. 2 Commercial losses estimated by different Monitoring Meters

8.2.5. Summary of the Revenue collected and losses:

Index Of the Meter Monitoring the Network	Money that should be collected according to the meter reading (Crores of Rupees)	Actual Money collected Per meter (Crores of Rupees)	Technical Losses (Crores of Rupees)	Commercial Losses (Crores of Rupees)
1	13.1550	9.4399	0.7509	2.9642
2	12.0497	9.1237	0.024	2.9020
3	0.3785	0.3162	0.0001	0.0622
4	15.6723	13.1698	0.5280	1.9745
5	0.9396	0.8112	0.0006	0.1278
6	20.7426	17.5464	0.2021	2,9941
7	11.0611	9.0633	0.1217	1.8762
8	10.3507	8.5699	0.0279	1.7528
9	19.0518	15.5152	0.4947	3.0420
10	17.8444	14.7248	0.2263	2.8933

Table 8. 2 Summary of the Revenue collected and losses.

Observation: Area monitored by Meter-9 (Lateral 4) is found to have high commercial losses with 3.0420 crores of rupees.

8.2.6 Comparison of Technical losses with commercial losses:

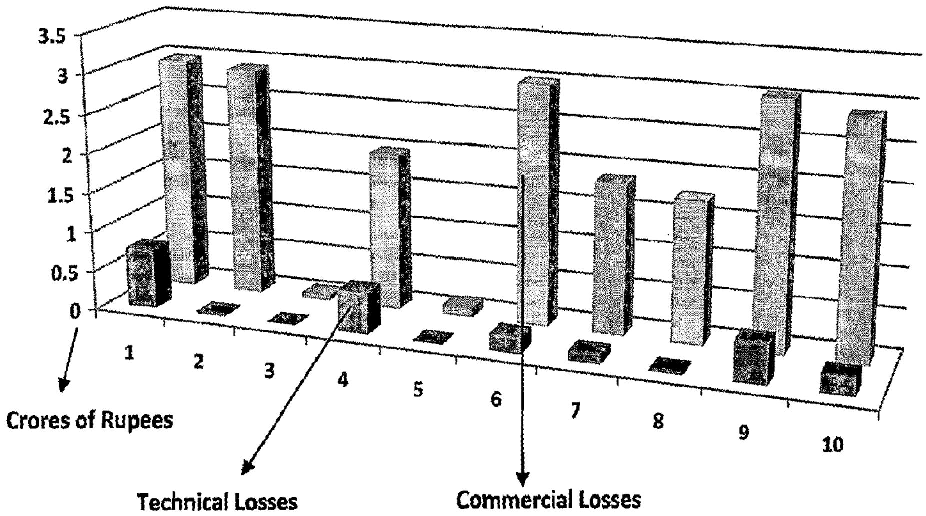


Figure 8. 3 Comparision of technical and commercial losses.

Observations:

- Total money that to be collected = 121.2458 crores.
- Total money collected = 98.2805 crores.
- Technical losses = 2.3761 crores.
- Commercial losses = 20.5892 crores.

The percentage of Technical losses to the total losses: **10.3465 %**

The percentage of Technical losses to the money to be collected: **1.96%**

The percentage of Commercial losses in total losses is: **89.6535%**

The percentage of Commercial losses to the money to be collected: **16.9814 %**

CHAPTER-9

CONCLUSIONS AND SCOPE FOR FUTURE WORK

9.1 Conclusions:

As the meter placement problem is the first and main step in the distribution system automation, improving system reliability, estimation of different losses etc.., the present work is mainly concentrated in this area of optimal placement of meters. A meter placement procedure is applied to 41-bus, 33 KV system using genetic algorithms. The solution to this optimization problem gives the metering setup which balances the Observability and cost constraints. Some disadvantages are found in this method of meter placement.

A new method is developed in this work and is applied to the same 41-bus 33 KV system, the main advantages of this new method when compared to the previous method are the reduction in search space by a factor of $\mathbf{1.6889\,x\,10^6}$, large reduction in the sizes of Jacobian and Gain matrices, reduction of the cost of the algorithm etc.., the fitness function in the genetic algorithm being same as the previous method.

Additional constraints are added to the solution which further reduces the redundant meters but keep the Observability undisturbed with accepted tolerance.

Using these meter placement, the commercial losses in this system are estimated from a revenue data available, energy cost at Rs. 2 per Kwh. The area monitored by **Meter 9** (lateral 4) is found to have Maximum commercial losses of 3.0420 crores of rupees. The technical losses constitute **10.3%** of total losses and **2%**(approx) of expected revenue. The commercial losses constitute **89.7%** of total losses and **16.98%** of expected revenue.

9.2 Scope for the Future work:

- A Power system network is taken which consists of relays and transformers, so that the observable islands come in to picture. There is a scope that the meter setup is observable even in the case when a relay is tripped or a part of the system is out of operation.
- The current work is done based on numerical Observability, the topological Observability can also be done with the help of advanced graph theory applications so that the operations on these big matrices can be eliminated.
- Work can be done on redundant measurements, which will increase the reliability of the measurements in the system. In this case, the critical measurements are included in the fitness function.
- Instead of genetic algorithms, new artificial intelligence techniques such as swarm optimization can be used and can be compared for the faster convergence than the previous methods.

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