POWER FLOW SOLUTION FOR MICRO GRIDS WITH DISTRIBUTED SLACK BUS

A

Dissertation

Submitted

In partial fulfillment

For the award of the Degree of Master of Science in Electrical & Electronics Engineering

In Department of Electrical & Electronics Engineering (EEE)

(With specialization in Power Systems)

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CANDIDATE'S DECLARATION

I hereby declare that the work, which is being presented in this dissertation, entitled " **Power Flow Solution for Micro-grids with Distributed Slack Bus**" in partial fulfillment for the award of Degree of " Master of Science in Electrical & Electronics Engineering(EEE)" at Department of Electrical & Electronics Engineering (EEE) with specialization in power systems and submitted to the Head, Department of Electrical & Electronics Engineering (EEE), BRAC University, Dhaka, Bangladesh, is a record of my own investigations carried under the Guidance of **Prof. Dr. S.M. Lutful Kabir**, Professor and Dean, United International University, Dhaka, Bangladesh & Professor, IICT, BUET, Dhaka, Bangladesh

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

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MG : Micro grid
DERs : Distributed Energy Sources
DGs : Distributed Generators
FDLF : Fast Decoupled Load flow
N-R : Newton-Rapshon Method
G-S : Gauss-Sheidel Method
PSERC : Power Systems Engineering Research Center

ABSTRACT

For power system planning and operation, load flow solution is an inevitable tool for power system engineers. Among various methods of load flow solution techniques Newton Raphson (N-R) and its derivatives are the most popular and widely used ones. In Newton Raphson method one of the generator buses is treated as slack bus which is kept out of calculation during iterations. This is because of the fact that the slack bus is to carry entire loss of the system and total loss cannot be calculated before the end of iterations. The exclusion of slack bus from the load flow iteration restricts many analyses to make. Consideration of distributed slack bus, load flow for micro-grids, study on minimization of system losses etc. cannot be performed when the slack bus is excluded from the iterations. This thesis reports the development of a method of including slack bus into the Jacobians for N-R load flow study. The method involves formulating the loss equation and then devising the formula for the terms to be included with the elements of the Jacobian matrix. The modified N-R method is applied to all of the buses and the losses are calculated in each iteration and included with the slack bus. The results obtained using the modified methods are compared with those using conventional method. The agreement of the results confirms the accuracy of the developments.

Indexing terms: Jacobian modification in N-R load flow, Slack bus inclusion in N-R load flow.

[**Key words-** Micro-grid, MATPOWER, MATLAB, Power flow, Newton-Rapshan Method, Slack Bus, Generator/PV Buses and Distributed Slack Bus]

The thesis titled, "**POWER FLOW SOLUTION FOR MICRO-GRID WIH DISTRIBUTION SLACK BUS"** submitted by **Jahangir Alam,** Roll. No. 10271004, Program-M.Sc In EEE, BRAC University has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Science in Electrical and Electronic Engineering (M.Sc In EEE) on ……..

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Chapter 1

INTRODUCTION

1.1 Background

Load flow analysis is the most important tools for power system analysis. It is essential for planning, operation and scheduling. The main information of load flow analysis is to search the magnitude and phase angle of voltage at each bus and the real and reactive power flowing in each transmission lines of a power system. Load flow (also known as Power flow study) analysis is being used for solving power flow problem by Newton-Raphson method and Gauss-Seidel method etc. There are three types of buses in the load flow system network (***i.e.*** Load buses, Voltage control buses and slack bus) [1, 2, 3, 4].In a power system each node or bus is associated with four quantities namely magnitude of voltage, phase angle of voltage, active or true power and reactive power. In load flow problem two out of these four quantities are specified and remaining two is required to be determined through the solution of equation. ***Slack bus*** (It is also known as the Reference Bus or the Swing Bus.) is used to balance the active and reactive power in the system. The Slack bus is selected to provide/absorb active and reactive power to/from the transmission line to provide losses since these are unknown until the final solution of the problem. For these reason, it is burden for slack bus in the power flow system network because of its value is computed at the end of convergence of the iteration. Keeping a bus as a slack bus may not be feasible for some systems. Especially in a Micro-grid, no one within all generating unit can be behaved as slack generator of eternal capability [5], where all generating unit are in commensurable sizes and small capacities.

1.2 The Concept of Micro-grid(MG)

A micro-grid is a small-scale power grid that can operate independently or in conjunction with the area’s main electrical grid. Any small-scale localized station with its own power resources, generation and loads and definable boundaries qualifies as a micro-grid. Micro-grids can be intended as back-up power or to strengthen the main power grid during periods of heavy demand. Micro-grids involve multiple energy sources as a way of incorporating renewable energy. The modular nature of micro-grids could make the main grid less susceptible to localized disaster. Modularity also means that micro-grids can be used, piece by piece, to gradually modernize the existing grid.

The idea of micro-grid (MG) has been taken into account by researchers more frequently in most current years, due to its role in driving modern power systems to acquire clean energy generation. MGs operate in two several modes, namely interconnected and islanded modes. In the old mode, the Distributed Energy Sources (DERs) in the MG contribute to the majority of the demand within the MG and the difference in supply and demand is made available from the utility; while in the latter mode, DERs supply reliable and financial energy serving different loads like residential buildings, commercial buildings and industrial parks etc.

1.3 The Problem

In load flow study, the buses of a power system are divided into three categories. They are PV, PQ and Slack bus. Slack Bus is also called infinite bus because theoretically the generation capacity at this bus is very large. It is treated as reference bus with respect to it all phase of the other bus voltages are calculated. In practice, in power flow solution, the slack bus is kept out of the iterative solution process and its power is calculated at the end of convergence of the iteration. Thus all losses of the network are burdened on this slack bus.

For different causes the consideration of keeping the slack bus creates restrictions in several studies. The new tools for planning and operating distribution systems have become essential with the increase of distributed generators (DGs) installed within power network called Micro-grid network. The application of conventional power flow solution techniques using one slack bus in many cases is not possible in Micro-grids (Today, several types of DGs are connected together and formed a small power system called micro-grid)[5, 6].This is because of the fact that the generating units are of small in capacity having comparable sizes and no one can be treated as slack generator of infinite capacity. So, the slack bus should be treated as normal PV bus. In other words slack bus should be included in the iterative process of load flow solution.

1.4 Literature Review

Load flow or the 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 to time dependent load flow.

Later Power flow analysis is solved by using MATLAB Computer software [7,8] and subsequently more revolution is done, Load flow and Optimal Power Flow problem is compute by MATPOWER [9,10,11] program (M-file of MATLAB) from 1996's.

Mohapatra [12] devised a method of eliminating burden of slack bus while maintaining the equal incremental loss criteria for optimum generation scheduling. Because of special characteristics of distribution systems, such as high R/X ratios and network imbalance, consideration of distributed slack bus is more realistic than a single slack bus. The previous work done for transmission system [13] cannot be applied directly in distribution system.

Shiqiong Tong, Miu K.N [14] presents a three-phase distribution power flow with a distributed slack bus model and studies of two different methods to calculate participation factors. The methods are based on network sensitivity factors and on the concepts of generator domains. Power flow with a distributed slack bus model is considered more realistic than a single slack bus model, since there is no slack bus in real power systems. Participation factors can be applied to assign slack for distributed slack bus models.

P. H. Haley and M. Ayres [15] presented the algorithm involving a simple modification to Stott & Alsac's Fast Decoupled Load flow (FDLF), along with the: implementation of a distributed slack bus. It yields a robust and fast algorithm for load flow problems involving large networks. Tests show that the algorithm can be more than twice as fast as FDLF.

Aleksandar Dimitrovski and Kevin Tomsovic [16] proposed Slack bus as a distributed PV Bus in their paper. In spite of Slack bus has been converted as PV/Generator bus in this paper but losses has not been distributed and slack bus has not been included in every iteration process.

Soumya Ranjan Panda [17] in this paper, the optimal cost of generation has been analyzed with a distributed slack bus model. In ordinary load flow method, the slack bus is bound to carry the entire extra burden of the system. In the proposed technique, the burden on slack bus shall be reduced and still maintain the equal incremental cost criteria. A new term called Participation factor shall be utilized to achieve the same as the total loss of the system at the end of iteration shall get distributed among all the generating units. Finally practical bus network problems shall be taken as case study and results shall be analyzed and compared with the existing ELD scheme to verify the usefulness of the proposed technique.

Shiqiong Tong [18] addresses the challenges through slack bus modeling studies. First, traditional distribution power flow with a single slack bus model is revisited and a distributed slack busmodel is proposed for distribution system analysis and planning. Network-based participation factors to distribute slack are developed. These participation factors capture network parameters, load distributions and generator capacities. Then, impacts on distribution operating and planning functions of slack bus modeling are investigated. Then, a distribution system expansion planning problem is addressed.

Peter M. Moses and Dr. N. A.Odero [19] presents that a distributed slack bus model using combined participation factors is developed in this paper to distribute the slack(real and reactive power losses).The combined participation factors are formulated using the method of Lagrange multipliers and the distributed slack bus model employs a Genetic Algorithm of a N-RSolver.

1.5 Scopes of the Research

Literature survey shows that a number of techniques had been proposed for load flow solution of distributed slack bus systems. No one could determine the power flow values in a single process; multiple iterations were necessary and decide on a suitable solution for micro-grid. The aim of this thesis work is to include slack as a normal PV bus during iteration process considering Generator of each small generation capacity of Micro-grids through MATPOWER using Newton-Rapshon method. Objective of the present work is to study and implement the load flow solution for distributed Slack bus of Island Micro-grids. The object is to use a method that can be applied to Island Micro-grids with minimum computational efforts. This thesis describes a method of including slack bus into the Jacobians of Newton-Rapshon method in the power flow analysis. The losses are computed in the every iteration and are incorporated with a single or multiple buses. This can be obtained by formulating losses equation and finally by including losses terms in the Jacobian in Newton-Rapshon method.

1.6 Thesis Layout

The work carried out in this thesis has been organized in five chapters. In the first chapter we have presented generally about primary summary topic of the thesis. It also includes a narration of literature survey involving an analysis of prior respecting work and highlighting their restriction. The opportunity of the current work is portrayed in this chapter and finally towards the ends of the chapter with this essay containing the organization of this report.

In chapter two we have explained about conventional load flow reasonably with buses classification and also formulated real and reactive power equation, Newton-Rapshon method iterative process, Jacobian Matrix.

Chapter three presents power and losses equation for new load flow and modify loss equation terms by including slack bus in Jacobian matrix. Besides this, the chapter three highlights MATPOWER program Running Procedure, its Solution techniques and Case study of IEEE system, MATPOWER m-file *newton.m* program has also been modified for our development.

Chapter four describes the results of IEEE five test system namely IEEE 9 bus, 14 bus, 30 bus, 39 bus & 57 bus cases. These results obtained by our developed technique are compared with those obtained by conventional load flow.

Lastly, the conclusions and scope of further work are detailed in chapter five.

Chapter 2

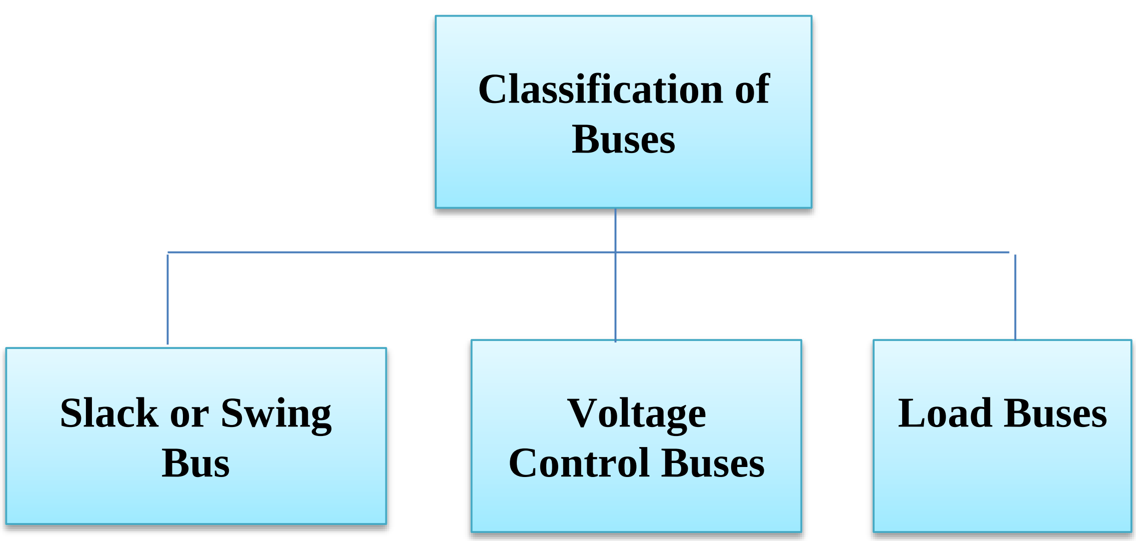
CONVENTIONAL LOAD FLOW

2.1 Introduction

Power flow analysis is used to determine the steady state operating condition of a power system. The load flow gives us the sinusoidal steady state of the entire system - voltages, real and reactive power generated and absorbed and line losses. Since the load is a static quantity and it is the power that flows through transmission lines, some researchers to call this power flow studies rather than load flow studies. Power flow analysis is widely used by power distribution professional during the planning and operation of power distribution system. The steady state power and reactive powers supplied by a bus in a power network are expressed in terms of nonlinear algebraic equations. We therefore would require iterative methods for solving these equations. We shall also delineate how to interpret the load flow results.

2.2 Classification of Buses

A bus is a node at which one or many lines, one or many loads and generators are connected. In a power system each node or bus in the system has four variables: voltage magnitude, voltage angle, real power and reactive power. During the operation of the power system, each bus has two known variables and two unknowns. The main objective of the load flow is to find the voltage magnitude of each bus and its angle when the powers generated and loads are pre-specified. To facilitate this we classify the different buses of the power system shown in the chart below.



Generally, the bus must be classified as one of the following bus types:

Generator Buses or Voltage Controlled Buses: These are the buses where generators are connected. Therefore the power generation in such buses is controlled through a prime mover while the terminal voltage is controlled through the generator excitation. Keeping the input power constant through turbine-governor control and keeping the bus voltage constant using automatic voltage regulator, we can specify constant P_{Gi} and $| Vi |$ for these buses. This is why such buses are also referred to as P-V buses. It is to be noted that the reactive power supplied by the generator Q_{Gi} depends on the system configuration and cannot be specified in advance. Furthermore we have to find the unknown angle δ_i of the bus voltage.

Slack Bus or Swing Bus or Reference Bus: This bus is considered as the reference bus. Usually this bus is numbered 1(one) for the load flow studies. It must be connected to a generator of high rating relative to the other generators. Since it is the angle difference between two voltage sources that dictates the real and reactive power flow between them, the particular angle of the slack bus is not important. However it sets the reference against which angles of all the other bus voltages are measured. During the operation, the voltage of this bus is always specified and remains constant in magnitude and angle. In addition to the generation assigned to it according to economic operation, this bus is responsible for supplying the losses of the system. For this reason the angle of this bus is usually chosen as 0°. Furthermore it is assumed that the magnitude of the voltage of this bus is known.

Load Buses*:* In these buses no generators are connected so that neither its voltage nor its real power can be controlled. On the other hand, the load connected to this bus will change the active and reactive power at the bus in a random manner. To solve the load flow problem we have to assume the complex power value (real and reactive) at this bus.

Hence the generated real power P_{Gi} and reactive power Q_{Gi} are taken as zero. The load drawn by these buses are defined by real power $-P_{Li}$ and reactive power $-Q_{Li}$ in which the negative sign accommodates for the power flowing out of the bus. This is why these buses are sometimes referred to as P-Q bus. The objective of the load flow is to find the bus voltage magnitude $|Vi|$ and its angle δ_i.

2.3 Objective of Load Flow

The main objectives of load flow studies use as follows:

a. Power flow analysis is very important in planning stages of new networks or addition to existing ones like adding new generator sites, meeting increase load demand and locating new transmission sites.

b. The load flow solution gives the nodal voltages and phase angles and hence the power injection at all the buses and power flows through interconnecting power channels.

c. It is helpful in determining the best location as well as optimal capacity of proposed generating station, substation and new lines.

d. It determines the voltage of the buses. The voltage level at the certain buses must be kept within the closed tolerances.

e. To study the performance of the transmission lines, transformer and generator at steady state condition.

f. System transmission loss minimizes.

g. Economic system operation with respect to fuel cost to generate all the power needed

h. The line flows can be known. The line should not be overloaded, it means, we should not operate the close to their stability or thermal limits.

i. To write a program for power flow analysis for education and training purposes.

2.4 Mathematical Formulation of Conventional Load Flow Methods

2.4.1 The Formulation of Real and Reactive Power

For the formulation of the real and reactive power entering in a bus, we need to define the following quantities.

Let the voltage at the i_{th} bus be denoted by,

$$V_i = |V_i| \angle \delta_i = |V_i| (\cos \delta_i + j \sin \delta_i) \qquad (2.1)$$

Also let us define the self-admittance at bus *i* as,

$$Y_{ii} = |Y_{ii}| \angle \theta_{ii} = |Y_{ii}| (\cos \theta_{ii} + j \sin \theta_{ii}) = G_{ii} + B_{ii} \qquad (2.2)$$

Similarly the mutual admittance between the buses *i* and *j* can be written as,

$$Y_{ij} = |Y_{ij}| \angle \theta_{ij} = |Y_{ij}| (\cos \theta_{ij} + j \sin \theta_{ij}) = G_{ij} + jB_{ij} \qquad (2.3)$$

Let the power system contains a total number of n buses, the current injected at bus *i* is given as,

$$I_i = Y_{i1}V_1 + Y_{i2}V_2 + ... + Y_{in}V_n = \sum_{k=1}^{n} Y_{ik}V_k \quad ....(2.4)$$

It is to be noted we shall assume the current entering a bus to be positive and that leaving the bus to be negative. As a consequence the power and reactive power entering a bus will also be assumed to be positive. The complex power at bus *i* is then given by,

$$P_i - jQ_i = V_i^* I_i = V_i^* \sum_{k=1}^{n} Y_{ik}V_k = |V_i| e^{-j\delta_i} \sum_{k=1}^{n} |Y_{ik}| e^{j\theta_{ik}} |V_k| e^{j\delta_k} = \sum_{k=1}^{n} |Y_{ik}V_iV_K| e^{j(\theta_{ik} + \delta_k - \delta_i)}$$

$$= \sum_{k=1}^{n} |Y_{ik}V_iV_k| \cos(\theta_{ik} + \delta_k - \delta_i) + j\sum_{k=1}^{n} |Y_{ik}V_iV_k| \sin(\theta_{ik} + \delta_k - \delta_i) \quad ....(2.5)$$

Therefore we get the real and reactive power as,

$$P_i = \sum_{k=1}^{n} |Y_{ik}V_iV_k| \cos(\theta_{ik} + \delta_k - \delta_i) \quad ....(2.6)$$

$$Q_i = -j\sum_{k=1}^{n} |Y_{ik}V_iV_k| \sin(\theta_{ik} + \delta_k - \delta_i) \quad ....(2.7)$$

2.4.2 Data for Load flow

Let real and reactive power generated at bus *i* be denoted by P_{Gi} and Q_{Gi} respectively. Also let us denote the real and reactive power consumed at the ith bus by P_{Li} and Q_{Li} respectively. Then the net real power injected in bus *i* is

$$P_{i,inj} = P_{Gi} - P_{Li} \quad ....(2.8)$$

Let the injected power calculated by the load flow program be $P_{i,calc}$. Then the mismatch between the actual injected and the calculated values is given by

$$\Delta P_i = P_{i,inj} - P_{i,calc} = P_{Gi} - P_{Li} - P_{i,Calc} \quad ....(2.9)$$

In a similar way the mismatch between the reactive power injected and calculated values is given by

$$\Delta Q_i = Q_{i,inj} - Q_{i,calc} = Q_{Gi} - Q_{Li} - Q_{i,Calc} \quad ....(2.10)$$

The purpose of the load flow is to minimize the above two mismatches. It is to be noted that (2.6) and (2.7) are used for the calculation of real and reactive power in (2.9) and (2.10). However, since the magnitude of all the voltages and their angles are not known a priori, an iterative procedure must be used to estimate the bus voltage and their angles in order to calculate the mismatches. It is expected that mismatched ΔP_i and ΔQ_i reduce with each iteration and the load flow is said to be have converged when the mismatches of all the buses become less than a very small number.

2.5 Load Flow Method (Technique of Solution)

As large AC power cannot be stored in any device, the generation of electric power must be balanced with the load demand. The demand of the load keeps on changing. So it becomes necessary for the power system to meet the peak load demand and base load demand for the reliable and economic use of power. To make most reliable and suitable system it becomes necessary to perform power flow analysis. There are many different solution techniques or methods for the analysis of Power flow in the power system network [4]. Mainly three methods namely Gauss -Siedel method, Newton- Raphson method, Fast decoupled method are used in load flow analysis. Among them the Newton-Raphson iterative methods is the one which is mostly used for the power flow analysis.The first method (Gauss -Siedel) is simpler but the second (Newton- Raphson method) is reported to have better convergence characteristics and is faster than (Gauss -Siedel) method. These methods are used generally on formula or mathematical step in order to solve power flow problem. The Fast Decoupled method is an approximation of Newton-Rapshon method and gives almost same results for most of systems.

But the Newton power flow is the most robust power flow algorithm used in practice. The Newton-Rapshon method is widely used for solving nonlinear equation and used frequently for the power flow because it has the advantage of processing large data for system comprising of large branches and buses. Besides this, Newton–Rapshon method is built-in or default program of MATPOWER solution. We will discuss here in details only about Newton-Rapshon method.

2.5.1 Solution of a set of Nonlinear Equations by Newton-Raphson

In this section we shall discuss the solution of a set of nonlinear equations through Newton-Raphson method. Let us consider that we have a set of *n* nonlinear equations of a total number of *n* variables $x_1, x_2, \ldots\ldots, x_n$. Let these equations be given by

$$f_1(x_1, \ldots\ldots, x_n) = \eta_1$$

$$f_2(x_1, \ldots\ldots, x_n) = \eta_2$$

$$\vdots \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.11)$$

$f_n(x_1,........,x_n) = \eta_n$

Where $f_1,……..,f_n$ are functions of the variables x_1, $x_2,….,$ x_n. We can then define another set of functions $g_1,…..,g_n$as given below

$$g_1(x_1,........,x_n) = f_1(x_1,........,x_n) - \eta_1 = 0$$
$$g_2(x_1,........,x_n) = f_2(x_1,........,x_n) - \eta_2 = 0 \quad ……………………..………………...………(2.12)$$
$$\vdots$$
$$g_n(x_1,........,x_n) = f_n(x_1,........,x_n) - \eta_n = 0$$

Let us assume that the initial estimates of the *n* variables are $x_1^{(0)}, x_2^{(0)},......., x_n^{(0)}$. Let us add corrections $\Delta x_1^{(0)}, \Delta x_2^{(0)},.........\Delta x_n^{(0)}$ to these variables such that we get the correct solution of these variables defined by

$$x_1^* = x_1^{(0)} + \Delta x_1^{(0)}$$
$$x_2^* = x_2^{(0)} + \Delta x_2^{(0)} \quad ………………………………………………………...………………… (2.13)$$
$$\vdots$$
$$x_n^* = x_n^{(0)} + \Delta x_n^{(0)}$$

The functions in (2.12) then can be written in terms of the variables given in (2.13) as

$$g_k(x_1^*,........,x_n^*) = g_k(x_1^{(0)} + \Delta x_1^{(0)},.......x_n^{(0)} + \Delta x_n^{(0)}) = 0, \text{ (Where k=1…….n)} \quad ….…… ... (2.14)$$

We can then expand the above equation in Taylor's Series around the nominal values of $x_1^{(0)}, x_2^{(0)},........, x_n^{(0)}$.. Neglecting the second and higher order terms of the series, the expansion of $g_k, k = 1,.........., n$ is given as

$$g_k(x_1^*,......., x_n^*) = g_k(x_1^{(0)},........, x_n^{(0)}) + \Delta x_1^{(0)} \left.\frac{\partial g_k}{\partial x_1}\right|^{(0)} + \Delta x_2^{(0)} \left.\frac{\partial g_k}{\partial x_2}\right|^{(0)} + ... + \Delta x_n^{(0)} \left.\frac{\partial g_k}{\partial x_n}\right|^{(0)} \quad …………...……….(2.15)$$

Where, $\partial g_k / \partial x_1|^{(0)}$ is the partial derivative of g_k evaluated at $x_2^{(1)},.........., x_n^{(1)}$.

Equation (2.15) can be written in vector-matrix form as

$$\begin{bmatrix} \partial g_1/\partial x_1 & \partial g_1/\partial x_2 & \cdots & \partial g_1/\partial x_n \\ \partial g_2/\partial x_1 & \partial g_2/\partial x_2 & \cdots & \partial g_2/\partial x_n \\ \vdots & \vdots & \ddots & \vdots \\ \partial g_n/\partial x_1 & \partial g_n/\partial x_2 & \cdots & \partial g_n/\partial x_n \end{bmatrix}^{(0)} \begin{bmatrix} \Delta x_1^{(0)} \\ \Delta x_2^{(0)} \\ \vdots \\ \Delta x_n^{(0)} \end{bmatrix} = \begin{bmatrix} 0 - g_1\left(x_1^{(0)},........, x_n^{(0)}\right) \\ 0 - g_2\left(x_1^{(0)},........, x_n^{(0)}\right) \\ \vdots \\ 0 - g_n\left(x_1^{(0)},........, x_n^{(0)}\right) \end{bmatrix} \quad \text{..................} \quad (2.16)$$

The square matrix of partial derivatives is called the Jacobian matrix *J* with $J^{(1)}$ indicating that the matrix is evaluated for the initial values of $x_2^{(0)},......., x_n^{(0)}$. We can then write the solution of (2.16) as

$$\begin{bmatrix} \Delta x_1^{(0)} \\ \Delta x_2^{(0)} \\ \vdots \\ \Delta x_n^{(0)} \end{bmatrix} = \left[J^{(0)}\right]^{-1} \begin{bmatrix} \Delta g_1^{(0)} \\ \Delta g_2^{(0)} \\ \vdots \\ \Delta g_n^{(0)} \end{bmatrix} \quad \text{..} (2.17)$$

$\Delta g_k^{(0)} = g_k\left(x_1^*,..., x_n^*\right) - g_k\left(x_1^{(0)},......, x_n^{(0)}\right)$, (K= 1……….… n).

Since the Taylor's series is truncated by neglecting the 2nd and higher order terms. We cannot expect to find the correct solution at the end of first iteration. We shall then have

$$\begin{aligned} x_1^{(1)} &= x_1^{(0)} + \Delta x_1^{(0)} \\ x_2^{(1)} &= x_2^{(0)} + \Delta x_2^{(0)} \quad \text{..} (2.18) \\ &\vdots \\ x_n^{(1)} &= x_n^{(0)} + \Delta x_n^{(0)} \end{aligned}$$

These are then used to find $J^{(1)}$ and $\Delta g_k^{(1)}$, k=1,……., n. We can then find $\Delta x_2^{(1)},.............,\Delta x_n^{(1)}$ from an equation like (2.17) and subsequently calculate $x_2^{(1)},.............., x_n^{(1)}$. The process continues till Δg_k, k =1, …………, n becomes less than a small quantity.

$$\Delta g_k^{(0)} = 0 - g_k\left(x_1^{(0)},.........., x_n^{(0)}\right)$$

2.5.2 Load Flow through Newton-Raphson Method

Let us assume that an n-bus power system contains a total n_p number of P-Q buses while the number of P-V (Generator) buses be n_g such as $n= n_p+ n_g+1$.

Bus 1 is assumed to be the slack bus. We shall further use the mismatch equations of ΔP_i and ΔQ_i given in (2.9) and (2.10) respectively. The approach to Newton-Rapshon load flow is similar to that of solving a system of nonlinear equation using well known Newton-Rapshon numerical method. At each iteration, we have to form a Jacobian matrix and solve for the corrections from an equation of the form shown below,

$$[J]\begin{bmatrix}\Delta\delta_2\\ .\\ .\\ \Delta\delta_n\\ \dfrac{\Delta|V_2|}{|V_2|}\\ .\\ .\\ \dfrac{\Delta|V_{1+n_p}|}{|V_{1+n_p}|}\end{bmatrix}=\begin{vmatrix}\Delta P_2\\ .\\ .\\ \Delta P_n\\ \Delta Q_2\\ .\\ .\\ \Delta Q_{1+n_p}\end{vmatrix} \quad \text{...(2.19)}$$

Where the Jacobian matrix is divided into sub-matrices as

$$[J]=\begin{bmatrix}J_{11}J_{12}\\ J_{21}J_{22}\end{bmatrix} \quad \text{...(2.20)}$$

It can be seen that the size of the Jacobian matrix is $(n+n_p-1)\times(n+n_p-1)$.

The dimensions of the sub-matrices are as follows:

$J_{11}:(n-1)\times(n-1), J_{12}:(n-1)\times n_p, J_{21}:n_p\times(n-1), J_{22}:n_p\times n_p;$

The elements of sub-matrices are:

$$J_{11}=\begin{bmatrix}\dfrac{\partial P_2}{\partial\delta_2}\text{.......}\dfrac{\partial P_2}{\partial\delta_n}\\ \text{..................}\\ \text{..................}\\ \dfrac{\partial P_n}{\partial\delta_2}\text{.......}\dfrac{\partial P_n}{\partial\delta_n}\end{bmatrix} \quad \text{...(2.21)}$$

$$J_{12} = \begin{bmatrix} |V_2|\left|\frac{\partial P_2}{\partial |V_2|}\right| \ldots\ldots |V_{1+n_p}|\left|\frac{\partial P_2}{\partial |V_{1+n_p}|}\right| \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ |V_2|\left|\frac{\partial P_n}{\partial |V_2|}\right| \ldots\ldots |V_{1+n_p}|\left|\frac{\partial P_n}{\partial |V_{1+n_p}|}\right| \end{bmatrix} \quad \ldots\ldots (2.22)$$

$$J_{21} = \begin{bmatrix} \frac{\partial Q_2}{\partial \delta_2} \ldots\ldots\ldots \frac{\partial Q_2}{\partial \delta_n} \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ \frac{\partial Q_{1+n_p}}{\partial \delta_2} \ldots\ldots \frac{\partial Q_{1+n_p}}{\partial \delta_n} \end{bmatrix} \quad \ldots\ldots (2.23)$$

$$J_{22} = \begin{bmatrix} |V_2|\left|\frac{\partial Q_2}{\partial |V_2|}\right| \ldots\ldots |V_{1+n_p}|\left|\frac{\partial Q_2}{\partial |V_{1+n_p}|}\right| \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ |V_2|\left|\frac{\partial Q_{1+n_p}}{\partial |V_2|}\right| \ldots\ldots |V_{1+n_p}|\left|\frac{\partial Q_{1+n_p}}{\partial |V_{1+n_p}|}\right| \end{bmatrix} \quad \ldots\ldots (2.24)$$

2.5.3 Algorithm of Newton-Rapshon Method

The Newton-Rapshon procedure is as follows:

Step 1: Choose the initial values of the voltage magnitudes $|V|^{(0)}$ of all n_p load buses and n-1 angles $\delta^{(0)}$ of the voltages of all buses except the slack bus.

Step 2: Use the estimated $|V|^{(0)}$ and $\delta^{(0)}$ to calculate a total (n-1) number of injected real power $P_{calc}^{(0)}$ and equal number of real power mismatch $\Delta P^{(0)}$.

Step 3: Use the estimated $|V|^{(0)}$ and $\delta^{(0)}$ to calculate a total n_p number of injected reactive power $Q_{calc}^{(0)}$ and equal number of reactive power mismatch $\Delta Q^{(0)}$.

Step 4: Use the estimated $|V|^{(0)}$ and $\delta^{(0)}$ to formulate the Jacobian matrix $J^{(0)}$.

Step 5: Solve (2.19) for $\Delta\delta^{(0)}$ and $\Delta|V|^{(0)}/|V|^{(0)}$.

Step 6: Obtain the updates from

$$\delta^{(1)} = \delta^{(0)} + \Delta\delta^{(0)} \quad \text{..(2.25)}$$

$$|V|^{(1)} = |V|^{(0)}\left[1 + \frac{\Delta|V|^{(0)}}{|V|^{(0)}}\right] \quad \text{..(2.26)}$$

Step 7: Check if all the mismatches are below a small number. Terminate the process if yes. Otherwise go back to step 1 to start the next iteration with the updates given by (2.25) and (2.26).

2.6 Formation of the Jacobian Matrix

We shall now discuss the formation of the sub-matrices of the jacobian matrix. To do that we shall use the real and reactive power equations (2.6) and (2.7). Let us rewrite them with the help of (2.2) as

$$P_i = |V_i|^2 G_{ii} + \sum_{\substack{k=1 \\ k\neq i}}^{n} |Y_{ik}V_iV_k| \cos(\theta_{ik} + \delta_k - \delta_i) \quad \text{..(2.27)}$$

$$Q_i = -|V_i|^2 B_{ii} - \sum_{\substack{k=1 \\ k\neq i}}^{n} |Y_{ik}V_iV_k| \sin(\theta_{ik} + \delta_k - \delta_i) \quad \text{..(2.28)}$$

(a) Formulation of J_{11}. Let us define J_{11} as

$$J_{11} = \begin{bmatrix} L_{22} \ldots\ldots\ldots\ldots L_{2n} \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ L_{n2} \ldots\ldots\ldots\ldots L_{nn} \end{bmatrix} \quad \text{..(2.29)}$$

It can be seen from (2.21) that L_{ik}'s are the partial derivatives of P_i with respect to δ_k. From equation (2.27), this derivative is obtained for $i \neq k$ as follows

$$L_{ik} = \frac{\partial P_i}{\partial \delta_k} = -|Y_{ik}V_iV_K| \sin(\theta_{ik} + \delta_k - \delta_i), i \neq k \quad \text{..(2.30)}$$

Similarly the partial derivatives of P_i with respect to δ_k for $i = k$ is given by

$$L_{ii} = \frac{\partial P_i}{\partial \delta_i} = \sum_{\substack{k=1 \\ k\neq 1}}^{n} |Y_{ik}V_iV_k| \sin(\theta_{ik} + \delta_k - \delta_i) \quad \text{..(2.31)}$$

Comparing the above equation (2.31) with (2.28), we can write,

$$L_{ii} = -Q_i - |V_i|^2 B_{ii} \quad \text{……………………………………………...…………………………} \quad (2.32)$$

(b) Formulation of J_{21}. Let us define J_{21} as,

$$J_{21} = \begin{bmatrix} M_{22} \ldots\ldots\ldots\ldots M_{2n} \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ M_{n_p,2} \ldots\ldots M_{n_p,n} \end{bmatrix} \quad \text{…………………………………...………………………...} (2.33)$$

From (2.33) it is evident that the elements of J_{21} are the partial derivative of Q_i with respect to δ_k .

From (2.28) we can write,

$$M_{ik} = \frac{\partial Q_i}{\partial \delta_k} = -|Y_{ik} V_i V_k| \cos(\theta_{ik} + \delta_k - \delta_i) \; i \neq k \quad \text{……………………………………….....} (2.34)$$

Similarly for i=k, we have

$$M_{ii} = \frac{\partial Q_i}{\partial \delta_i} = \sum_{\substack{k=1 \\ k \neq 1}}^{n} |Y_{ik} V_i V_k| \cos(\theta_{ik} + \delta_k - \delta_i) \quad \text{……………………………………...……….} \quad (2.35)$$

Comparing the above equation (2.35) with (2.27), we can write,

$$M_{ii} = P_i - |V_i|^2 G_{ii} \quad \text{……………………………………………………….........................} (2.36)$$

(c) Formulation of J_{12}. Let us define J_{12}

$$J_{12} = \begin{bmatrix} N_{22} \ldots\ldots\ldots\ldots N_{2n_p} \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ N_{n2} \ldots\ldots\ldots\ldots N_{nn_p} \end{bmatrix}$$

……………………………………………………...……….(2.37)

As evident from (2.22), the elements of J_{12} Involve the derivatives of real power P_i with respect to magnitude of bus voltage $|V|$ .For $i \neq k$, we can write from (2.27)

$$N_{ik} = |V_k| \frac{\partial P_i}{\partial |V_k|} = |Y_{ik} V_i V_k| \cos(\theta_{ik} + \delta_k - \delta_i) = -M_{ik} \; i \neq k \quad \text{…………………………...……..} (2.38)$$

$$N_{ii} = |V_i| \frac{\partial P_i}{\partial |V_i|} = |V_i| \left[2|V_i| G_{ii} + \sum_{\substack{k=1 \\ k \neq 1}}^{n} |Y_{ik} V_k| \cos(\theta_{ik} + \delta_k - \delta_i) \right]$$

$$= 2|V_i|^2 G_{ii} + \sum_{\substack{k=1 \\ k\neq 1}}^{n} |Y_{ik} V_i V_k| \cos(\theta_{ik} + \delta_k - \delta_i)$$

$$= 2|V_i|^2 G_{ii} + M_{ii}$$

$$= P_i + |V_i|^2 G_{ii} \qquad (2.39)$$

(d) Formulation of J_{22}. For the formation of J_{22}

$$J_{22} = \begin{bmatrix} O_{22} \ldots\ldots\ldots O_{2n_p} \\ \ldots\ldots\ldots\ldots \\ \ldots\ldots\ldots\ldots \\ O_{n_p,2} \ldots\ldots\ldots O_{n_p,n_p} \end{bmatrix} \qquad (2.40)$$

For $i \neq k$, we can write from (2.28)

$$O_{ik} = |V_k| \frac{\partial Q_i}{\partial |V_k|} = -|V_k||Y_{ik} V_i| \sin(\theta_{ik} + \delta_k - \delta_i) = L_{ik}\, , i \neq k \qquad (2.41)$$

Finally for $i = k$, we have

$$O_{ii} = |V_i| \frac{\partial Q_i}{\partial |V_i|} = |V_i| \left[-2|V_i| B_{ii} - \sum_{\substack{k=1 \\ k\neq 1}}^{n} |Y_{ik} V_k| \sin(\theta_{ik} + \delta_k - \delta_i) \right]$$

$$= -2|V_i|^2 B_{ii} - \sum_{\substack{k=1 \\ k\neq 1}}^{n} |Y_{ik} V_i V_k| \sin(\theta_{ik} + \delta_k - \delta_i)$$

$$= -2|V_i|^2 B_{ii} - L_{ii}$$

$$= Q_i - |V_i|^2 B_{ii} \qquad (2.42)$$

We therefore see that once the sub-matrices J_{11} andJ_{21} are computed, the formation of the sub-matrices J_{12} and J_{22} is fairly straight forward. For large system, this will result in considerable saving in the computation time.

Chapter 3

INCLUSION OF SLACK BUS IN THE ITERATION PROCESS

3.1 Introduction

This thesis analyzes the system losses equation and it is found to be a function of bus voltage magnitudes and their angles. Since the elements of Jacobian in Newton-Raphson method are the derivatives of real and reactive power with respect to voltage magnitudes and angles, hence with the inclusion of loss, it is necessary to modify the elements of Jacobian matrices by adding terms involving the rate of change of loss with respect to the two variables. The thesis devised an accurate formulation for such inclusion. Finally the method has been applied to solve the load flow considering slack bus to carry all losses and the results obtained from the new method are compared with those obtained using conventional method. The accuracy of the new method is found to be in close agreement with the conventional method.

3.2 Mathematical Formulation of New Load Flow

The Popular Newton- Raphson method has been modified to formulate the new method of load flow. For given loads in a system, the load flow solution provides us the powers at the generating units to be maintained in order to balance the loads and the losses in the line. The losses cannot be pre-calculated. Following certain criteria (usually on economic ground), the initial values of the powers to be supplied by the generating units are decided first. In our developed system, at the beginning of iteration the losses are assumed to be zero and so, the generation powers are pre-selected to supply the loads only. The loss is calculated at each iteration and included with the slack bus. This is achieved by including the rate of change of the losses with the magnitude of voltage magnitudes and angles into the Jacobians in the iterative process. Therefore, the loss is calculated on the fly. The calculated loss can be distributed among the generation units according to a pre-specified proportion on top of the present generations of the units. At the end of convergence the final distribution of generation is found out. The schedule of generations is the result of the load flow for the given system under the given scenario.

3.2.1 The Power Equation

The apparent power injected at a bus *i*, is given by

$$S_i = P_i + jQ_i = V_i I_i^* = V_i \sum_{k=1}^{n} V_k^* Y_{bus_{ik}}^* \quad \text{.....} \quad (3.1)$$

The real and reactive power is separated as,

$$P_i = \mathrm{Re}\left[V_i^* \sum_{k=1}^{n} V_k Y_{bus_{ik}} \right] \quad \text{.....} \quad (3.2)$$

$$Q_i = -\mathrm{Im}\left[V_i^* \sum_{k=1}^{n} V_k Y_{bus_{ik}} \right] \quad \text{....} \quad (3.3)$$

Since, we have considered that the slack bus will take the total loss of the system, so the loss calculated after each iteration is added with original scheduled power considered at the beginning of the iteration. The modified scheduled real power should be equated with the injected real power, P_i (where bus number *i* is slack bus of IEEE Cases) obtained from equation (3.2). In other words, the original scheduled real power at slack bus can be equated with the injected power obtained from equation (3.2) minus the losses calculated after each iteration. The modified injected power may be termed as modified injected power at the slack bus. The modified injected power at bus *i* is given by,

$$P_i^{'} = P_i - loss \quad \text{....} \quad (3.4)$$

By combining equation (3.2) and (3.4) we obtain,

$$P_i^{'} = \mathrm{Re}\left[V_i^* \sum_{k=1}^{n} V_k Y_{bus_{ik}} \right] - loss \quad \text{....} \quad (3.5)$$

The total loss is summation of losses of all branch lines of the system. It is a function of voltage of the buses.

3.2.2 The Losses Equation

The total loss can be expressed as,

$$loss = \sum_{i=1}^{n-1} \sum_{k=i+1}^{n} \left| (V_i - V_k)^2 Y_{bus_{ik}}^2 \ \mathrm{Re}\left[\frac{-1}{Y_{bus_{ik}}} \right] \right|$$

$$= \sum_{i=1}^{n-1} \sum_{k=i+1}^{n} \left| (V_i - V_k)^2 C_{ik} \right| \quad \text{....} \quad (3.6)$$

Where, $C_{ik} = Y_{bus_{ik}}^2 \ \mathrm{Re}\left[\dfrac{-1}{Y_{bus_{ik}}} \right]$ ....(3.7)

3.3 Inclusion of Loss Equation in the Jacobian Matrix.

Now in elements the loss terms in the Newton- Raphson method [12], the elements of the Jacobian corresponding to ΔP_i is given by,

$$\frac{\partial P_i}{\partial \delta_i} = \frac{\partial}{\partial \delta_i}\left\{\mathrm{Re}\left[V_i^* \sum_{k=1}^{n} V_k Y_{bus_{ik}}\right]\right\} - \frac{\partial loss}{\partial \delta_i} \quad \text{..} (3.8)$$

$$\frac{\partial P_i}{\partial |V|_i} = \frac{\partial}{\partial |V|_i}\left\{\mathrm{Re}\left[V_i^* \sum_{k=1}^{n} V_k Y_{bus_{ik}}\right]\right\} - \frac{\partial loss}{\partial |V|_i} \quad \text{..} (3.9)$$

$\{Conventional \ \ term\}$ $\{New \ \ term\}$

The derivation of the conventional terms can be found in ref. [20].

The new terms in equation (3.8) and (3.9) can be obtained by differentiating equation (3.6) with respect to δ_i and $|V|_i$ respectively.

The losses terms which are functions of V_i can be obtained. It is expressed as

$$\mathrm{Loss}(V_i) = \sum_{\substack{k=1 \\ k\neq 1}}^{n} (V_i - V_k)^2 C_{ik} \quad \text{..} (3.10)$$

So, when the equation (3.10) is differentiated with respect to δ_i and $|V|_i$, where $V_i = |V_i| e^{j\delta_i}$ In order to incorporate the new term, the expression of the derivatives of loss are found to be as follows,

$$\frac{\partial loss}{\partial \delta_i} = 2\sum_{\substack{k=1 \\ k\neq 1}}^{n} C_{ik}(V_i - V_k)\, jV_i \quad \text{..} (3.11)$$

$$\frac{\partial loss}{\partial |V|_i} = 2\sum_{\substack{k=1 \\ k\neq 1}}^{n} C_{ik}(V_i - V_k) e^{j\delta_i} \quad \text{..} (3.12)$$

Therefore, the elements of J_{11} and J_{12} of the Jacobian [J] given by equation (3.8) and (3.9) should be updated by including the new terms.

3.4 MATPOWER Program

MATPOWER [21] is an open-source MATLAB-based power system simulation package that provides a high-level set of power flow, optimal power flow (OPF), and other tools targeted toward researchers, educators and students. MATPOWER was developed by Ray Zimmerman and Deqiang Gan of PSERC (Power Systems Engineering Research Center) at Cornell University in ref [22] under the direction of Robert Thomas. The initial need for MATLAB based power flow and optimal power flow code was born out of the computational requirements of the Power Web project in ref [23].

The power flow analysis can be performed using various simulations software. The basic simulations software used are MATPOWER, PSAT, NETBAS, EPSO and SWARM [24]. PSAT and MATPOWER are the MATLAB toolboxes/M-files used for power flow analysis and are freeware software. In MATPOWER it becomes difficult to enter data for complex network. PSAT is more user friendly than the MATPOWER. NETBAS is the sophisticated among the other software, in which we can easily perform the power flow analysis of complex system and can provide many useful and relevant data of the system. In spite of MATPOWER is difficult but we will use MATPOWER in this thesis.

3.4.1MATPOWER Running Procedures

MATPOWER code is written in MATLAB M-files, is specifically targeted at researchers and educators in the field of power engineering [25]. MATPOWER is designed to give the best performance while keeping the code simple and easy to modify by the user. It could be downloaded free of charge from [11].

To install MATPOWER on a personal computer, MATLAB version 6 or a later version with optimization toolbox is needed [18]. The downloaded file requires to be unzipped and placed in a location on MATLAB path. For example, an installation of 4.1 version of MATPOWER is demonstrated as follows: ***C: \ ProgramFiles\MATLAB\R2006a\matpower4.1.***

To run a programme in MATPOWER, start-up MATLAB and type the desired M-file name at the command window prompt, then press the enter key. For example, typing:

>>runpf (´case9´)

And thereafter press the enter key at the command window prompt of MATLAB would run a power flow of 9-bus power system already pre-stored in MATPOWER. This file could then be saved in another name and modified to the taste of the user as appropriate.

To carry out a load flow analysis, MATPOWER has five solvers to do this. These solvers are Newton, Gauss-Seidel, Fast Decoupled and DC power flow; which can be accessed via the '*runpf*' function. The power flow default solver uses the Newton's method. To use any of the rest solvers, it is necessary that the PF_ALG option must be set explicitly. Interested reader could consult ref [24] for detail explanation of each of these solvers and their settings.

3.4.2 The MATPOWER Solution Technique

Solving the power flow problem using MATPOWER requires the system data to be entered such as IEEE Case 9, Case 14, Case 30, Case 39 & Case57 etc. In entering the bus data, type 1, type 2, type 3, type 4 are used for the voltage control buses, the load buses, the slack bus and the isolated buses respectively. It is assumed in these cases that the voltage level of the line is 132KV, though any voltage level could be entered as the base KV.

It should be noted that the total line charging susceptance are entered in the ***branch data*** even though one-half line charging susceptance are supplied. The ***status 1*** in the generator and ***branch data*** denotes that both devices are in service. ***Status 0*** means the devices are out of service, while ***Status 2*** indicates that the devices are isolated from the rest power system. The power flow of system under consideration is run by typing at the MATLAB command prompt

>>runpf (´Case n`)

[Where n = IEEE Case number = 9,14,30,39 etc., and Case 9 is by default case in MATPOWER]

and striking the enter key. The result which converged in few seconds is presented in the MATLAB command prompt / Window.

The result of the power flow problem obtained from MATPAOWER package is exactly as that obtains in MATLAB command window. This fact confirms the accuracy of the MATPOWER Package. Another beauty of MATPOWER is that it has the capability to compute and display some other details of the system that are not available in the anther programs such as PSAT, NETBAS and SWARM etc . These details, tagged ***system summary*** are present in MATLAB command window. In the said ***system summary***, all the power flow results of the system under consideration could be viewed at a glance.

3.4.3Case Study of IEEE System by MATPOWER

In this thesis we have used total 5 no. case. These are IEEE Case 9, Case14, Case 30, Case 39 and Case 57. We will discuss in details only about case 9 as example because of Case 9 is default case of MATPOWER Program. In case 9, total buses number is 9(nine) such as bus_i (where, i=1, 2, 3……...n)as shown in the figure-2.4(a). In which first three buses (1, 2, and 3) are Generator or Voltage control buses. Bus number 2 is Generator bus but generation capacity (***Pg***) of this bus very higher than others as shown in fig 2.4(b) after also subtracting from Load demand (***Pd***) as shown in figure 2.4(a). So we will count to this bus as Slack Bus. Besides this, all of buses (4 to 9) are Load buses.

```
%% bus data
% bus_itypePdQdGsBs  area  VmVabaseKV zone  Vmax      Vmin
mpc.bus = [
      1  2   0   0   0   0    1    1     0      345   1     1.1   0.9;
      2  3   0   0   0   0    1    1     0      345   1     1.1   0.9;
      3  2   0   0   0   0    1    1     0      345   1     1.1   0.9;
      4  1   0   0   0   0    1    1     0      345   1     1.1   0.9;
      5  1   90  30  0   0    1    1     0      345   1     1.1   0.9;
      6  1   0   0   0   0    1    1     0      345   1     1.1   0.9;
      7  1  100  35  0   0    1    1     0      345   1     1.1   0.9;
      8  1   0   0   0   0    1    1     0      345   1     1.1   0.9;
      9  1  125  50  0   0    1    1     0      345   1     1.1   0.9;
];
```

Figure 2.4(a): Bus Data for IEEE Case 9

```
%% generator data
%bus  PgQgQmaxQmin Vg mBase status sPmaxPmin Pc1 Pc2 Qc1min Qc1max
Qc2min Qc2max ramp_agc ramp_10 ramp_30 ramp_qapf
mpc.gen = [
     1  0    0 300 -300 1 100 1  250 10 0  0  0 0  0  0  0  0  0  0  0;
     2  163  0 300 -300 1 100 1  300 10 0  0  0 0  0  0  0  0  0  0  0;
     3  85   0 300 -300 1 100 1  270 10 0  0  0 0  0  0  0  0  0  0  0;
];
```

Figure 2.4(b): Generator Data for IEEE Case 9

3.5 Modification of MATPOWER Program

The original MATPOWER program is used for the validation purpose. The original program is based on considering single slack bus outside the iterations and the modified method is by considering the slack bus inside the iterative process.

We have modified and designed many codes for converging and supporting in the case of "modification in Jacobian Matrix in Newton-Rapshon iterative process" in MATLAB m-file ***newtonpf.m*** (MATPOWER file). New codes (with previous necessity Codes) of ***newtonpf.m*** will work properly if we use ***modify=1.*** On the other hand, previous ***newtonpf.m*** will be tasks without any changed for conventional load flow if we select ***modify=0.***

We have included losses equation in***newtonpf.m*** of MATPOWER. The program gives the solution of the new term of losses equation using the Newton-Raphson method. The equations and the Jacobian matrix are explicitly entered in the program itself. The program gives the solution of losses equation through the Jacobian sub-matrices solution by the number of iterations. The modified program listing is given in Appendix -1.

Chapter 4

TEST RESULT

4.1 Comparison of the Development Technique with Conventional One

IEEE 9 bus, 14 bus, 30 bus, 39 bus & 57 bus test systems [26] have been considered for testing the developed method. The number of generator and the total power are different in different systems. At the beginning of the iteration the generation and the load power were made equal. The line parameters and other system data of the five systems may be obtained in ref. [26].

Load flow analysis is carried out in IEEE 9 bus, 14 bus, 30 bus, 39 bus & 57 bus test system using conventional load flow and our developed load flow. The magnitudes of voltage and phase angle have been compared between conventional load flow and new load flow. All data's are in per unit and the angles are given in degree.

The bus voltage and their angles were found be exactly equal in both the cases. Therefore only a sample result is shown in following table and it is shown for IEEE 9 bus system.

Method Proof:

Buses Number	Voltages at different Buses	
	Conventional	Losses at Slack Buses
1	$1.000\angle 0.000$	$1.000\angle 0.000$
2	$1.000\angle 10.157$	$1.000\angle 10.157$
3	$1.000\angle 5.233$	$1.000\angle 5.233$
4	$0.987\angle -2.242$	$0.987\angle -2.242$
5	$0.975\angle -3.571$	$0.975\angle -3.571$
6	$1.003\angle 2.387$	$1.003\angle 2.387$
7	$0.985\angle 1.196$	$0.985\angle 1.196$
8	$0.996\angle 4.457$	$0.996\angle 4.457$
9	$0.957\angle -4.022$	$0.957\angle -4.022$

Table 4.1(a): Comparison of magnitude and phase angle of voltage for IEEE 9 bus system.

4.2 Case Studies Considering Distributed Slack Bus

The original program was used for comparison purpose with our development program. First of all the original program is run with the data for IEEE 9 bus, 14 bus ,30 bus, 39 bus & 57 bus[6]. The original program is based on considering single slack bus outside the iterations. On the contrary, in the modified program slack bus is included inside the iterative process by modifying the Jacobian. In the modified program, the losses are calculated in each iteration and subtracted from the calculated injected power to compare with the scheduled power of the slack bus. Secondly, the modified program is run for verifying our developed program where losses are considered only in one bus. Thirdly the modified program is run where losses has been distributed according to proportional of generation capacity.

Loss figure when calculated during iterative process in our modified load flow, result obtain indicates that the inclusion of loss and its effect on Jacobian is correct.

In conventional load flow, total losses of the system have added in the slack bus. But in the modified program slack bus have considered as a normal PV bus. Burden of slack bus has been removed because of total loss of the system has been distributed according to proportion of generation capacity. In all the cases the final results are same. So accuracy of modified program has been proved from obtained result. The necessary tables are given below for IEEE case9, case14, case30, case39 & case 57.

Distributed Losses (Losses proportional of generation capacity)for Micro-grid:

Generator Buses		Generation with loss		
			Developed load flow	
Bus No.	Generation(MW)	Conventional Load flow(MW)	Considering loss at slack bus(MW)	Considering loss divided according to proportion of generator(MW)
1	67	67.00	67.00	68.095
2	163(Slack)	168 .21	168 .21	165.658
3	85	85.00	85.00	86.388
Total	315	320.21	320.21	320.142

Table 4.2(a): Comparison of losses for IEEE 9 bus system.

Generator Buses		Generation with loss		
Bus No.	Generation(MW)	Conventional Load flow(MW)	Developed load flow	
			Considering loss at slack bus(MW)	Considering loss divided according to proportion of generator(MW)
1	219(Slack)	232.39	232.39	230.236
2	40	40.00	40.00	42.045
Total	259	272.39	272.39	272.281

Table 4.2(b): Comparison of losses for IEEE-14 bus system.

Generator Buses		Generation with loss		
Bus No.	Generation(MW)	Conventional Load flow(MW)	Developed load flow	
			Considering loss at slack bus(MW)	Considering loss divided according to proportion of generator(MW)
1	23.54	23.54	23.54	23.841
2	60.97(Slack)	63.40	63.40	61.749
13	37.00	37.00	37.00	37.473
22	21.59	21.59	21.59	21.866
23	19.20	19.20	19.20	19.445
27	26.91	26.91	26.91	27.254
Total	189.21	191.64	191.64	191.628

Table 4.2(c): Comparison of losses for IEEE-30 bus system.

Generator Buses		Generation with loss		
Bus No.	Generation(MW)	Conventional Load flow(MW)	Developed load flow	
			Considering loss at slack bus(MW)	Considering loss divided according to proportion of generator(MW)
30	250.00	250.00	250.00	251.777
31	634.23	634.23	634.23	638.715
32	650.00	650.00	650.00	654.619
33	632.00	632.00	632.00	636.486
34	508.00	508.00	508.00	511.598

35	650.00	650.00	650.00	654.619
36	560.00	560.00	560.00	563.998
37	540.00	540.00	540.00	543.820
38	830.00(Slack)	876.05	876.05	835.907
39	1000.00	1000.00	1000.00	1007.106
Total	6254.23	6300.28	6300.28	6298.645

Table 4.2(d): Comparison of losses for IEEE-39 bus system.

Generator Buses		Generation with loss		
Bus No.	Generation(MW)	Conventional Load flow(MW)	Developed load flow	
			Considering loss at slack bus(MW)	Considering loss divided according to proportion of generator(MW)
1	450.8(Slack)	478.66	478.66	460.434
3	40.00	40.00	40.00	40.856
8	450.00	450.00	450.00	459.634
12	310.00	310.00	310.00	316.636
Total	1250.8	1278.66	1278.66	1277.56

Table 4.2(e): Comparison of losses for IEEE-57 bus system.

4.3Minimization of Losses

The following table presents the losses in convention load flow and our developed load flow. It shows that the loss, P (MW) has been minimized. These results indicate that the modified load flow can be used for loss optimization.

Case Studies	Losses($I^2 \times R$) in Conventional load flow, P(MW)	Losses ($I^2 \times R$) in developed load flow, P(MW)	Losses Reduction (%)
IEEE Case-9	5.214	5.142	1.38
IEEE Case-14	13.393	13.281	0.84
IEEE Case-30	2.435	2.417	0.74
IEEE Case-39	46.049	44.415	3.55
IEEE Case-57	27.864	26.760	3.96

Table 4.3 (a): Comparison total losses for distributed system with Conventional.

4.4 Discussion of Results

In this section we have discussed about results of conventional load flow and our modified load flow. We have noticed that voltages magnitudes and phase angles of the all buses between conventional load flow and new load flow is always same. Besides this, we see that losses are minimized at the ends of the iterations (when convergence occurred) if total losses are distributed according to generation capacity. Consequently, burden of slack bus has been removed by our developed new method and so this method has been suitable for micro-grids.

Chapter 5

CONCLUSION

5.1 Conclusion

A method of including the slack bus during iterative process of Newton-Raphson method has been presented. It is based on inclusion of line losses at every iteration. The effect of inclusion of loss has an impact on Jacobian elements. The mathematical formulation of this impact has been analyzed and the expressions of the variation of loss with voltage magnitudes and their angles have been presented in the thesis. The validity of the formulation has been applied in five another case test systems. The agreement between the results of the new method with the convention has proved the accuracy of the development.

In this thesis we have presented that total loss can be distributed in the all generator buses without considering slack bus as per generation capacity and summation of total losses of the system is less than that stained by considering a single slack bus.

The ease of new method has opened us a new avenue to explore numerous studies which were not possible by the conventional method.

5.2 Further Works

Further research may be carried out to address the following issues:

1. Study of amount of total losses based on different criteria.
2. Optimization of losses applying our development technique.

Appendix-1

```
if modify==1
   for ii=1:npv
       forjj=1:(npv+npq)
           sum1=0.0;
           forkk=1:(npv+npq)
              ifkk~=jj
                const(jj,kk)=0.0;
                ifYbus(jj,kk)~=0
                  const(jj,kk)=abs((Ybus(jj,kk)^2)* real(-
1/Ybus(jj,kk)));
               end
                    sum1=sum1+2*abs(const(jj,kk)*(V(jj)-V(kk))*V(jj));
            end
        end
            j11(ii,jj)=j11(ii,jj)-sum1*perc(pv(ii));
      end
  end

for ii=1:npv
    forjj=1:npq
           sum2=0.0;
       forkk=1:(npv+npq)
          ifkk~=jj
            const(jj,kk)=0.0;
            ifYbus(jj,kk)~=0
              const(jj,kk)=abs((Ybus(jj,kk)^2)* real(-1/Ybus(jj,kk)));
            end
                    sum2=sum2+2*abs(const(jj,kk)*(V(jj)-V(kk)));
          end
        end
            j12(ii,jj)=j12(ii,jj)-sum2*perc(pv(ii));
      end
end

end



if modify==1
   for i1=1:npv
        Sbus(pv(i1))=p0(pv(i1))+loss*perc(pv(i1)) + 1j *
imag(Sbus(pv(i1)));
   end
end
```

REFERENCES

[1] J. J. Grainger and W. D. Stevension, : “Power System Analysis”, a book published by Tata-McGraw Hill Education, 2003

[2] I.J Nagrath& D.P Kothari:" Modern Power System Analysis” by Tata-McGraw Hill, ISBN 978-0-07-049489-3. [26] H. Saadat: “Power System Analysis, 2002,” McGraw- Hill Higher Education (ISBN 0-07-284-896-3)

[3] L.P. Singh: "Advanced Power System Analysis & Dynamics” by New age International, ISBN 978-0-07-049489-3.

[4] B.Stott: " Review of Load –Flow Calculation Methods" proceedings of the IEEE, Vol.2, No.7, p.p 916-929, July 1974.

[5] R. M. Kamel, A. Chaouci, K. Nagasaka, : “Detailed Analysis of Micro-Grid Stability during Islanding Mode under Different Load Conditions”, online journal *www.SciRP.org*, May 2011.

[6] Thai Hau Vo , Mingyu Liao, Tianhui Liu, Anushree, JayashriRavishankar, ToanPhung, John Fletcher: “Unbalanced Power Flow Analysis in a Micro Grid”. International Journal of Emerging Technology and Advanced Engineering, ISSN 2250-2459, ISO 9001:2008 Certified Journal, Volume 3, Issue 1, January 2013.

[7] J.B. Ward ant H.W Hale:" Digital Computer Solution of Power flow problems" AZEEtrans. (Power App. Syst.), Vol.75, PP.398-404, June 1986.

[8] MohdShahimi Bin Mohammad ISA: " Power Flow Analysis Software using MATLAB" University of Malaysia Pahang. Page 1-24.

[9] MATLAB™ Power System Simulation Package for Matpower: *“www.pserc.wisc.edu/ecow/get/publicatio/1998public/manual.pdf”*

[10] R.D Zimmeman and B. Littlefield, Mastering Mathlab 6: “a comprehensive tutorial and references”: Prentice Hall NJ, 2001.

[11] MATPOWER Package: "*http://www.pserc.cornell.edu/matpower/*"

[12] A. Mohapatra, : "Distributed Slack Bus Algorithm for Economic Load Dispatch", An undergraduate thesis, 2006, NIT, Roukela, India.

[13] Chayakulkheeree, K. Sripatum: "Application of Distributed Slack Bus Power Flow to Competitive Environments", Australian Universities Power Engineering Conference, (AUPEC), Dec2007, PP 1-6.

[14] Shiqiong Tong, Miu K.N. : "Participation Factor Studies for Distributed Slack Bus Models in Three-Phase Distribution Power Flow Analysis", Transmission and Distribution Conference and Exhibition, 2005/2006, IEEE PES, 21-24 May 2006, Pages 92-96.

[15] P. H. Haley and M. Ayres: "Super Decoupled Load Flow with Distributed Slack Bus", IEEE transactions on Power Apparatus and Systems, Vol. PAS-104, 1985, PP 104-113.

[16] AleksandarDimitrovski and Kevin Tomsovic: "Slack Bus Treatment in Load flow solutions with Uncertain Nodal powers." 8th International conference on Probabilistic Methos Applied to power System, lowa State University, Ames,lowa, September 12-16,2004.

[17] SoumyaRanjan Panda: "Distributed Slack Bus Model for Qualitative Economic Load Dispatch." An undergraduate thesis, May-2013, National Institute of Technology, Rourkela, India.

[18] ShiqiongTong:"Slack Bus Modeling for Distributed Generation and Its Impacts on Distribution System Analysis, Operation and Planning" PHD research, Drexel University, October 2006.

[19] Peter Musau Moses1, Dr. Nicodemus AbunguOdero: "Distributed Slack Bus Model for a Wind-Based Distributed Generation using Combined Participation Factors". International Journal of Emerging Technology and Advanced Engineering, ISSN 2250-2459, Volume 2, Issue 10, October 2012

[20] H. Saadat: "Power System Analysis, 2002," McGraw- Hill Higher Education (ISBN 0-07-284-896-3)

[21] 21 Ray Daniel Zimmerman, Carlos Edmundo Murillo-Sanchez and Robert John Thomas: "MATPOWER: Steady-State Operations, Planning and Analysis Tools for Power Systems Research and Education." IEEE Transaction on Power Systems, Vol. 26, Issue 1, PP 12-19, Feb 2011.

[22] Resources: Power Systems Engineering Research Centerhttp://www.pserc.cornell.edu/

[23] Resources: Power web http://www.pserc.cornell.edu/powerweb/.

[24]Vladimiro Miranda &Nuno Fonseca: "New Evolutionary Particle SWAR Algorithm (ESPO) Applied to Voltage/VAR control"., INESC(Instituto de Engenharia de Sistemas e Computadores do Porto P. Republica 93-4050 porto –Portugul, FEUP- Faculdatde de Engenharia da Universidade do Porto, Portugal.

[25] R.D. Zimmermen and C.E. Murillo-sanchez," Matpower 3.2 user's manuals".

[26] Resources: "Power System Test Case Archive: "*www.ee.washington.edu/research/pstca/*"

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