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Comparison of Power Flow Algorithms for inclusion in On-line Power Systems Operation Tools

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Comparison of Power Flow Algorithms for inclusion in
On-line Power Systems Operation Tools

A Thesis

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University of New Orleans
In partial fulfillment of the
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Abstract

The goal of this thesis is to develop a *new*, *fast*, *adaptive* load flow algorithm that "automatically alternates" numerical methods including Newton-Raphson method, Gauss-Seidel method and Gauss method for a load flow run to achieve *less run time*. Unlike the proposed method, the traditional load flow analysis uses only one numerical method at a time. This adaptive algorithm performs all the computation for finding the bus voltage angles and magnitudes, real and reactive powers for the given generation and load values, while keeping track of the proximity to convergence of a solution. This work focuses on finding the algorithm that uses multiple numerical techniques, rather than investigating programming techniques and programming languages. The convergence time is compared with those from using each of the numerical techniques. The proposed method is implemented on the IEEE 39-bus system with different contingencies and the solutions obtained are verified with PowerWorld Simulator, a commercial software for load flow analysis.

Key Words: Power flow, Gauss method, Gauss-Seidel method, Newton-Raphson method, switching technique, convergence time.

Chapter 1

Introduction

1.1 Concept of Power Flow:

The power flow analysis is a very important tool in power system analysis. Power flow studies are routinely used in planning, control, and operations of existing electric power systems as well as planning for future expansion. The successful operation of power systems depends upon knowing the effects of adding interconnections, adding new loads, connecting new generators or connecting new transmission line before it is installed. The goal of a power flow study is to obtain complete voltage angle and magnitude information for each bus in a power system for specified load and generator real power and voltage conditions [1-3].

The goal of a power flow study is to obtain complete voltage angle and magnitude information for each bus in a power system for specified load, generator real power, and voltage conditions. Once this information is known, real and reactive power flow on each branch as well as generator reactive power can be analytically determined. Due to the nonlinear nature of the problem, numerical methods are employed to obtain a solution that is within an acceptable tolerance [16].

Power flow calculation is fundamental in power systems. Power systems are non-linear system of equations in general, the solution for these equations can be found using iterative methods. There are several different iterative methods to solve the power flow problems. The iterative methods give the accurate solution as they approach towards the convergence of the solution by replacing the already calculated value and minimize the tolerance value. There are

also some direct methods that converge in less number of iterations compared to iterative methods [3]. The memory requirements and time of calculation increases as the problem size increases (increase in number of buses), so the direct methods are effective for small power system problems. However, it is difficult to say which method is effective as the power flow calculation depends on various factors like the size of the problem, the method used and the type of problem to be solved.

In the iterative methods, the memory requirements and the number of iterations increase as the size of the problem increases [3]. For large-sized problems only iterative methods are proved to be efficient. In the past the problem size was small compared to the present day, hence the direct methods were used, and there was an urgent need to find out a method that could ensure the convergence for small-sized and large-sized problems.

The recent development in the field of digital computer technology led for the development of a number of methods for solving the power flow problems. Some of the iterative methods that are mainly used today are Gauss method, Gauss-Seidel method and Newton-Raphson [5]. These methods are efficient but the comparisons between the methods are difficult because of differences in computers, programming methods and languages, and the test problems. However, Newton-Raphson method due to its calculation simplifications, fast convergence and reliable results is the most widely used method of large load flow analysis.

In large-sized problems, Newton-Raphson method generates the solution in less time, but for small-sized problems this method is not efficient in terms of time. Many research works are still in process of finding a method that gives an efficient solution that can work for small problems as well as for large problems.

1.2 Literature review:

Power flow analysis came into existence in the early 20th century. There were many research works done on the power flow analysis. In the beginning, the main aim of the power-flow analysis was to find the solution irrespective of time. Over the last 20 years, efforts have been expended in the research and development on the numerical techniques.

Before the invention of digital computers, the load flow solutions were obtained using the network analysis. In the year 1956 the first practical automatic digital solution was found. The early generation computers were built with less memory storage, the Y-Bus matrix iterative method was well suitable for these computers. Although performance was satisfactory on many power flow problems, the time taken to convergence was very slow and sometimes they never converged [1].

In order to overcome the difficulties of this method a new method was developed based on the Z-Bus matrix. This new method converges more reliably compared to the Y-Bus matrix method, but it requires more memory storage when solving large problems. During this time, the iterative methods were showing very powerful convergence properties but were difficult in terms of computation [8]. In the mid 1960's major changes in the power system came with the development of very efficient sparsity programmed ordered elimination by Tinny [1].

1.3 Numerical Methods:

The concept of Power Flow problem was introduced by Carpentier in 1962. The power system equations are non-linear in nature, Carpentier formulated a non-linear programming technique to study the economic dispatch of the system [26].

The goal of power Flow is to minimize the total cost of meeting the load demand for the power system while maintaining the security of the system. The developments in computer technology helped in developing efficient algorithms for Power Flow solutions. Numerous different mathematical techniques have been employed for solving the Power Flow problems.

Some of the existing methods used for solving Power Flow problem are Gauss method, Gauss-Seidel method, Newton-Raphson method and Fast Decoupled Power Flow method. The methods are briefly described in the following paragraphs:

1) Gauss method: This is an iterative method used in the calculation of power flow analysis. This method was named after the German mathematician Carl Friedrich Gauss and Philipp Ludwig von Seidel. It is also known as Liebmann method or the method of successive displacement. In this method an initial value of voltage is guessed and a new value for the voltage is calculated for each bus. In this method the new voltage value obtained at the other bus cannot be used for the calculation of voltage at another bus until the iteration is completed. This disadvantage is one of the disadvantages of Gauss method.

2) Gauss-Seidel method: This method is based on the Gauss method. In this method an initial value of voltage is guessed and the newly calculated value replaces the initial value and the iteration is stopped when the solution converges. But later this method was limited for only small problems because of the complexity in the calculations [9].

3) Newton-Raphson method: This is the most effective iterative method used in the present day power flow analysis. It was named after Isaac Newton and Joseph Raphson. In this method the convergence is reliable and guaranteed. If the assumed value is near the solution then

the result is obtained very quickly, but if the assumed value is farther away from the solution then the method may take longer to converge [9].

4) Fast Decoupled Power Flow method: The Fast Decoupled Power Flow Method (FDPFM) is one of the improved methods, which is based on a simplification of the Newton-Raphson method and reported by Stott and Alsac in 1974 [7]. This method, like the Newton-Raphson method, offers calculation simplifications, fast convergence and reliable results and became a widely used method in load flow analysis. However, FDPFM for some cases, where high resistance-to-reactance(R/X) ratios or heavy loading (low voltage) at some buses are present, does not converge well. For these cases, many efforts and developments have been made to overcome these convergence obstacles. Some of them targeted the convergence of systems with high R/X ratios, and others with low voltage buses [28]. The FDPFM method has the disadvantage of not yielding the accurate solution.

Though many efforts and elaborations have been achieved in order to improve the power flow methods, these methods can still attract many researchers, especially when computers and simulations are becoming more developed and are now able to handle and analyze large-sized system.

Today, with processor's speed being higher than 3 GHz, any improvement in the speed of convergence of the power flow methods, provided it leads to reliable results, is of great value. This speed improvement is very important when involved in operational stages of power distribution, where any millisecond saving can hugely increase the probability of the right decision of the control and dispatch computerized system [29].

1.4 Scope of Work:

Power flow analysis became a fundamental and important tool in the power systems these days. Before the development of the power flow analysis on the digital computers, the power flow was done based on network analysis. The network analysis is a time consuming method and the convergence is not guaranteed. The backdrops of this method led for the development of powerful computer methods. With the advancement in the fields of digital computer technologies these power flow methods gained more importance and the solutions achieved convergence very quickly.

The goal of this research is to develop a load flow algorithm that uses multiple numerical methods so that the convergence time is lesser than using each traditional method alone. Combining the benefits of different methods by switching among the methods during a single run of load flow calculation has been proved possible in this work and resulted in the improved run time taken to converge to a solution.

To achieve the goal, the following tasks have been performed.

1. Review the numerical techniques for load flow analysis

2. Develop the mathematical model to adaptively use multiple numerical techniques

3. Develop software program implementing the mathematical model

4. Test the algorithms with the IEEE 39-bus system

5. Develop the IEEE 39-bus system in PowerWorld as a benchmark for the load flow solutions

6. Compare the convergence time of the switching technique with that of traditional methods and adjust the approach accordingly

1.5 Overview:

The power flow algorithm written in this thesis is based on the Gauss-Seidel method and Newton-Raphson method. A software program has been developed. The program gives the power flow solution for a given problem as well as computes the complete voltage angle and magnitude information for each bus in a power system for specified load and generator real power and voltage conditions.

The remainder of this thesis is organized as follows. Chapter 2 of this thesis will discuss the Gauss method, Gauss-Seidel method and Newton-Raphson method. It will also discuss the application of each method in the power system. Chapter 3 will discuss the switching technique used in developing the program for the power flow analysis. It will also discuss the input files and the other terms used in developing the program in Matlab. Chapter 4 will give a detailed explanation of the test system developed in PowerWorld. The test system developed in this thesis is IEEE-39 bus system. The topics in this chapter include generators, loads, transmission lines, transformers, and buses etc. used in building the IEEE-39 bus system. Chapter 5 will discuss the test results of the proposed switching algorithm which is based on the traditional methods, tested on the IEEE-39 bus system and compare the results with each traditional method when used by itself. Chapter 6 will conclude this thesis and also discuss the future works.

Chapter 2

Application of numerical techniques to Power Flow Calculation

2.1 Numerical Techniques for Power Flow Analysis:

Power flow analysis is an evaluation process for operation and planning to determine the steady-state condition of a power system given a condition of the system. Power flow analysis is based on a large-scale nonlinear set of equations that require iterative techniques to obtain their solution. There are a number of traditional iterative techniques to solve large non-linear equations. The major methods used in the Power Systems are:

1) Gauss method

2) Gauss-Seidel method

3) Newton-Raphson method

2.1.1 Gauss method:

Gauss method is one of the oldest of the iterative techniques that is still in use in some areas. Gauss iterative method has its own advantages and disadvantages. This technique is simple and easy to compute. The time taken for the method to converge to a solution is generally more compared to other iterative methods.

Consider a system of n linear equations with x unknowns:

$$Ax = b \tag{2.1}$$

where:

$$A = \begin{bmatrix} a_{11} & a_{12} & .. & a_{1n} \\ a_{21} & a_{22} & .. & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & .. & a_{nn} \end{bmatrix}, \quad x = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}, \quad \text{and } b = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_n \end{bmatrix}$$

The Gauss–Seidel method is an iterative technique that solves the left hand side of this expression (2.1) for **x**, using assumed value for **x** on the right hand side. Analytically, this may be written as:

$$x_i^{k+1} = \frac{1}{a_{ii}} \left(b_i - \sum_{\substack{i=1 \\ i \neq j}}^{n} a_{ij} x_j^k \right) \tag{2.2}$$

where k is the iteration number

The computation of $x_i^{(k+1)}$ requires each element in $x^{(k)}$ except $x_i^{(k)}$ itself. The procedure is generally continued until the changes made by iteration are within some tolerance.

2.1.2 Gauss-Seidel method:

This is a simple iterative technique based on gauss method that was popular in the early days of digital computer. The more powerful N-R method is however used these days.

The gauss seidel iterative technique is still used for small power systems where program simplicity is more important than computing costs, and in many cases it is used in large scale systems to obtain an initial solution for the continuation of Newton-Raphson method [13].

All the calculations done in gauss seidel method are same as the gauss method except in the equation (2.2) the value of x calculated at one equation immediately replaces the x calculated form previous iteration. Equation (2.2) changes to:

$$x_i^{k+1} = \frac{1}{a_{ii}} \left(b_i - \sum_{\substack{i=1 \\ i \neq j}}^{n} a_{ij} x_j^{k+1} \right) \tag{2.3}$$

2.1.3 Newton-Raphson method:

The Gauss-Seidel method is very simple but convergence becomes increasingly slow as the system size grows. The Newton-Raphson technique converges fast in less than 4-5 iterations regardless of system size. This technique is mainly useful for large-sized system with thousands of buses [13, 16].

Consider a function $f(x) = 0$, and its derivative $f'(x)$, we begin with a first guess x_0. Provided the function is reasonably well-behaved a better approximation x_1 is

$$x_1 = x_0 - \frac{f(x_0)}{f'(x_0)} \tag{2.4}$$

Geometrically, x_1 is the intersection point of the tangent line to the graph of f, with the x-axis. The process is repeated until a sufficiently accurate value is reached:

$$x_{k+1} = x_k - \frac{f(x_k)}{f'(x_k)} \tag{2.5}$$

2.2 Bus Classification:

In a power system each bus or node is associated with four quantities, real and reactive powers, bus voltage magnitude and phase angle. In a load flow solution two out of the four quantities are specified and the remaining two are required to be obtained through the solution of the equations. Depending upon which quantities have been specified, the buses are classified into three categories. They are:

1) Generator bus or PV bus:

At this bus the voltage magnitude corresponding to the generation voltage and real power P_G corresponding to its ratings are specified. It is required to find out the reactive power generation Q_G and the phase angle of the bus voltage.

2) Load bus or PQ bus:

Here the real and the reactive components or power are specified. It is desired to find out the voltage magnitude and the phase angle through the load flow solution. It is required to specify P_D and Q_D at such a bus at a load bus voltage can be allowed to vary within the permissible values.

3) Slack bus or reference bus:

In a power system there are mainly two types of buses, load and generator buses. For these buses we have specified the real power P injections. Now $\sum_{i=1}^{n} P_i$ = real power loss P_L where P_i is the power injections at the buses, which is taken as positive for generator buses and is negative for load buses. The losses remain unknown until the load flow solution is complete. It is for this reason that generally one of the generator buses is made to take the additional real and reactive power to supply transmission losses. That is why this type of bus is also known as the slack bus or reference bus. At this bus, the voltage magnitude V and the phase angle δ are specified, whereas real power and reactive power P_G and Q_G are obtained through the load flow solution. The table 2.1 includes a summary of:

Type of Bus	Known Quantities	Quantities to be specified
Generator bus	P, Q	$\|V\|$, δ
Load bus	P, $\|V\|$	Q, δ
Slack bus	$\|V\|$, δ	P, Q

Table 2.1 Bus Classification

The phase angle of the voltage at the slack bus is usually taken as the reference. In the following analysis the real and reactive components of voltage at a bus are taken as the independent variables for the load flow equations i.e.

$$V_i \angle \delta_i = e_i + jf_i \qquad (2.6)$$

where e_i and f_i are the real and reactive components of voltage at the ith bus. There are various other formulations wherein either voltage or current or both are taken as the independent variables. The load flow equations can be formulated using either the loop or bus frame of reference. However, from the viewpoint of computer time and memory, the nodal admittance formulation, using the nodal voltage as the independent variables is the most economic.

2.3 Formation of Y Bus Admittance matrix:

Power system analysis, like load flow studies, short circuit studies, and transient stability studies, has become very convenient with the advent of digital computers. More and more complex systems can now be handled by suitable mathematical models, constituting an ordered collection of system parameters in the form of matrices. These models depend on the selection of independent variables. When the voltages are selected as independent variables, the

corresponding currents are dependent and the matrix relating the voltages to the currents is then in the admittance form. When these voltages and currents are referred to the buses (independent nodes), the reference is the bus frame, and the resulting equations are usual independent nodal equations. The voltages and currents, when referred to independent loops, are related by the admittance matrix in the loop frame of reference. When the currents are treated as independent variables, the matrices are impedance matrices in the respective frames of reference.

It is seen from the study of the literature that these bus admittance and impedance matrices, as well as loop admittance and impedances, have been widely used for various power system calculations. There are traditional methods of forming these matrices for a given system, which require various connection or incidence matrices. Algorithms for forming the bus impedance matrix and its dual, the loop admittance matrix, have been developed and are widely used in various system studies [14]. Fig 2.1 clearly explains the formation of Nodal Admittance matrix. The load flow equations, using nodal admittance formulation for a three-bus system are developed first and then they are generalized for an n-bus system.

Fig 2.1 3-bus system

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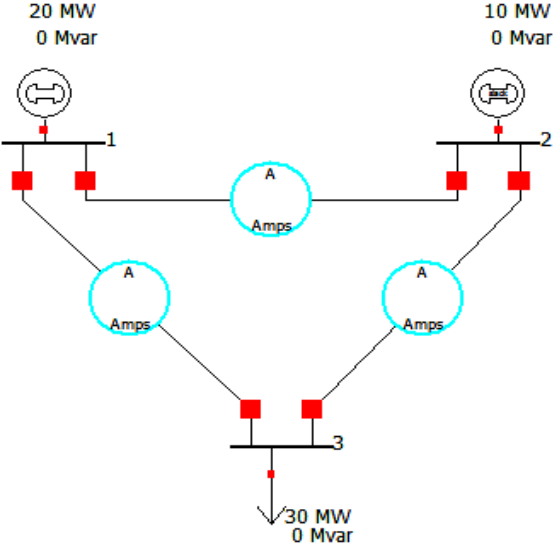
At node 1:

$$I_1 = I_{11} + I_{12} + I_{13}$$

$$= V_1 y_{11} + (V_1 - V_2) y_{12} + (V_1 - V_3) y_{13}$$

$$= V_1 (y_{11} + y_{12} + y_{13}) - V_2 y_{12} - V_3 y_{13}$$

$$I_1 = V_1 Y_{11} + V_2 Y_{12} + V_3 Y_{13} \tag{2.7}$$

Y_{11} is the diagonal element and Y_{12}, Y_{13} are the off diagonal elements, and these can be calculated

using

$$Y_{ij} = \sum_{i=1, i \neq j}^{n} \frac{1}{r_{ij} + jx_{ij}} \quad \text{for off diagonal elements} \tag{2.8}$$

$$Y_{ii} = \sum_{i=1, i \neq j}^{n} Y_{ij} \quad \text{for on diagonal elements} \tag{2.9}$$

where in this case y11 is the shunt charging admittance at bus 1 and

$$Y_{11} = y_{11} + y_{12} + y_{13}$$

$$Y_{12} = -y_{12}$$

$$Y_{13} = -y_{13}$$

Similarly nodal current equations for the other nodes can be written as follows

$$I_2 = V_1 Y_{21} + V_2 Y_{22} + V_3 Y_{23} \tag{2.10}$$

$$I_3 = V_1 Y_{31} + V_2 Y_{32} + V_3 Y_{33} \tag{2.11}$$

These equations can be written in a matrix form as:

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{21} & Y_{22} & Y_{23} \\ Y_{31} & Y_{32} & Y_{33} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \tag{2.12}$$

or in a compact form equation (2.12) can be written as:

$$I_i = \sum_{j=1}^{3} Y_{ij} V_j \quad , p = 1 \text{ to } 3 \tag{2.13}$$

From this we now write nodal current equation for n bus system where each node is connected

to all other nodes.

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j \quad , p = 1, 2\ldots n \tag{2.14}$$

Equation 2.14 can be represented in matrix form as

$$
\begin{bmatrix} I_1 \\ I_2 \\ : \\ I_n \end{bmatrix}
=
\begin{bmatrix}
Y_{11} & Y_{12} & \ldots & Y_{1n} \\
Y_{21} & Y_{22} & \ldots & Y_{2n} \\
: & : & \ldots & : \\
Y_{n1} & Y_{n2} & \ldots & Y_{nn}
\end{bmatrix}
\begin{bmatrix} V_1 \\ V_2 \\ : \\ V_n \end{bmatrix}
\tag{2.15}
$$

It can be observed that the nodal admittance matrix is a sparse matrix (a few number of elements

are non-zero) for an actual power system. Consider Fig.2.2
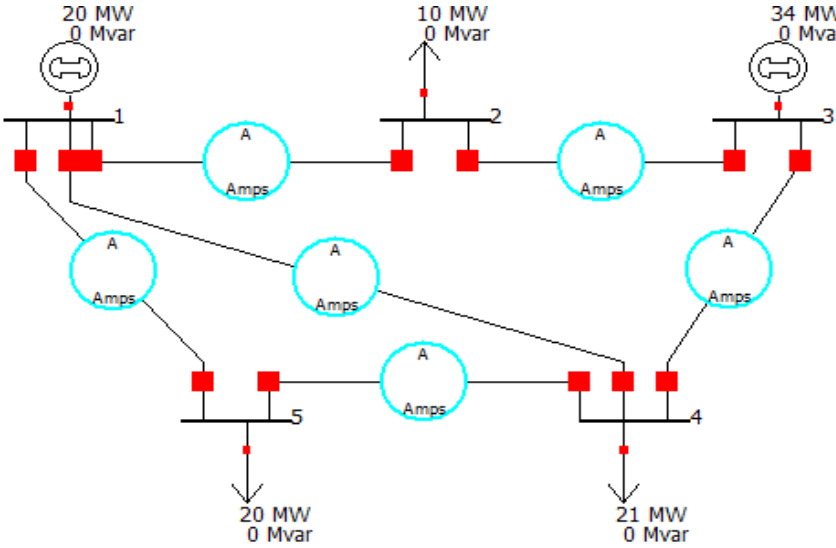
Fig 2.2 5-bus system

The nodal admittance matrix for system in Fig 2.2 is as follows:

$$Y_{bus} = \begin{bmatrix} Y_{11} & Y_{12} & 0 & Y_{14} & Y_{15} \\ Y_{21} & Y_{22} & Y_{23} & 0 & 0 \\ 0 & Y_{32} & Y_{33} & Y_{34} & 0 \\ Y_{41} & 0 & Y_{43} & Y_{44} & Y_{45} \\ Y_{51} & 0 & 0 & Y_{54} & Y_{55} \end{bmatrix} \tag{2.16}$$

It can be observed that out of 25 elements, eight elements are zero whereas 17 are non-zero. In a large system of 100 nodes, these non-zero elements may be as small as 2% of the total elements. This is where we see that the computer memory requirement for storing the nodal admittance matrix is very low. It need store only a very few non-zero elements, it need not stare the zeros of the matrix. Again the nodal admittance being a symmetric matrix along the leading diagonal, the computer need store the upper triangular nodal admittance matrix only. Thus, the computer memory requirement for storing the nodal admittance is all the more reduced.

If the interconnection between the various nodes for a given system and the admittance value for each interconnecting circuit are known, the admittance matrix may be assembled as follows:

a) The diagonal element of each node is the sum of the admittances connected to it.

b) The off-diagonal element is the negative admittance between the nodes.

However, it can be seen that the sum of the elements in each columns of the admittance matrix summates to zero which means that nodal admittance matrix is a singular matrix and hence the rows of the matrix are linearly dependent.

We have already justified the necessity of selecting one of the buses as the slack or reference bus based on power balance in the system. Based on the admittance matrix approach, it can be said mathematically that one of the buses should be taken as slack; otherwise the nodal matrix is

singular and cannot be handled. By taking one of the buses as reference, corresponding row and column are deleted from the nodal admittance matrix and hence the reduced matrix becomes non-singular, which can be handled very easily.

2.4 Formation of Power Flow Equations:

The power flow problem is the computation of voltage magnitude and phase angle at each bus in a power system under system steady conditions. As a by-product of this calculation, real and reactive power are calculated, as well as equipment losses, can be computed [30]. The input data for the power flow consists of bus data, transmission line data, and transformer data .

The first step in a power flow is the calculation of bus admittance matrix Y bus, the Y bus can be constructed from the transmission line and transformer input data (Formulation of Y bus admittance matrix is explained in section 2.3).

Using Y bus, we can write nodal equation for a power system network as:

$$I \;=\; Y_{bus}V$$

(2.17)

where I is the n column vector of source currents injected into each bus and V is the n column vector of bus voltages. For bus k, the kth equation in (2.17) is:

$$I_i = \sum_{j=1}^{n} Y_{ij}V_j$$

(2.18)

The complex power delivered to bus k is

$$S_i = P_i + jQ_i = V_i I_i^*$$

(2.19)

Power flow equations by Gauss and Gauss-Seidel are based on nodal equations (2.18), where each current source I_k is calculated from (2.19). Using (2.18) in (2.19)

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$$S_i = P_i + jQ_i = V_i \left[\sum_{j=1}^{n} Y_{ij} V_j \right]^* \tag{2.20}$$

i = 1, 2, 3……..n

(2.20) can be rewritten in polar form as

$$P_i + jQ_i = V_k \sum_{j=1}^{n} Y_{ij} V_j e^{j(\delta_i - \delta_j - \theta_{ij})} \tag{2.21}$$

Taking the real and imaginary parts of (2.21), power balance equations can be written as

$$P_i = V_i \sum_{j=1}^{n} Y_{ij} V_j \cos(\delta_i - \delta_j - \theta_{ij}) \tag{2.22}$$

$$Q_i = V_i \sum_{j=1}^{n} Y_{ij} V_j \sin(\delta_i - \delta_j - \theta_{ij}) \tag{2.23}$$

or when the Y_{ki} is expressed in rectangular coordinates

$$P_i = V_i \sum_{j=1}^{n} V_j [G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j)] \tag{2.24}$$

$$Q_i = V_i \sum_{j=1}^{n} V_j [G_{ij} \sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j)] \tag{2.25}$$

where
$$G_{ij} = |Y_{ij}| \cos(\theta_{ij}) \tag{2.26}$$

$$B_{ij} = |Y_{ij}| \sin(\theta_{ij}) \tag{2.27}$$

2.5 Algorithms for Power Flow methods:

Gauss-Seidel method is an iterative method for solving a set of non-linear equations. This method starts with an assumption of a set of solution vector. In this method the new calculated voltage value immediately replaces the present value and is used in the solution of the

subsequent equations. This process is repeated for all the other variables for the completion of current iteration. If the solution is converged to a certain tolerance value then the iteration is stopped else the iteration process is repeated till convergence is achieved. This method is more dependent on the initially assumed values.

The general load flow equation of the Gauss method is:

$$V_i = \frac{1}{Y_{ii}}\left(\frac{S_i^*}{V_i^*} - \sum_{\substack{j=1 \\ j \neq i}}^{n} Y_{ij} V_j\right)$$
(2.28)

where v is the iteration number

Equation (2.28) can be rewritten in a new form to update the value of V_i^k with new calculated voltage V_i^{k+1} :

$$V_i^{k+1} = \frac{1}{Y_{ii}}\left(\frac{P_i - jQ_i^k}{(V_i^k)^*} - \sum_{\substack{j=1 \\ j \neq i}}^{n} Y_{ij} V_j^k\right)$$
(2.29)

In Equation (2.29) the value of the reactive power Q_i for a generator bus is unknown and can be calculated from the equation (2.25). As a general start the initial voltage magnitude $/Vi/$ and the phase angle δ_i can be initialized to 1pu and 0 degrees. In doing so, there are total of (n-1) load flow equations for n buses as the voltage magnitude and the phase angle for the slack bus are already specified and the remaining unknown's real power P_i and the reactive power Q_i can be calculated from the power flow equations (2.24) and equation (2.25).

The value of the reactive power calculated at the generator bus has to be checked if this value violates the reactive power generation at that bus (if it is less than the minimum reactive

power generation or more than the maximum reactive power generation).If it violates the reactive power generation limits than the bus time will be switched to load bus for that iteration. If Q_i is less than $Q_{\min}$ then it will be set to $Q_{\min}$ or if Q_i is more than $Q_{\max}$ then it will be set to $Q_{\max}$. If the reactive power is within the limits, it is substituted in the equation for the calculation of the voltage magnitude.

2.5.1 Algorithm for Gauss method:

Gauss Method is done by the following steps:

    Step 1: Form the nodal admittance matrix (Y_{ij}).

    Step 2: Choose a tolerance value ε.

    Step 3: Assume the initial voltage values to be 1pu and 0degree except for the slack bus.

    Step 4: Start iteration for bus $i=1$ with count 0.

    Step 5: Check for the slack bus if for i=slack bus or PV bus update the value of Q_i using equation (2.25).

    Step 6: Calculate the new bus voltage V_i from the load flow equation (2.27).

    Step 7: Find the difference in the voltages

$$\Delta V_i^{k+1} = V_i^{k+1} - V_i^k$$

    Step 8: Go for the next bus and repeat the steps 5 to 7 until a new set of values V_i^{k+1} of bus voltages are obtained for all the buses.

    Step 9: Continue the iteration from 5 to 9 until the value of ΔV_i^k at all the buses is within the chosen tolerance value

$$\Delta V_i^{k+1} < \varepsilon$$

where k gives the number of iterations.

The algorithm for gauss method is depicted in Figure 2.3.

2.5.2 Algorithm for Gauss-Seidel (GS) Method:

Gauss-Seidel Method is done by the following steps:

Step 1: Form the nodal admittance matrix (Y_{ij}).

Step 2: Choose a tolerance value ε .

Step 3: Assume the initial voltage values to be 1pu and 0degree except for the slack bus.

Step 4: Start iteration for bus $i =1$ with count 0.

Step 5: Check for the slack bus if for i=slack bus or PV bus update the value of Q_i using

equation (2.25).

Step 6: Calculate the new bus voltage V_i from the load flow equation (2.27).

Step 7: Find the difference in the voltages

$$\Delta V_i^{k+1} = V_i^{k+1} - V_i^k$$

Step 8: The new calculated value of the bus voltage is updated in the old bus voltage

value and is used for the calculations at the next bus.

Step 9: Go for the next bus and repeat the steps 5 to 7 until a new set of values of bus

voltages are obtained for all the buses.

Step 10: Continue the iteration from 5 to 9 until the value of ΔV_i^k at all the buses is

within the chosen tolerance value

$$\Delta V_i^{k+1} < \varepsilon$$

where k gives the number of iterations.

The algorithm for Gauss-Seidel method is presented as a diagram in Figure 2.4.

2.5.3 Algorithm for Newton-Raphson (NR) method:

Power flow solutions by Newton-Raphson are based on the nonlinear power-flow equations given by (2.24) and (2.25).

Equations (2.24) and (2.25) are analogous to the nonlinear equation of the form $y = f(x)$, we define x, y and f are vectors for the power flow problem as

Let the composite vector of δ and |V| is $x = \begin{bmatrix} \delta \\ |V| \end{bmatrix}$

$$\delta = \begin{bmatrix} \delta_2 \\ \delta_3 \\ : \\ : \\ \delta n \end{bmatrix} \quad \text{and} \quad |V| = \begin{bmatrix} |V_2| \\ |V_3| \\ : \\ : \\ |Vn| \end{bmatrix}$$

and
$$y = \begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} P_2 \\ : \\ P_n \\ Q_2 \\ : \\ Q_n \end{bmatrix} \tag{2.30}$$

$$f(x) = y = \begin{bmatrix} P(x) \\ Q(x) \end{bmatrix} \tag{2.31}$$

where all *V, P* and *Q* terms are in per-unit and δ terms are in radians. The slack bus variables are omitted from (2.28), since they are already known.

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Newton-Raphson method is a complex calculation involving derivative of real power and

reactive power with respect to V and δ. Jacobian matrix is the matrix formed out of the

derivatives of power with V and δ and is indicated by J, where

$$J = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \qquad (2.32)$$

Where $J_{11} = \dfrac{\partial P_i(x)}{\partial \delta_j}$

$J_{12} = \dfrac{\partial P_i(x)}{\partial |V_j|}$

$J_{21} = \dfrac{\partial Q_i(x)}{\partial \delta_j}$

$J_{22} = \dfrac{\partial Q_i(x)}{\partial |V_j|}$ i = 1, 2, 3... n and j = 1, 2, 3... n

The iterative process for Newton-Raphson method:

$$J^k \Delta x^k = -f(x^k) \qquad (2.33)$$

$$\Delta P(x) = \begin{bmatrix} P_2 - P_2(x) \\ : \\ P_n - P_n(x) \end{bmatrix} \qquad (2.34)$$

$$\Delta Q(x) = \begin{bmatrix} Q_2 - Q_2(x) \\ : \\ Q_n - Q_n(x) \end{bmatrix} \qquad (2.35)$$

$\Delta P(x)$ and $\Delta Q(x)$ are the mismatch vectors then equation (2.33) can be expressed as

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$$f(x) = - \begin{bmatrix} \Delta P(x) \\ \Delta Q(x) \end{bmatrix} \tag{2.36}$$

It is well known that a small change in phase angle changes the flow of active power and does not affect much the flow of reactive power. Similarly a small change in nodal voltage affects the flow of reactive power whereas active power practically does not change. Keeping these facts in mind and using the polar coordinates, the set of linear load flow equations can be written in matrix form as follows:

$$\begin{bmatrix} J_{11}^k & J_{12}^k \\ J_{21}^k & J_{22}^k \end{bmatrix} \begin{bmatrix} \Delta \delta^k \\ \Delta |V|^k \end{bmatrix} = \begin{bmatrix} \Delta P(x^k) \\ \Delta Q(x^k) \end{bmatrix} \tag{2.37}$$

Here J_{11} correspond to the elements $\dfrac{\partial P_i(x)}{\partial \delta_j}$ which exist and are not zero in most cases.

J_{12} and J_{21} corresponds to the elements $\dfrac{\partial P_i(x)}{\partial |V_j|}$ and $\dfrac{\partial Q_i(x)}{\partial \delta_j}$ respectively which does not exist and, therefore, are zero.

J_{22} corresponds to the elements $\dfrac{\partial Q_i(x)}{\partial |V_j|}$ which exist and are not zero.

To find x^{k+1}, equation (2.37) is solved for Δx^k and use equation (2.38). At this point the mismatch vector and the Jacobian matrix are updated and the iteration is continued.

$$x^{k+1} = x^k + \Delta x^k \tag{2.38}$$

Steps to perform Newton-Raphson method:

Step 1: Form the nodal admittance matrix (Y_{ij}).

Step 2: Assume an initial set of bus voltage and set bus n as the reference bus.

Step 3: Calculate the real Power P_i using the equation (2.24).

Step 4: Calculate the reactive Power Q_i using the equation (2.25).

Step 5: Form the Jacobian matrix.

Step 6: Find the power differences ΔP_i and ΔQ_i for all the $i=$1, 2, 3… (n-1).

Step 7: Choose the tolerance values.

Step 8: Stop the iteration if all ΔP_i and ΔQ_i are within the tolerance values.

Step 9: Substitute the values obtained in step 4 and step 5 in the equation (2.30), and then

find the vectors $\Delta\theta$ and $\dfrac{\Delta|V_i|}{|V_i|}$

Step 10: Update the values $|V_i|$ and θ_i for all i , using $x^{k+1} = x^k + \Delta x^k$

Step 11: Repeat the steps from 3.

The algorithm for Newton-Raphson method is shown in Figure 2.5.
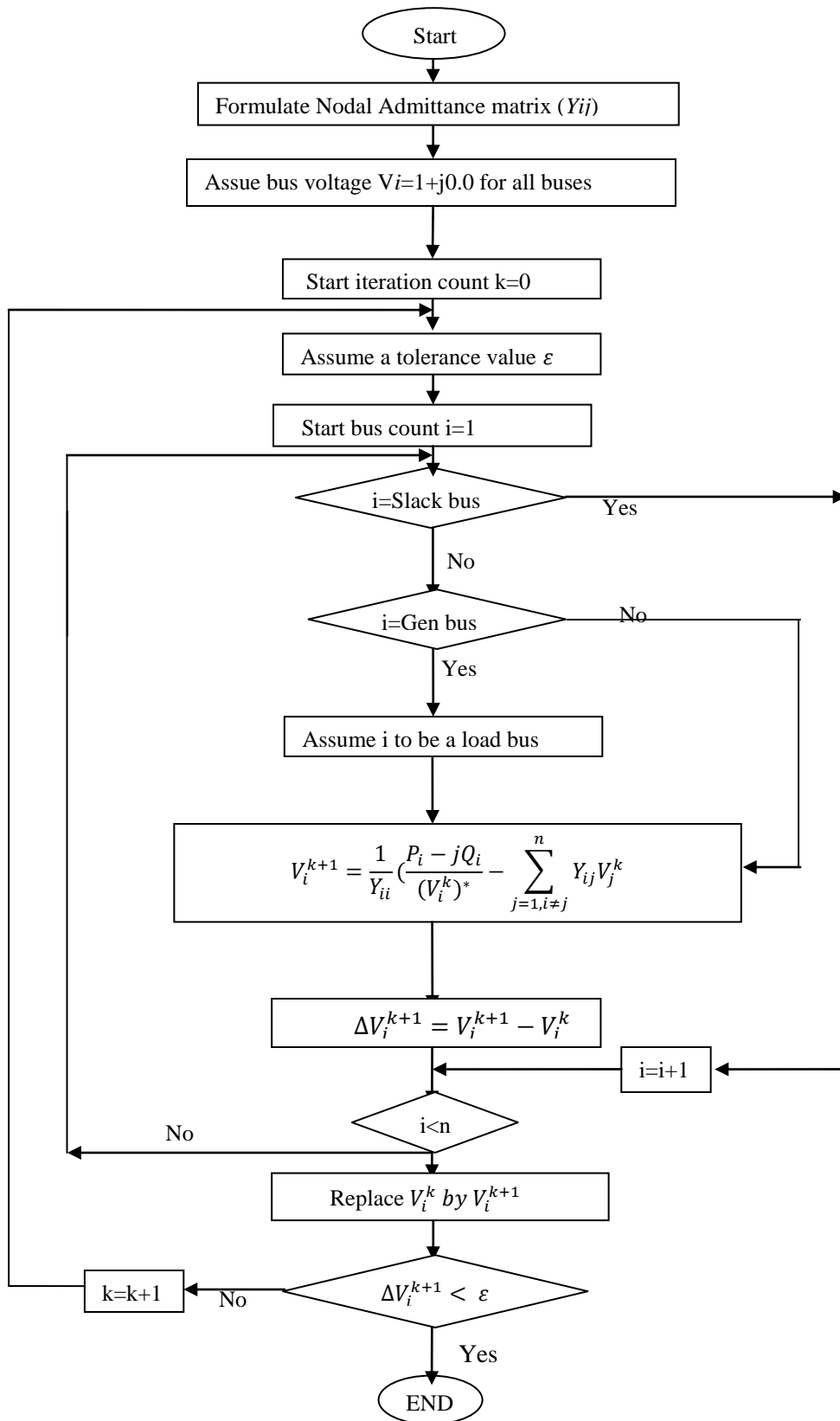
Fig 2.3 Flow Chart for load flow solution using Gauss method (load bus only)

Start

Formulate Nodal Admittance matrix (*Yij*)

Assue bus voltage V*i*=1+j0.0 for all buses

Start iteration count k=0

Assume a tolerance value ε

Start bus count i=1

i=Slack bus — Yes

No

i=Gen bus — No

Yes

Assume i to be a load bus

$$V_i^{k+1} = \frac{1}{Y_{ii}}(\frac{P_i - jQ_i}{(V_i^k)^*} - \sum_{j=1,i\neq j}^{n} Y_{ij}V_j^k$$

$$\Delta V_i^{k+1} = V_i^{k+1} - V_i^k$$

i=i+1

i<n

No

Replace V_i^k by V_i^{k+1}

$\Delta V_i^{k+1} < \varepsilon$

k=k+1 — No

Yes

END

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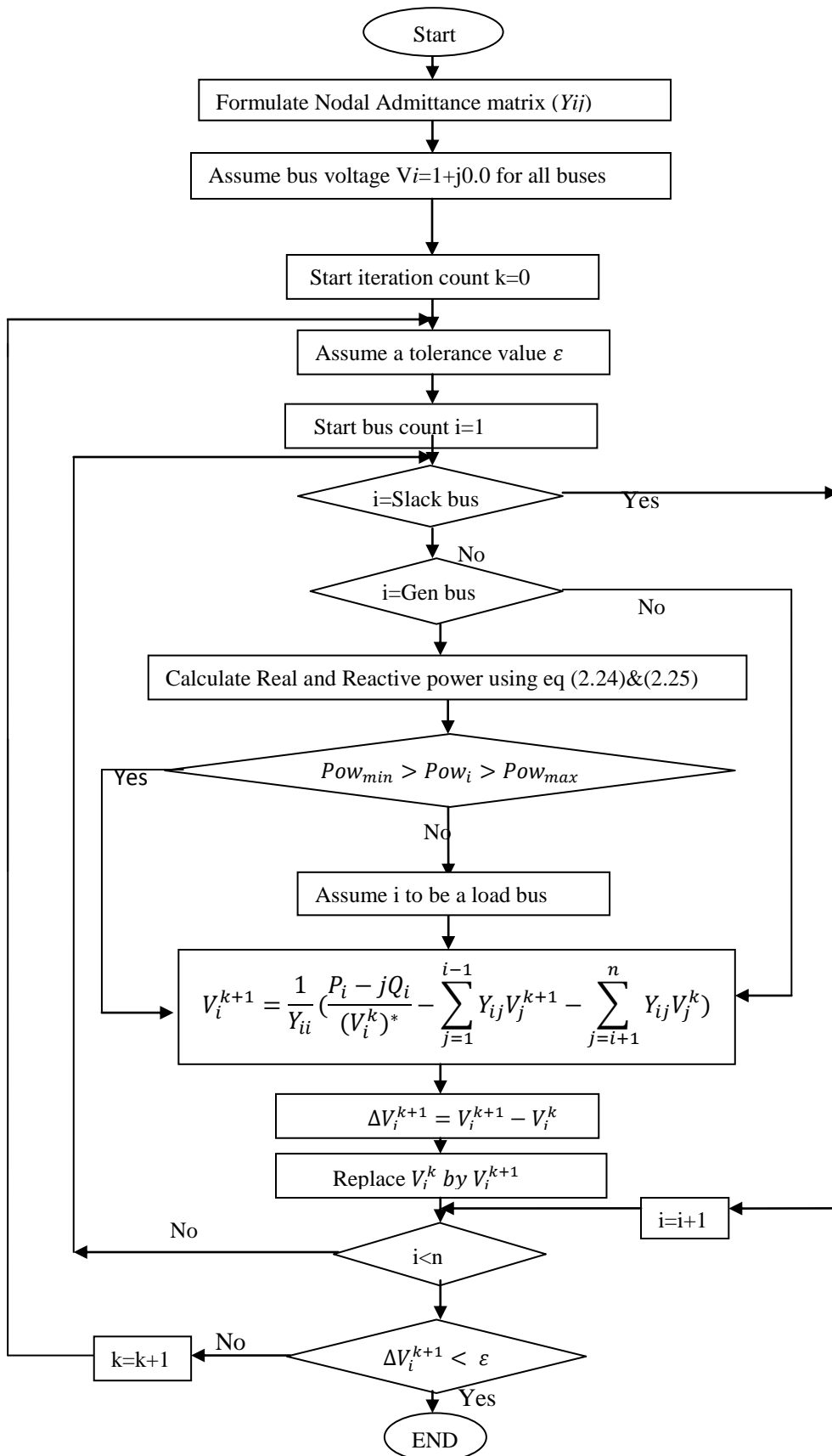
Fig 2.4 Flow Chart for load flow solution using Gauss-Seidel method

```
                              ┌──────────┐
                              │  Start   │
                              └────┬─────┘
                                   │
              ┌────────────────────┴────────────────────┐
              │ Formulate Nodal Admittance matrix (Yij)  │
              └────────────────────┬────────────────────┘
                                   │
              ┌────────────────────┴────────────────────┐
              │ Assume bus voltage Vi=1+j0.0 for all buses│
              └────────────────────┬────────────────────┘
                                   │
                       ┌───────────┴───────────┐
                       │ Start iteration count k=0│
                       └───────────┬───────────┘
                                   │
                       ┌───────────┴───────────┐
                       │ Assume a tolerance value ε│
                       └───────────┬───────────┘
```

Start iteration count k=0

Assume a tolerance value ε

Start bus count i=1

i=Slack bus   No ————————   Yes

Calculate Pi and Qi using equation (2.24) and (2.25)

Evaluate $\Delta P_i^k = P_i^{k+1} - P_i^k$

i=Gen bus   No   Yes

Evaluate $\Delta Q_i^k = Q_i^{k+1} - Q_i^k$

Evaluate $|\Delta V_i|.^2 = |\Delta V_{is}|.^2 - |V_n|.^2$

i = i+1

If i > n

Calculate the voltage magnitude |Vi| and phase angle δ_i

if ΔP_i^k and ΔQ_i^k are within the tolerance   Yes   END

No

Update the value of |Vi| and δ_i using
$$x^{k+1} = x^k + \Delta x^k$$

Fig 2.5 Flow Chart for load flow solution using Newton-Raphson method

2.6 Concept of Big O Notation:

Big O notation is used to describe the performance or complexity of an algorithm. Big O specifically describes the **worst-case** scenario, and can be used to describe the execution time required or the space used (e.g. in memory or on disk) by an algorithm [9]. Big O notation characterizes functions according to their growth rates: different functions with the same growth rate may be represented using the same O notation.

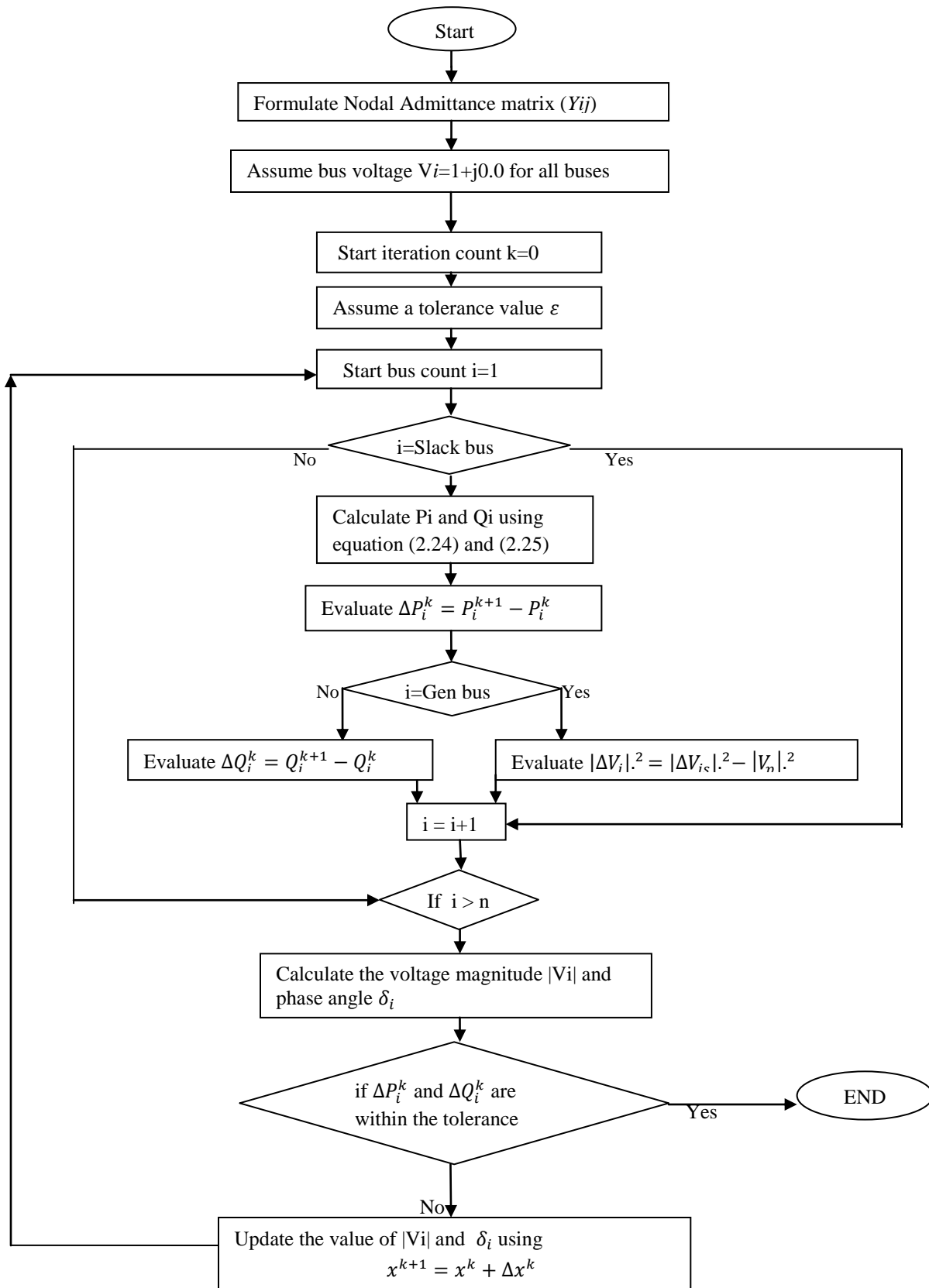Although developed as a part of pure mathematics, this notation is now frequently also used in the analysis of algorithms to describe an algorithm's usage of computational resources: the worst case or average case running time or memory usage of an algorithm is often expressed as a function of the length of its input using big O notation. This allows predicting the behavior of their algorithms and to determine which of multiple algorithms to use, in a way that is independent of computer architecture or clock rate. Because Big O notation discards multiplicative constants on the running time, and ignores efficiency for low input sizes, it does not always reveal the fastest algorithm in practice or for practically-sized data sets, but the approach is still very effective for comparing the scalability of various algorithms as input sizes become large [9].

The worst case scenario will give the maximum run time. Any improvement in the worst case to make it an average case or best case will result in improved run time. As a part of literature review Big O notation was used to study the order and the behavior of the traditional methods. The order of Gauss method and Gauss-Seidel method is same as they have the same algorithm except the Gauss method do not replace the calculated values in the same iteration and this algorithm does not involve any complex calculations. The order of Newton-Raphson method

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is high compared to Gauss methods, as it involves the calculation of Jacobian matrix which is an n by n matrix of all first-order partial derivatives of a vector- or scalar-valued function with respect to another vector. From the order of the method it is clear that the average run time and algorithm complexity of Newton-Raphson method is high. This makes the Gauss methods advantageous over Newton-Raphson method for small system which converges in less number of iterations. Hence, it can be observed that the method to be used to run a power flow solution also depends on the size of the system.

Chapter 3

Power Flow Calculation

This chapter discusses the development of the new algorithm, development of the program to implement the used algorithm.

3.1 Switching technique:

While performing the power flow it is often necessary to obtain an accurate result with less convergence time. For a small system as can be observed from the results for 3-bus and 5-bus systems the convergence time is not very high, in this case any of the traditional method can be used to find the power flow. For a large-size system where the convergence time is high the selection of best method plays a vital role.

The switching technique is performed using two traditional methods to perform the load flow problem. The first step is to produce a good initial condition for the second method and the second step is to generate an accurate solution.

The switching method can be done in any of the following order

1) Start with Newton-Raphson method and then switch to gauss method
2) Start with Newton-Raphson method and then switch to gauss-seidel method
3) Start with gauss method and then switch to Newton-Raphson method
4) Start with gauss-seidel method and then switch to Newton-Raphson method

Selection of the switching order differs from one system to another depending on the size of the system. It is expected that switching between two methods yields a faster convergence time compared to running a power flow on one traditional method.

The first method starts with an assumed initial values and a least tolerance value. When the solution is within the tolerance value the load flow is stopped for the first method and switched to second method. The results thus obtained from the first method are taken as the initial values for the second method. The second method starts with these initial values and a good tolerance values. The load flow is run until the solution converges with the second method.

Small System:

For a small system the selection of traditional methods can be in the order of Gauss method, Gauss-Seidel method and Newton-Raphson method. The selection is mainly based on the average convergence time and total convergence time. It is expected that the number of iterations for this system is less and so is the total convergence time. In this case the method with less average convergence time is expected to give better convergence time than high average iteration time method. The average iteration time of Gauss and Gauss-Seidel method is less compared to the Newton-Raphson method. Moreover the total convergence time using Gauss and Gauss-Seidel method is almost less than or equal to the time taken to complete one iteration of Newton-Raphson method. In this case switching from one method to another does not yield any advantage over the traditional method. The 3-bus and 5-bus test systems are used to test the switching order.

Large System:

For a large system the selection of traditional methods can be in the order of Newton-Raphson method, Gauss-Seidel method and Gauss method. The selection is mainly based on the average convergence time and total convergence time. It is expected that the number of iteration for this system are large and so is the total convergence time. In this case the method with less number of iteration gives better convergence time than large number of iterations.

For a large system the first method is either Gauss method or Gauss-Seidel method and the last method will be Newton-Raphson method. As Newton-Raphson converges faster than Gauss and Gauss-Seidel method it is desired to follow this order. Taking into account the total number of iterations, the system achieves convergence in relatively less number of iterations. Typically the first method should run 0.1 tolerance value and then switched to another method till an accurate solution is achieved with 0.001 tolerance value. IEEE 39-bus test system is used to test the switching order.

3.2 Development of software to implement the new switching algorithm:

Power flow solution yields valuable information regarding a power system, the implementation of the numerical techniques in a power system simulation environment holds even greater promise. In this environment, simulation of a system over time can be done while maintaining it at its optimal condition. In this section all the programming technique, with the input format, initial condition and the importance of the tolerance value are explained.

3.2.1 Input Files:

The input files for this program to execute are the transmission line data, transformer details, generators, loads.

The transmission line data will have matrix five columns. The first two columns (from bus & to bus) will give the details of the buses which are connected with the transmission lines. Third column is for the resistance of the respective transmission line connected to the buses in column 1 and 2. Fourth column has the reactance of the transmission line and the fifth column has the susceptance of the transmission line. All the parameters of the transmission line are taken in p.u. The transformer details are similar as transmission line except the transformer input matrix will have only four columns, it does not have the susceptance column.

The generator input is a matrix with five columns and as many number of rows as the generators. The first column will have the details of the bus number to which the generator is connected. The second column is to specify the generator number, this column is of no importance while the time of execution but is used to generate a detailed output format. The third column specifies the rated voltage of the generator in kv. The fourth column gives the p.u voltage value of the generator. The fifth column is to specify the active power of the generator before the execution. The load input is almost similar to the generator matrix with additional reactive power details.

3.2.2 Initial Condition:

All the iterative methods are more or less sensitive to initial assumed values. For a load flow solution to run the initial values are to be assumed with a good knowledge of the system

properties and its behavior to the initial values. The closer the initial assumed value to the solution the faster is the convergence achieved and vice versa. In this load flow programs the initial values are the magnitude of the voltage at the bus and the angle at bus.

The voltage magnitude at the generator buses are specified in the input generator matrix, they are to be maintained fixed throughout the load flow run while finding the optimal solution. For buses other than the generator buses the unknown values the voltage magnitude and the angle are assumed before running the load flow solution.

Typically, the voltage magnitude and angle are specified 1.0 p.u and 0 degree respectively. Once the initial values are assumed then the load flow is run to obtain an optimal solution. During the load flow run these initial values are replace with the values that are close to the solution and as the final result an optimal values of the voltage magnitude and angle is obtained.

3.2.3 Tolerance:

Tolerance value is an important factor that determines the accuracy of the solution. Typically, most of the programmers take 0.001 as the tolerance value. If tolerance value is chosen less than 0.001 the solution converges in less time and less iteration. For a higher tolerance value convergence time and iteration number is high. But, as the tolerance value increases the accuracy of the solution increases. At certain value of tolerance the solution attains an optimal value which does not change even if the tolerance is increased beyond this value.

Total Convergence time:

Convergence time is a measure of how fast a power flow reaches the state of convergence. Total convergence time is the total time elapsed after the system is converged. It is one of the main goals of an algorithm to implement a mechanism that allows all the conditions and inputs to quickly and reliably converge. Of course, the size of the network also plays an important role; a larger network will converge slower than a small one.

Certain loads and generator conditions will prevent a power flow from ever converging and lead to a blackout situation. For instance, if the total load of the system is much higher than the maximum generating capacity of all generators, this might cause a system blackout and never converge for the current. Under certain circumstances it might even be desired to change the inputs or the assumed initial conditions to force the system to converge.

Average convergence time:

In numerical analysis, the speed at which a convergent sequence approaches its limit is called the rate of convergence or average convergence time. Although strictly speaking, a limit does not give information about any finite first part of the sequence, this concept is of practical importance if we deal with a sequence of successive approximations for an iterative method, as then typically fewer iterations are needed to yield a useful approximation if the rate of convergence is higher. This may even make the difference between needing ten or a million iterations [29].

Average convergence time or average iteration time is the time elapsed for an iteration to complete. It can be calculated by taking the average of total convergence time by the total number of iteration.

Chapter 4

IEEE 39 bus Test System

4.1 IEEE-39 bus system details:

The IEEE-39 bus system is built in PowerWorld and is used to find the power flow using the following methods

1) Gauss method

2) Gauss-Seidel method

3) Newton-Raphson method

and the time taken to get the solution in these methods is calculated.

The details of the IEEE-39 bus system are [15]:

Number of buses – 39

Number of generators – 10

Number of loads – 19

Number of transmission lines – 34

Number of transformers – 12

The buses with generators connected to it are called the generators buses or PV buses.

The buses with loads connected to it are called the load buses or PQ buses.

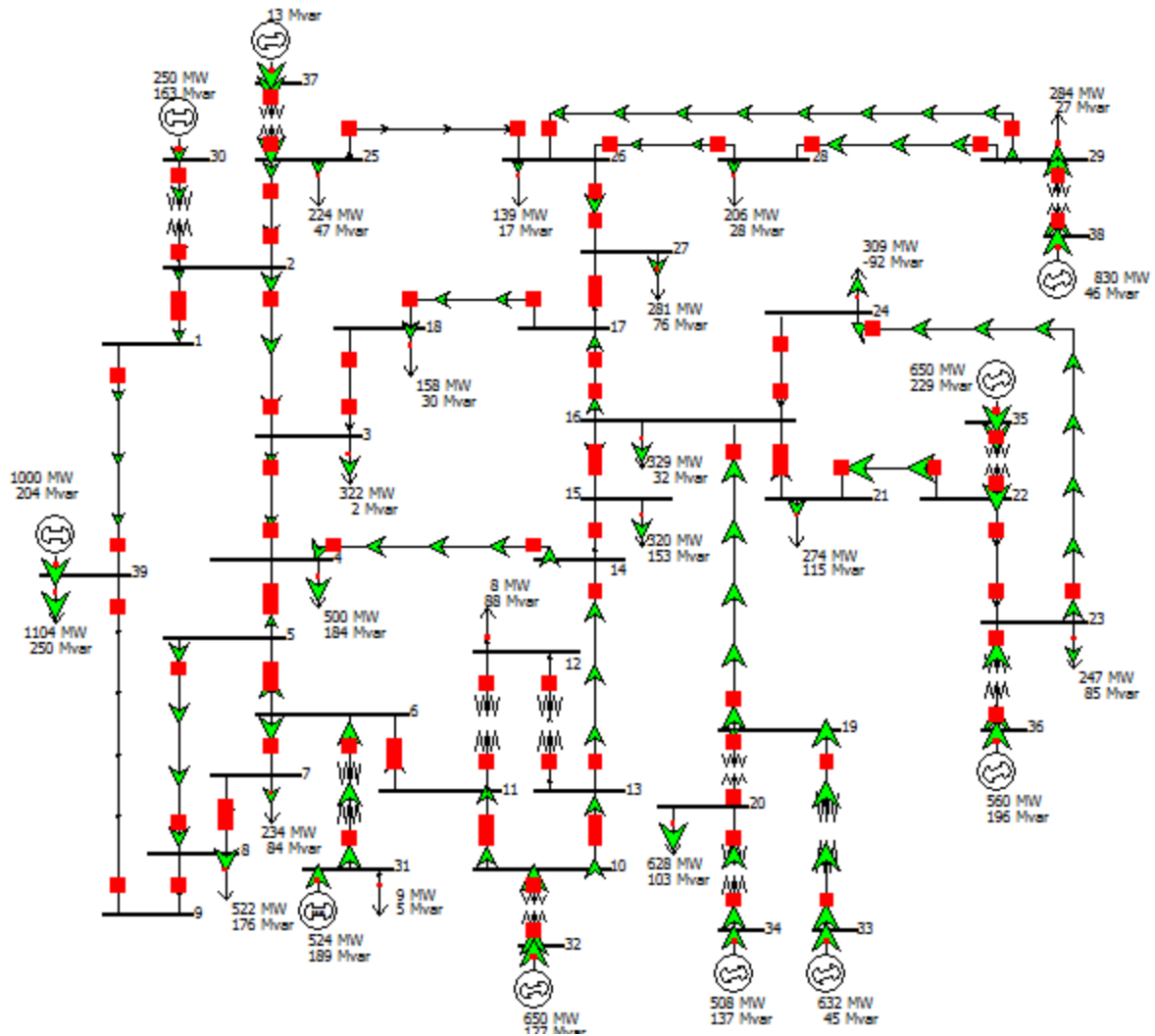For this system Bus 1 is chosen as the slack bus.

Fig 4.1 PowerWorld Representation of IEEE 39 bus system Model

4.2 Transmission Lines:

As stated in section 4.1 the IEEE-39 bus system has 34 transmission lines. The transmission lines are used to connect the various buses. Each transmission line is of different length depending on how far the two buses are located, and each transmission line has its own resistance, impedance and suceptance. But for this particular thesis work the length of the transmission line is not of much concern.

The details of all the transmission lines with its resistance, impedance and suceptance and the connection from which bus to other bus are listed in the table 4.1.

Transmission Line data:

From Bus	To Bus	Resistance(p.u)	Reactance(p.u)	Suceptance(p.u)
1	2	0.0035	0.0411	0.6987
1	39	0.001	0.025	0.75
2	3	0.0013	0.0151	0.2572
2	25	0.007	0.0086	0.146
3	4	0.0013	0.0213	0.2214
3	18	0.0011	0.0133	0.2138
4	5	0.0008	0.0128	0.1342
4	14	0.0008	0.0129	0.1382
5	6	0.0002	0.0026	0.0434
5	8	0.0008	0.0112	0.1476
6	7	0.0006	0.0092	0.113

Table 4.1 Transmission line data

From Bus	To Bus	Resistance(p.u)	Reactance(p.u)	Suceptance(p.u)
6	11	0.0007	0.0082	0.1389
7	8	0.0004	0.0046	0.078
8	9	0.0023	0.0363	0.3804
9	39	0.001	0.025	1.2
10	11	0.0004	0.0043	0.0729
10	13	0.0004	0.0043	0.0729
13	14	0.0009	0.0101	0.1723
14	15	0.0018	0.0217	0.366
15	16	0.0009	0.0094	0.171
16	17	0.0007	0.0089	0.1342
16	19	0.0016	0.0195	0.304
16	21	0.0008	0.0135	0.2548
16	24	0.0003	0.0059	0.068
17	18	0.0007	0.0082	0.1319
17	27	0.0013	0.0173	0.3216
21	22	0.0008	0.014	0.2565
22	23	0.0006	0.0096	0.1846
23	24	0.0022	0.035	0.361
25	26	0.0032	0.0323	0.513
26	27	0.0014	0.0147	0.2396
26	28	0.0043	0.0474	0.7802
26	29	0.0057	0.0625	1.029
28	29	0.0014	0.0151	0.249

Table 4.1 Transmission line data

4.3 Transformers:

The model is built with 12 transformers connected at various buses. Those details consist of R_T (Resistance) and X_T (Reactance) which are equivalent resistance and reactance referred with respect to primary or secondary. For this system assume those values are with respect to primary winding of the transformer.

All the values in above table are in per unit. For this system transformer at generators primary winding is delta lag with rated voltage of 20KV. Secondary winding is star grounded with rated voltage of 345KV. All the remaining transformers are grounded stat-star with both the windings rated at 345KV. Transformer details are given in the table 4.2.

Transformer details:

From Bus	To Bus	Resistance	Reactance
30	2	0.0000	0.0181
37	25	0.0006	0.0232
31	6	0.0000	0.0250
32	10	0.0000	0.0200
11	12	0.0016	0.0435
13	12	0.0016	0.0435
34	20	0.0009	0.0180
20	19	0.0007	0.0138
33	19	0.0007	0.0142
36	23	0.0005	0.0272
35	22	0.0000	0.0143
38	29	0.0008	0.0156

Table 4.2 Transformer details

4.4 Generator Buses:

The IEEE-39 bus system has total of 10 generators. The buses for which generators are connected to it are called the generator buses or PV-buses. For all the generator buses the value of the real power P (MW) and the magnitude of the voltage are known and the unknown values are the reactive power Q (MVAr) and angle of the voltage. The generator buses in this case are from the bus 30 to 39.

The detail information of all the generators with their respective bus numbers are listed in the table 4.3.

Generators Details:

Bus Number	Generator ID	Rated Voltage (kv)	Voltage (p.u)	Active power (p.u)
31	10	20	1.0475	2.50
1	2	20	0.9820	Slack Generator
32	3	20	0.9831	6.50
33	4	20	0.9972	6.32
34	5	20	1.0123	5.08
35	6	20	1.0493	6.50
36	7	20	1.0635	5.60
37	8	20	1.0278	5.40
38	9	20	1.0265	8.30
39	1	345	1.0300	10.0

Table 4.3 Generators

4.5 Load Buses:

The IEEE -39 bus system has total 19 loads connected to it. The buses for which loads are connected to it are called the load bus or PQ-bus. For all the generator buses the value of the Complex Power-real Power P (MW) and reactive power Q (MVar) are known at this buses.

The detail information of all the loads with their respective bus numbers are listed in the Table 4.4.

Loads Details:

Bus Number	Rated Voltage (kv)	Load (MW)	Load (MVAr)
4	345	322	2.40
5	345	500	184
8	345	233.8	84.0
9	345	522	176.0
13	345	7.5	88.0
16	345	320	153.0
17	345	329	32.3
19	345	158	30.0
21	345	628	103.0
22	345	274	115.0
24	345	247.5	84.6
25	345	308.6	-92.2
26	345	224	47.2
27	345	139	17.0
28	345	281	75.5
29	345	206	27.6
31	345	283.5	26.9
1	20	9.2	4.6
39	345	1104	250

Table 4.4 Loads

Chapter 5

Test Results

The IEEE 39 bus system built in Chapter 4 was tested using the traditional methods and the switching method and best solution is determined. The details of the system are already explained in Chapter 4. The results from the Power World are used as the reference to verify the result using the traditional methods in matlab.

5.1 Result of the power flow run with all the parameters at each bus:

The final results of the IEEE 39 bus system are:

Bus Number	Voltage (p.u)	Angle (degree)	Real Power (MW)	Reactive Power (MVar)
1	0.982	0	524.674	237.2981
2	1.0152	-0.1542	0.0148	-0.001
3	0.9956	-0.0983	0.046	-0.0159
4	0.9572	-0.1528	-321.97	-2.4013
5	0.9234	-0.1778	-499.98	-184.0008
6	0.9282	-0.1574	0.0667	-0.0036
7	0.9312	-0.1439	0.0353	-0.002
8	0.9208	-0.1881	-233.77	-84.0013
9	0.9209	-0.1981	-522	-175.9994
10	0.9856	-0.1915	0.0086	-0.0004
11	0.9426	-0.0829	0.0865	-0.0065
12	0.9355	-0.1116	0.0207	-0.001
13	0.9232	-0.1106	-7.4862	-88.001
14	0.9407	-0.0852	0	0
15	0.9293	-0.1404	0	0

Table 5.1 Test Result of IEEE 39 bus test system

Bus Number	Voltage (p.u)	Angle (degree)	Real Power (MW)	Reactive Power (MVar)
16	0.9288	-0.1221	-319.975	-153
17	0.9501	-0.0945	-328.9	-32.308
18	0.9504	-0.1204	0.0413	-0.0032
19	0.9505	-0.1415	-158	-30
20	0.9745	0.0141	0.0384	-0.0035
21	0.9754	-0.0014	-627.966	-103
22	0.9702	0.0014	-273.972	-115
23	1.0017	0.0943	0.029	-0.0033
24	1.0168	0.2005	-247.489	-84.601
25	0.9546	-0.1149	-308.6	92.2008
26	1.0045	-0.0698	-223.981	-47.202
27	0.969	-0.0871	-138.974	-17.003
28	0.9516	-0.126	-281	-75.499
29	0.98	-0.0173	-205.983	-27.602
30	0.9928	0.036	-283.483	-26.902
31	1.0475	-0.0549	250.001	305.655
32	0.9831	0.0579	650.001	244.888
33	0.9972	0.1054	632.001	156.777
34	1.0123	0.0895	508.001	204.938
35	1.0493	0.1829	650.001	378.203
36	1.0635	0.3409	560.001	211.47
37	1.0278	0.0511	540	121.961
38	1.0265	0.1616	830.001	230.339
39	1.03	-0.1864	-103.999	250.567

Table 5.1 Test Result of IEEE 39 bus test system

Table 5.1 is the output generated from matlab which has the final results after the solution is converged. It has the details of Voltage magnitude and phase angle at each bus, Real Power and reactive power at each bus. The positive sign in the fourth and fifth column indicates the power delivered out or the power coming out at that bus and the negative sign indicates the power consumed or the power coming in at that bus. The solution using all the methods are observed and recorded. The system was tested using same initial condition and tolerance value for all the traditional methods and the results are compared.

5.2 Results of IEEE 39 bus system using different methods:

IEEE 39 bus test system	Gauss Method	Gauss-Seidel Method	Newton-Raphson Method	Switching Method GS followed by NR	Switching Method NR followed by GS	Switching Method Gauss followed by NR	Switching Method NR followed by Gauss
Initial voltage and phase angle	1 p.u and 0 degree	1 p.u and 0 degree	1 p.u and 0 degree	1 p.u and 0 degree	1 p.u and 0 degree	1 p.u and 0 degree	1 p.u and 0 degree
Assumed tolerance value	0.001	0.001	0.001	0.1 for GS 0.001 for NR	0.1 for NR 0.001 for GS	0.1 for Gauss 0.001 for NR	0.1 for NR 0.001 for Gauss
Number of Iterations	1253	171	60	56	111	216	1228
No. of Gauss Iterations	1253	0	0	0	0	155	1220
No. of Gauss-Seidel Iterations	0	171	0	25	103	0	0
No. of Newton-Raphson iterations	0	0	60	31	8	51	8
Convergence time (in seconds)	5.637	0.812	0.751	Total Time - 0.5977 GS – 0 .1178 Switch Time – 0.0046 NR - 0.4753	Total - 0.6166 NR - 0.1767 St - 0.0037 GS - 0.4362	Total - 1.5459 G - .6425 St - 0.0430 NR - 0.8614	Total - 5.2583 NR - 0.1761 St - 0.0037 G - 5.0785
Time taken for each iteration (average time in seconds)	0.0049	0.0047	0.0125	0.0103	0.0055	0.0071	0.0042
Maximum Mismatch	7.25	10.24	8.21	10.24	8.21	7.25	8.21

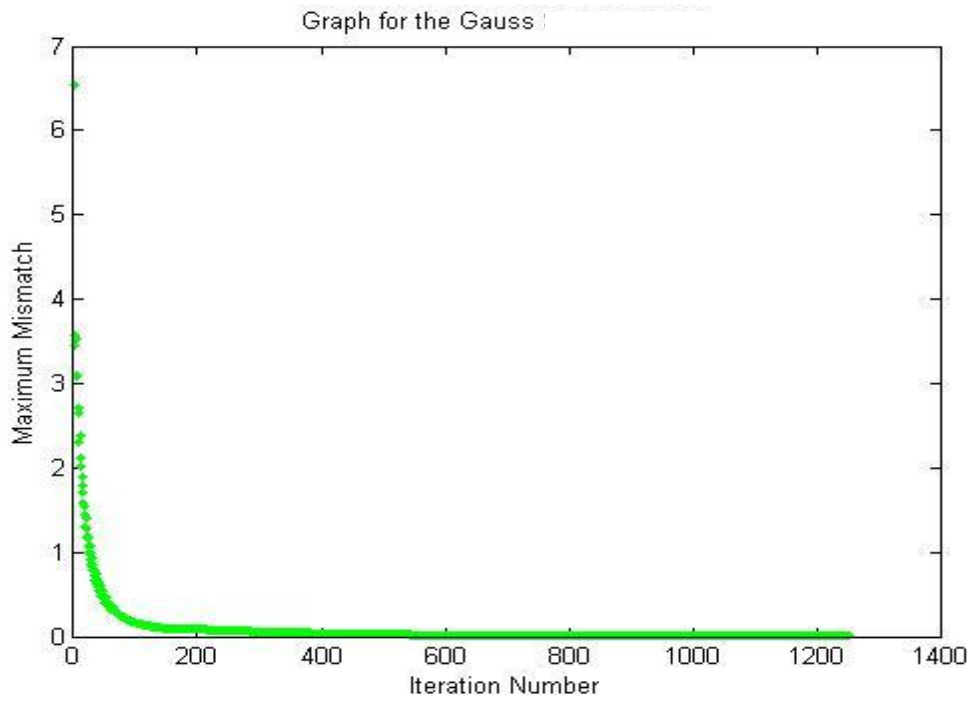Table 5.2 Comparative Results of IEEE 39 bus System

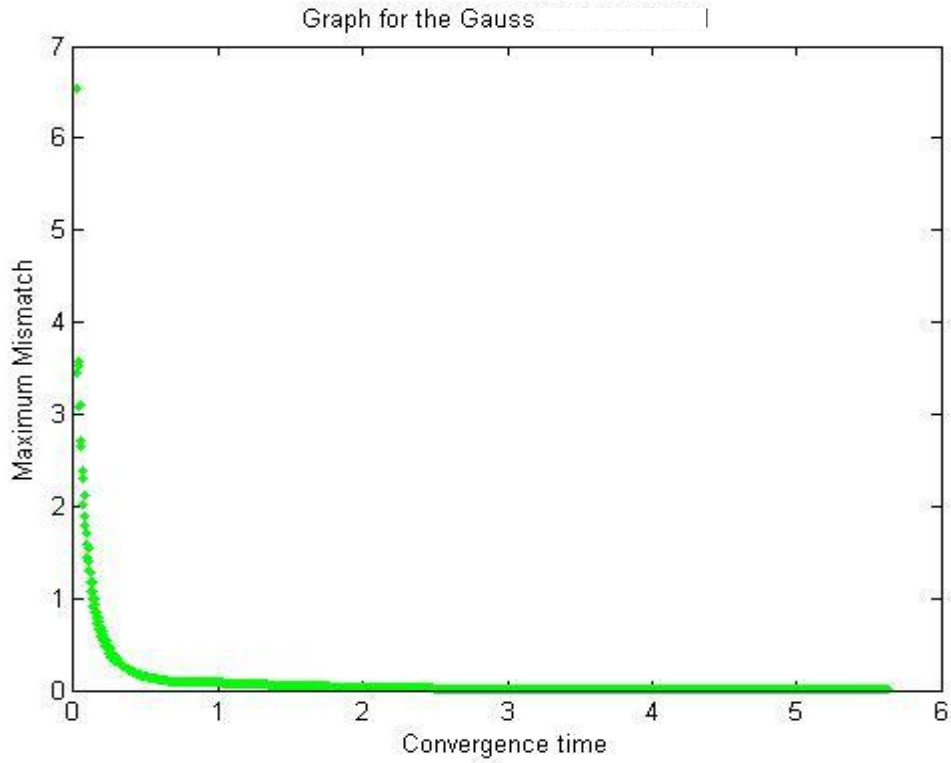Fig 5.1 Graph using the Gauss method for Max Mismatch vs Number of Iteration

Fig 5.2 Graph using the Gauss method for Max Mismatch vs Convergence time
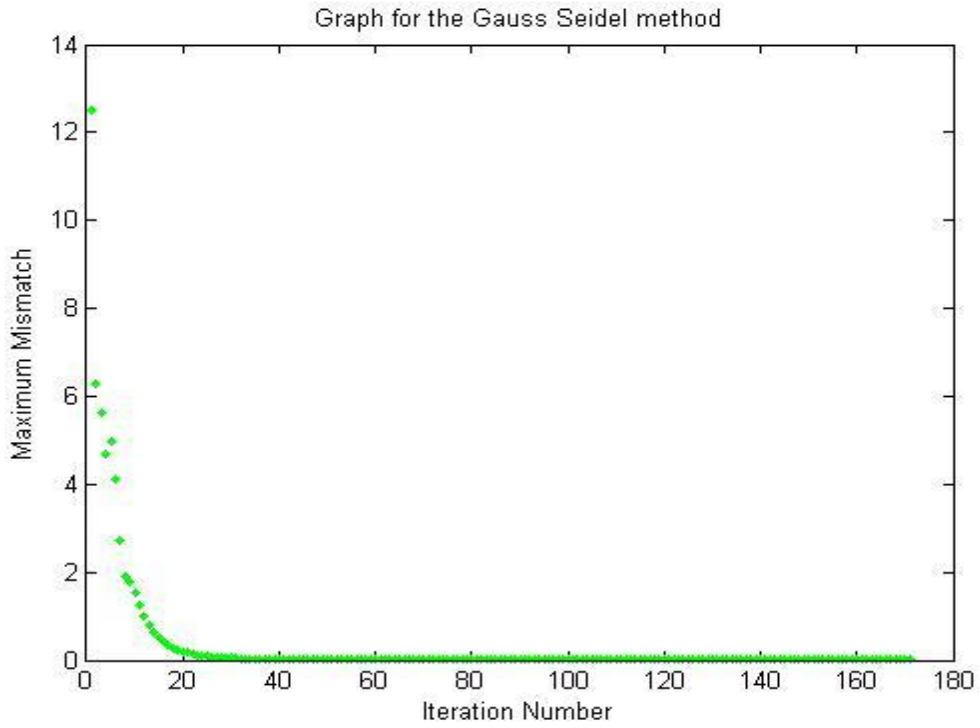
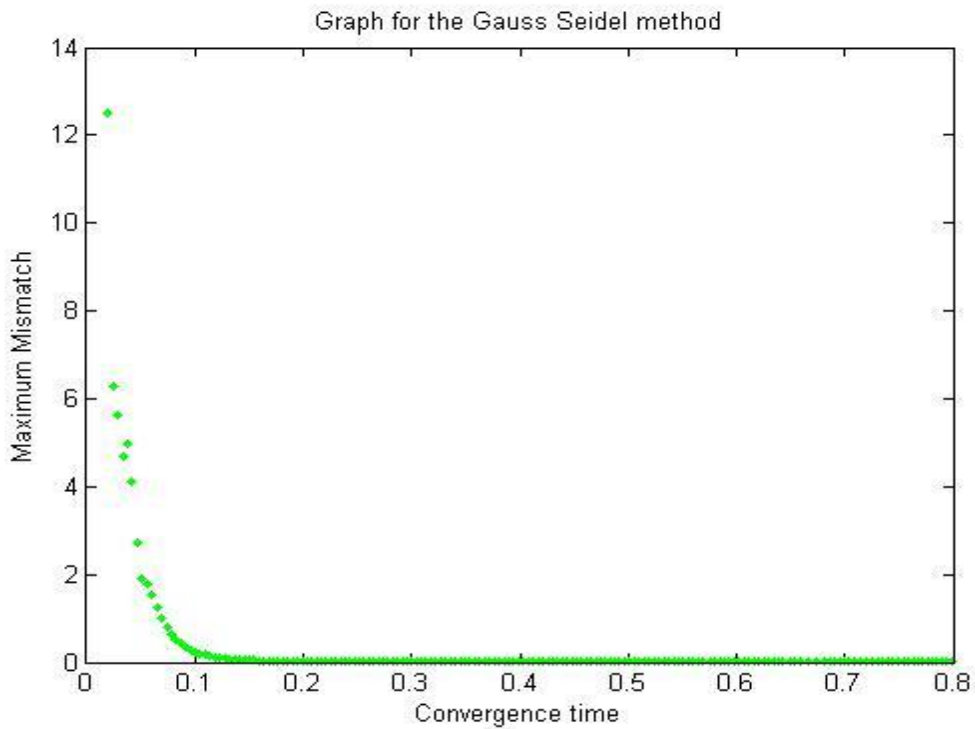Fig 5.3 Graph using Gauss-Seidel method for Max Mismatch vs Number of Iteration

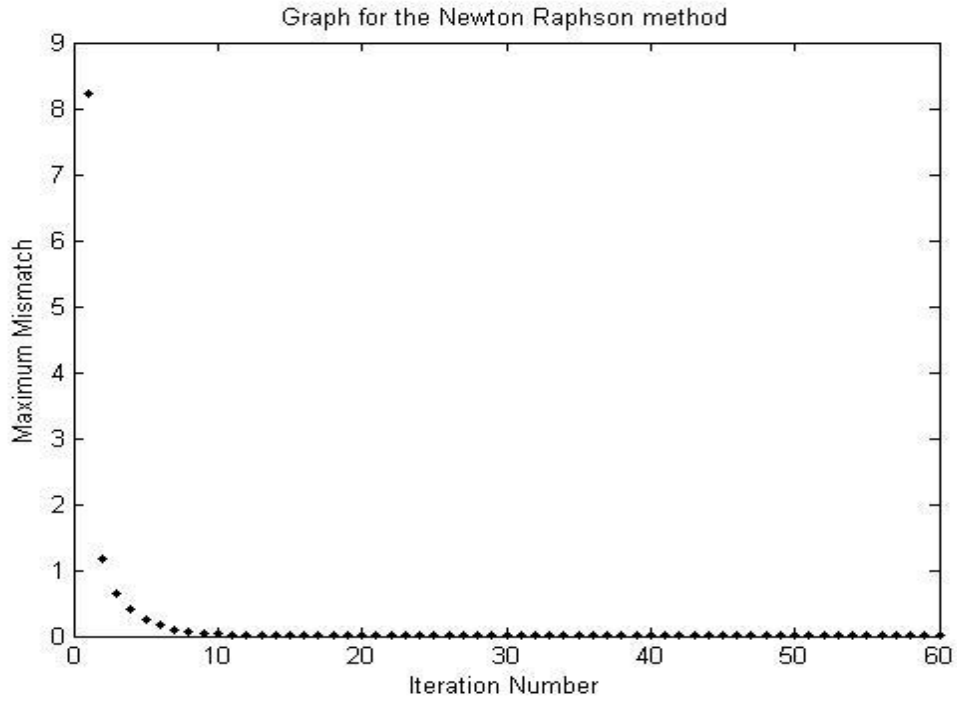Fig 5.4 Graph using Gauss-Seidel method for Max Mismatch vs Convergence time

Fig 5.5 Graph using Newton-Raphson method for Max Mismatch vs Number of Iterations
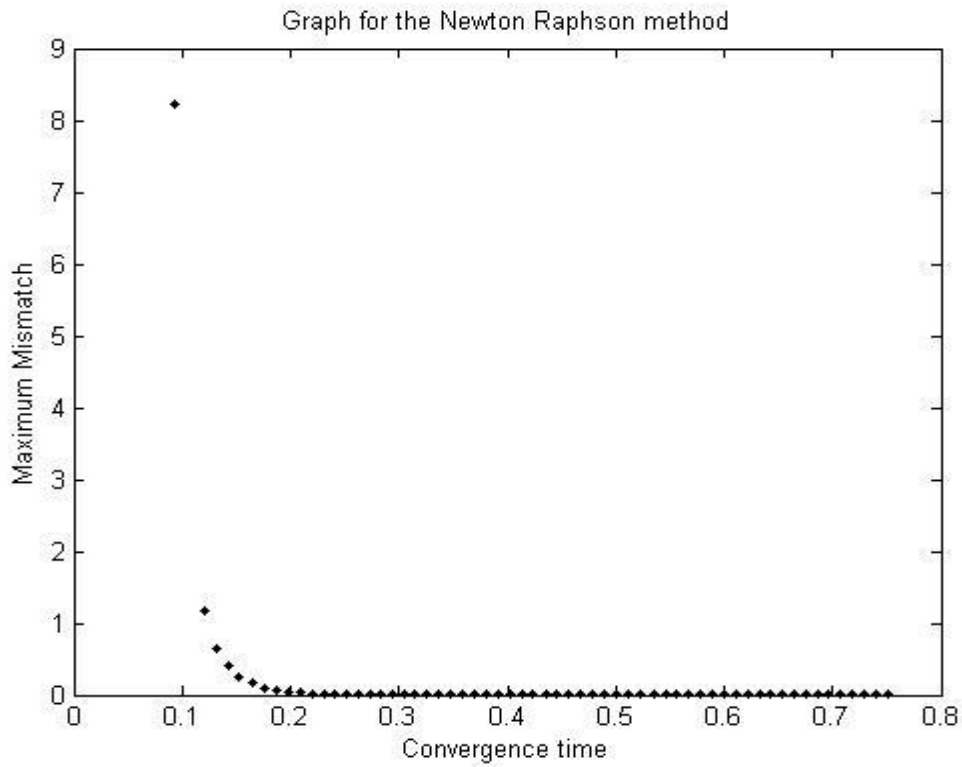

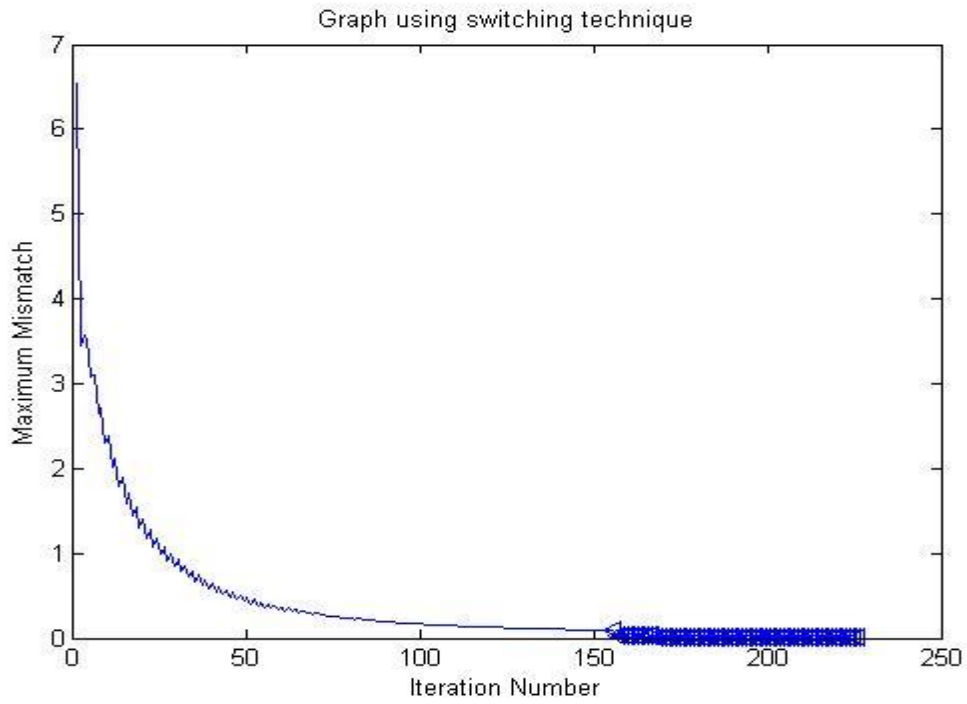Fig 5.6 Graph using Newton-Raphson method for Max Mismatch vs Convergence time

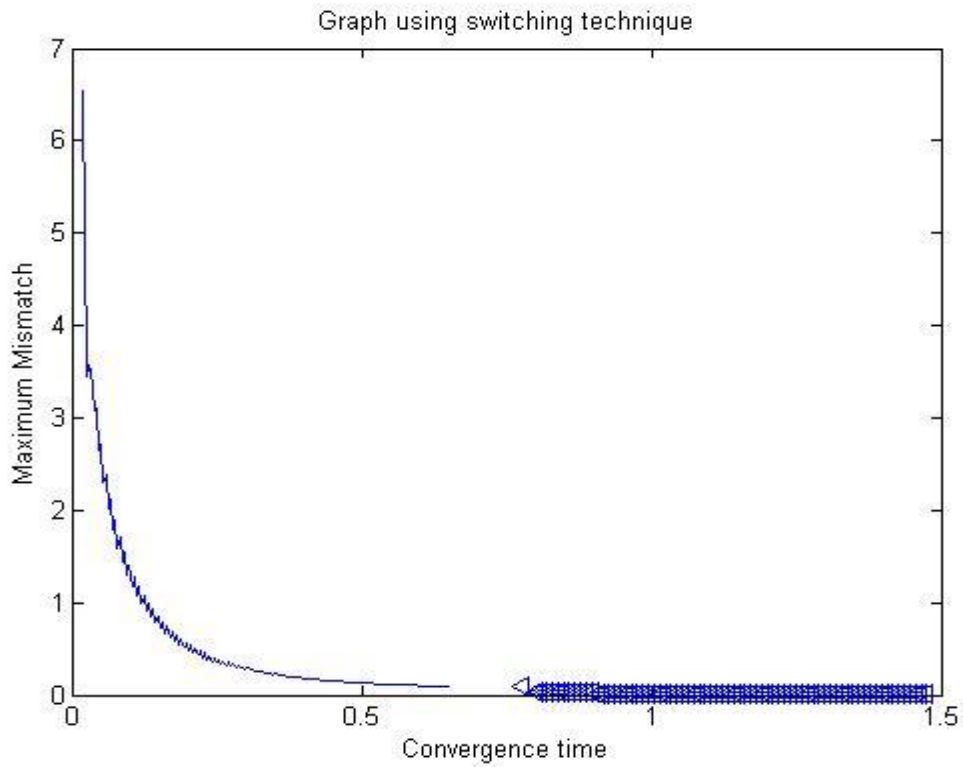Fig 5.7 Graph using NR and Gauss method (Max Mismatch vs Iteration Number)

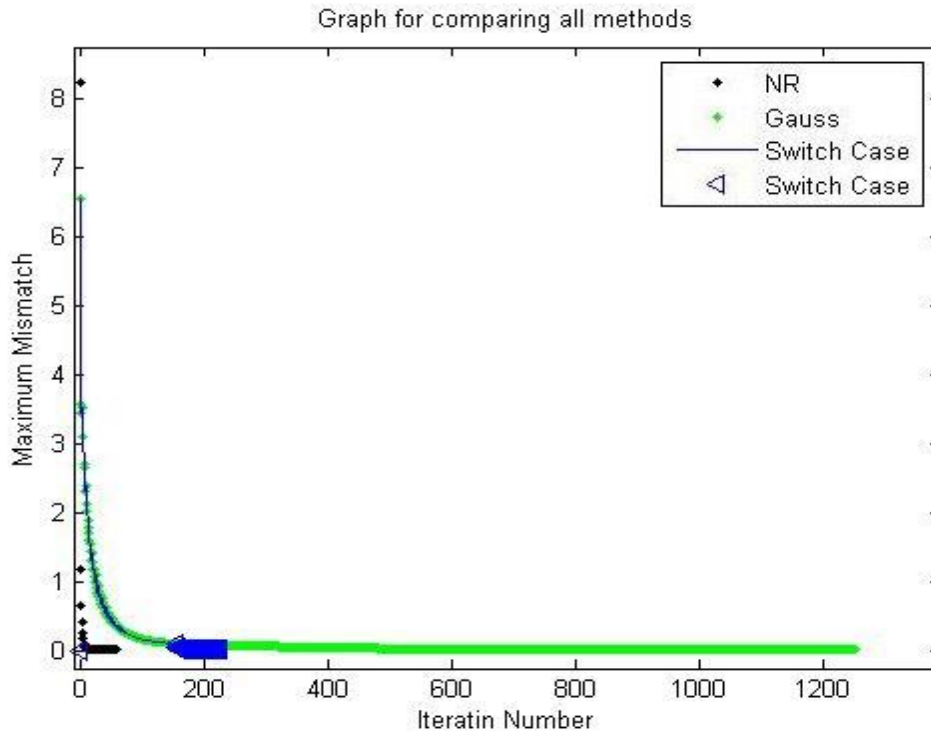Fig 5.8 Graph using NR and Gauss method (Max Mismatch vs Convergence time)

Fig 5.9 Comparative results of Gauss, NR and switching technique (Number of iterations)
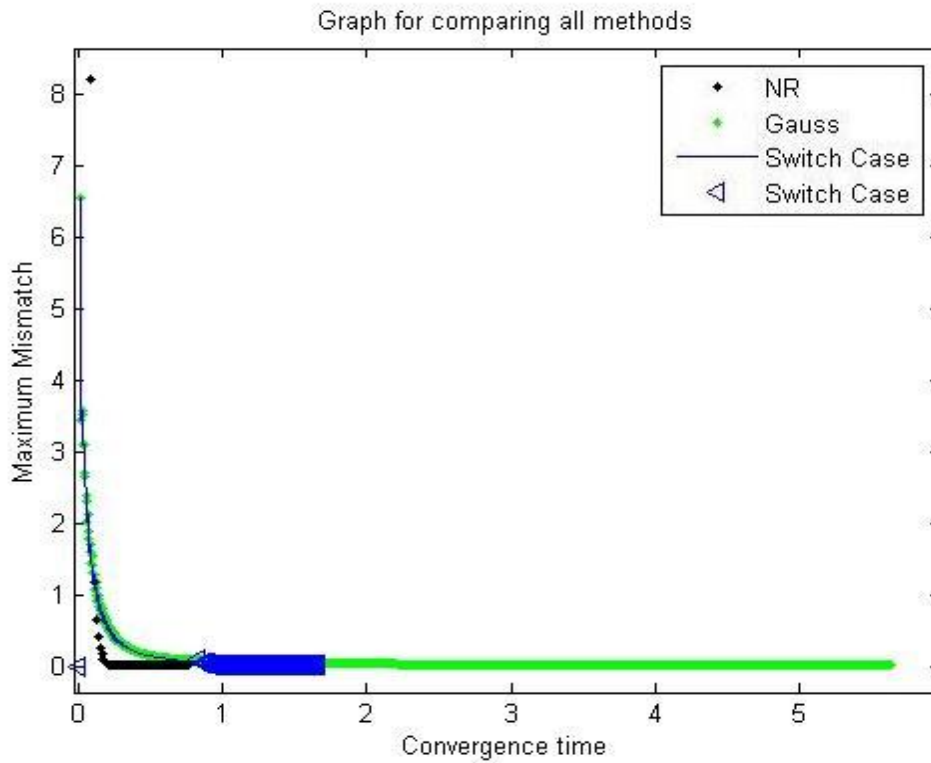

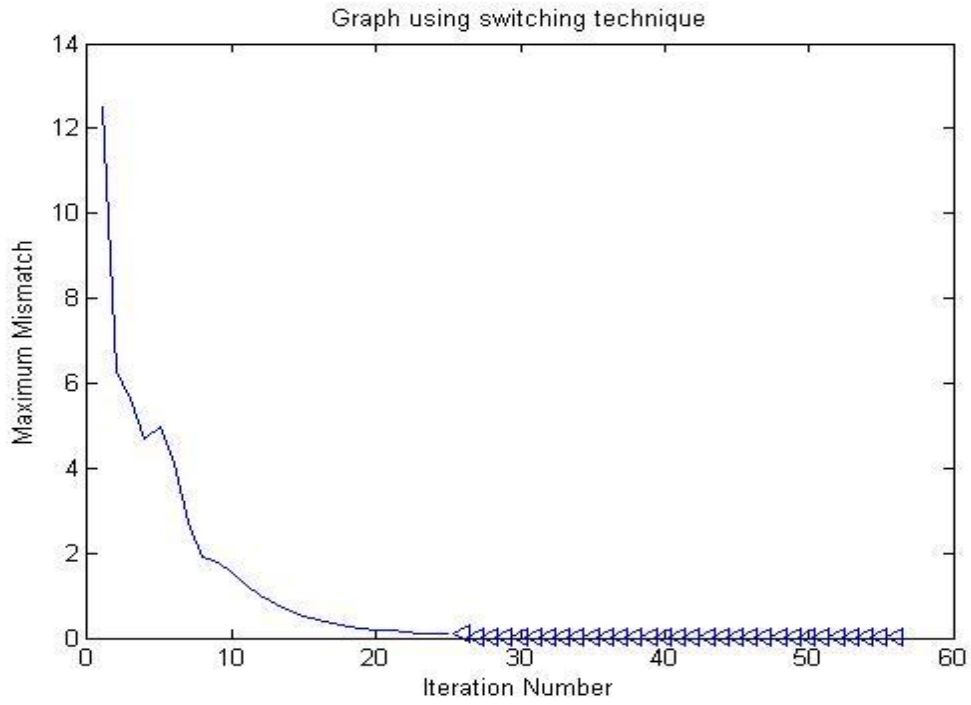Fig 5.10 Comparative results of Gauss, NR and switching technique (Convergence time)

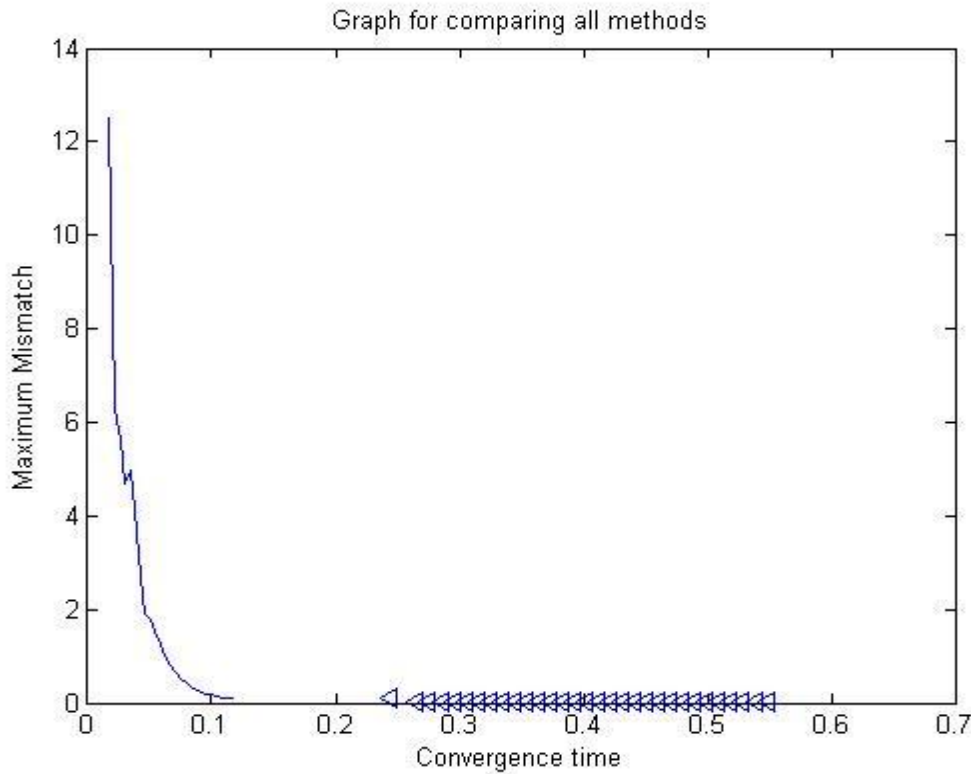Fig 5.11 Graph using Newton-Raphson and Gauss-Seidel method (Number of Iterations)

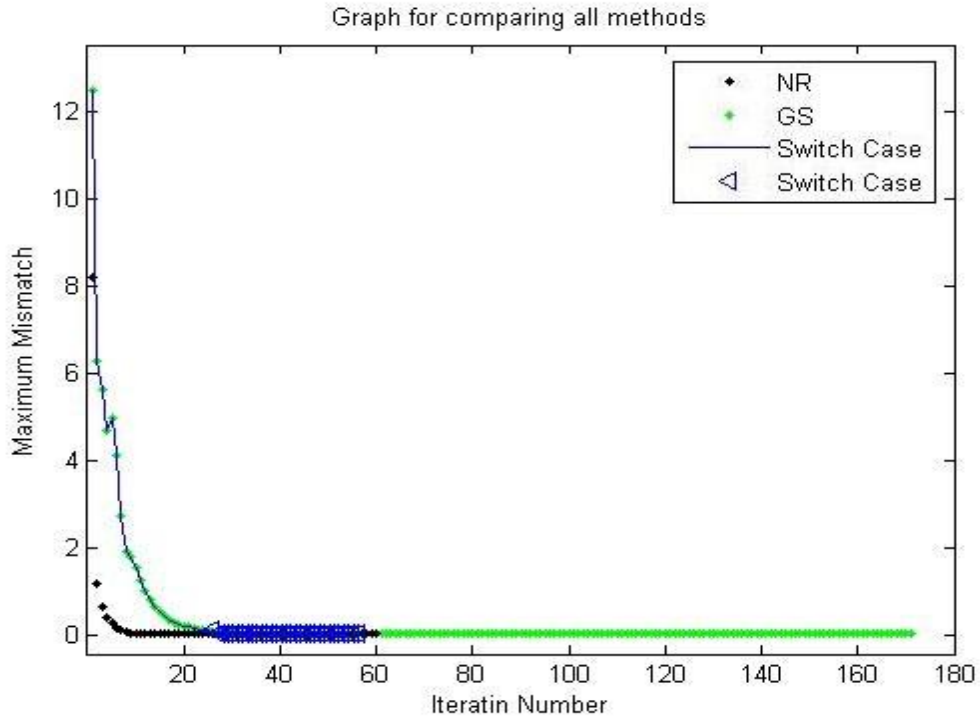Fig 5.12 Graph using Newton-Raphson and Gauss-Seidel method (Convergence time)

Fig 5.13 Comparative results of GS, NR and switching technique (Number of Iterations)
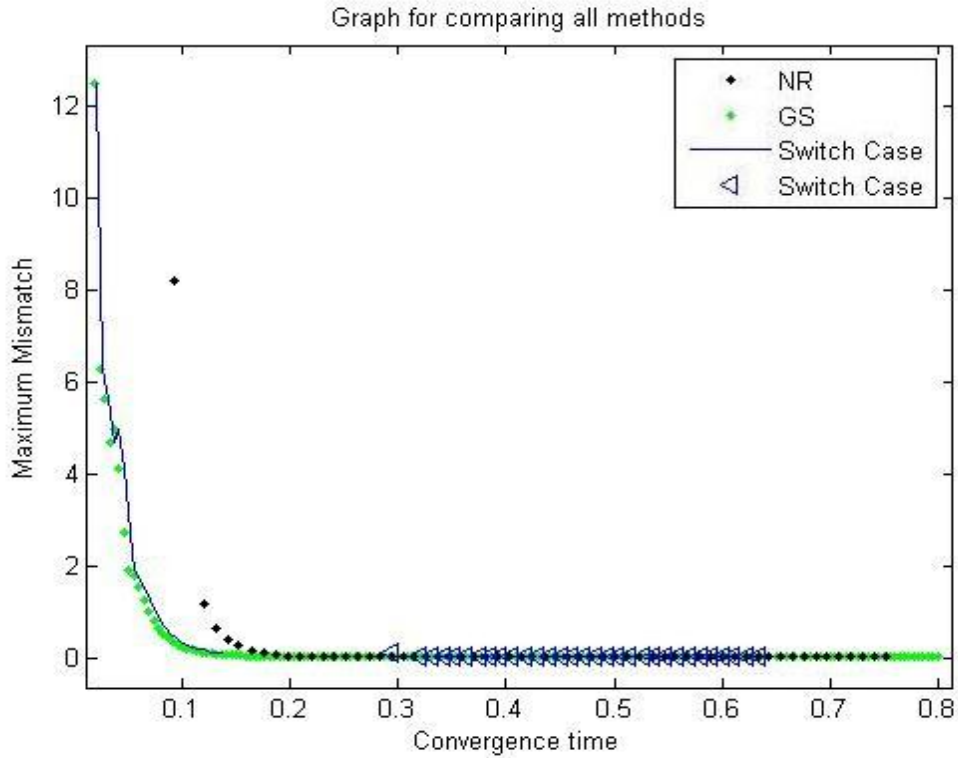

Fig 5.14 Comparative results of GS, NR and switching technique (Convergence time)

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5.3 Results using different methods:

All the graphs in the results are for the IEEE 39 bus test system, explained in Chapter 4.

Figure 5.1 and 5.2 are graphs generated using the Gauss method by itself. The tolerance value chosen for this method is 0.001. It can be observed the total number of iterations to complete the power flow is 1253 and the total time take to run 1253 iterations is 5.637 seconds.

Figure 5.3 and 5.4 are graphs generated using the Gauss-Seidel method by itself. The tolerance value chosen for this method is 0.001. It can be observed the total number of iterations to complete the power flow is 171 and the total time take to run 171 iterations is 0.812 seconds.

Figure 5.5 and 5.6 are graphs generated using the Gauss method by itself. The tolerance value chosen for this method is 0.001. It can be observed the total number of iterations to complete the power flow is 60 and the total time take to run 60 iterations is 0.751 seconds.

Figure 5.7 and 5.8 are graphs generated using the Switching technique. In this switching method the first step starts with the Gauss method and then switches to Newton Raphson. The tolerance value chosen for Gauss method is 0.1; this is to use less number of iterations of Gauss method and switch to Newton Raphson method with good initial values. The tolerance value chosen for Newton Raphson method is 0.001. It can be observed the total number of iterations to complete the power flow is 216 (Gauss-155 & NR- 51) and the total time take to complete 216 iterations is 1.5459 seconds.

Figure 5.9 and 5.10 are graphs to compare the performance of Gauss, Newton-Raphson and Switching methods.

Figure 5.11 and 5.12 are graphs generated using the Switching technique. In this switching method the first step starts with the Gauss-Seidel method and then switches to Newton Raphson. The tolerance value chosen for Gauss-Seidel method is 0.1; this is to use less number of iterations of Gauss-Seidel method and switch to Newton Raphson method with good initial values. The tolerance value chosen for Newton Raphson method is 0.001. It can be observed the total number of iterations to complete the power flow is 56 (GS-25 & NR-31) and the total time take to complete 56 iterations is 0.5977 seconds.

Figure 5.13 and 5.14 are graphs to compare the performance of Gauss-Seidel, Newton-Raphson and Switching methods.

5.4 Comparative results:

In this section we will discuss the results of the load flow. It can be observed Gauss method; Gauss-Seidel, Newton-Raphson methods and the final result obtained using the switching technique are the same. Switching from Gauss to Newton Raphson method improved the convergence time over the Gauss method by itself, anyhow the resultant convergence time is more compared to Newton-Raphson. However the switching method converged faster than the traditional method (Fig 5.10 and 5.14), when switched from Gauss-Seidel to Newton-Raphson method. The bus voltage magnitudes, angles of each bus along with power generated and consumed at each bus are given in Table 5.1. It can be seen from this table that for IEEE 39 bus system the total power generated is 1408 MW whereas the total load is 1349 MW. This indicates that there is a line loss of about 59 MW for all the lines put together. It can be observed that the real and reactive power of the slack bus and the reactive power of the P-V bus are computed from equation (2.9) and equation (2.10) after the convergence of the load flow.

Chapter 6

Conclusion and Future Work

6.1 Conclusion:

The Program written for this thesis has been very successful in achieving the goals set forth for a Power flow study. Achievement of lesser convergence time, while maintaining the accuracy of the power flow calculation, was accomplished through the implementation of switching technique to the Power Flow problem. Switching technique has proven to be very adept at solving the Power Flow problem.

Research has been done to conclude a numerical technique for a power flow to converge with less convergence time, tests were done under various conditions and Switching from Gauss-Seidel method to Newton-Raphson method was found to ensure less convergence time. Gauss and Gauss-Seidel methods are good for small system where the computation complexity is less. Though Gauss and Gauss-Seidel methods require fewest numbers of arithmetic operations and less average time to complete iteration, for a large system there convergence time is slower compared to Newton-Raphson method.

The Power Flow performs generator control and transmission system control while taking into account system limits. At present, the Switching technique works very well for large system (tested on 39 bus systems) and is proven to be the best for large systems.

6.2 Future Work:

Improvements would be made to the software programming of this work in order to improve the overall program run time. Program techniques shall be considered to achieve the mathematical operations in each numerical technique with less run time.

Testing has to be done with more test systems to identify and verify other switching orders that could potentially improve the power flow calculation.

Tests has to be done on the tolerance value and other factors that could be improved to improve the overall run time.

With the above improvements the use of multiple traditional numerical methods together will be more efficient.

Appendix A

A.1 Software Development:

This section of the report explains the software used for implementing the techniques presented in Chapter 3. The entire code is written in Matlab 7.5.0 (R2007b). The solution consists of the following parts:

1) Power Flow using Gauss method (testGS.m)

2) Power Flow using Gauss-Seidel method (GSFinal.m)

3) Power Flow using Newton-Raphson method (NRFinal2.m)

4) Power Flow using the switching technique (GSNR.m)

All of the above programs are fed with the following input files:

1) Transmission line data (trline.txt)

2) Transformer data (transformer.txt)

3) Generator data (genvalue.txt)

4) Load data (load.txt)

Among all the four programs the first three programs run independently on one method irrespective of the other methods. Whereas, the fourth method has a code that has certain functions to call the first three programs and are switched in the order based on the size of the system.

Some important inbuilt functions of matlab were used in the program to make the environment of the code appropriate to the numerical techniques. Even though the code can be

written in a function free way it is a better practice to use functions. The functions used for these programs are:

a) tic-toc:

Syntax:

tic

    any statements

toc

t = toc

Description:

tic starts a stopwatch timer; toc prints the elapsed time since tic was used. t = toc returns the elapsed time in t.

b) Jacobian:

Syntax:

    jacobian(f,v)

Description:

jacobian(f,v) computes the Jacobian of the scalar or vector f with respect to v. The (i,j)th entry of the result is a derivative. Note that when f is scalar, the Jacobian of f is the gradient of f. Also, note that v can be a scalar, although in that case the result is the same as diff(f,v).

c) gmres:

Syntax:

x = gmres(A,b)

Description :

x = gmres(A,b) attempts to solve the system of linear equations A*x = b for x.The n-by-n coefficient matrix A must be square and should be large and sparse. The column vector b must have length n. A can be a function handle afun such that afun(x) returns A*x. See Function Handles in the MATLAB Programming documentation for more information. For this syntax, gmres does not restart; the maximum number of iterations is min(n,10).

The first function tic-toc is used in all the methods to calculate the elapsed time to compare the results of different methods.

The functions jacobian and gmres are used in Newton-Raphson method. As the Newton-Raphson method is a derivative calculation it is necessary to use gmres to improve the calculation time.

A.2 Results of 3 bus system using different methods:

3 bus system	Gauss Method	Gauss-Seidel Method	Newton-Raphson Method	Switching Method GS followed by NR	Switching Method NR followed by GS	Switching Method Gauss followed by NR	Switching Method NR followed by Gauss
Initial voltage and phase angle	1 p.u and 0 degree	1 p.u and 0 degree	1 p.u and 0 degree	1 p.u and 0 degree	1 p.u and 0 degree	1 p.u and 0 degree	1 p.u and 0 degree
Assumed tolerance value	0.001	0.001	0.001	0.1 for GS 0.001 for NR	0.1 for NR 0.001 for GS	0.1 for Gauss 0.001 for NR	0.1 for NR 0.001 for Gauss
Number of Iterations	7	17	6	11	12	9	7
No. of Gauss Iterations	7	0	0	0	0	6	5
No. of Gauss-Seidel Iterations	0	17	0	9	7	0	0
No. of Newton-Raphson iterations	0	0	6	2	5	3	2
Convergence time (in seconds)	0.0155	0.01553	0.1360	Total Time - 0.1266 GS – 0 .0 118 Switch Time – 0.0039 NR - 0.1039	Total - 0.1321 NR - 0.1167 St - 0.0047 GS - 0.0107	Total - 0.1577 G - 0.0135 St - 0.0041 NR - 0.1424	Total – 0.1523 NR - 0.1061 St - 0.0058 G – 0.0119
Time taken for each iteration (average time in seconds)	0.0022	0.0009	0.0226	0.01150	0.0110	0.0175	0.0217
Maximum Mismatch	0.8	1.14	2.8	1.14	2.8	0.8	2.8

Table A.1 Comparative Results of 3 bus System

A.3 Results of 5 bus system using different methods:

5 bus system	Gauss Method	Gauss-Seidel Method	Newton-Raphson Method	Switching Method GS followed by NR	Switching Method NR followed by GS	Switching Method Gauss followed by NR	Switching Method NR followed by Gauss
Initial voltage and phase angle	1 p.u and 0 degree	1 p.u and 0 degree	1 p.u and 0 degree	1 p.u and 0 degree	1 p.u and 0 degree	1 p.u and 0 degree	1 p.u and 0 degree
Assumed tolerance value	0.001	0.001	0.001	0.1 for GS 0.001 for NR	0.1 for NR 0.001 for GS	0.1 for Gauss 0.001 for NR	0.1 for NR 0.001 for Gauss
Number of Iterations	20	11	4	8	7	7	6
No. of Gauss Iterations	20	0	0	0	0	4	4
No. of Gauss-Seidel Iterations	0	11	0	5	5	0	0
No. of Newton-Raphson iterations	0	0	4	3	2	3	2
Convergence time (in seconds)	0.0155	0.0182	0.1256	0.1516	0.1612	0.1577	0.1523
Time taken for each iteration (average time in seconds)	0.00075	0.0016	0.0314	0.01883	0.0230	0.0225	0.0253
Maximum Mismatch	0.35	0.28	0.8	0.28	0.8	0.35	0.8

Table A.2 Comparative Results of 5 bus System

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Vita

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