CHAPTER 1: INTRODUCTION

Bulk electrical power is generated by three main methods: hydro sources, thermal stations and geo-thermal generating stations. Offgrid (Isolated power supplies) are obtained from diesel engine driven generators. Others are cogeneration and wind. The power is generated at 11kV and is stepped up to high voltages of 220kV and 132 kV for transmission. The transmission voltages are to a large extent determined by system loss considerations. High voltage transmission requires conductors of larger cross-section which results in lower resistances, hence less energy losses on transmission lines. The load centres are usually located away from generating stations. Therefore, the power is transmitted to the load centres where it is stepped down to 66kV or 33kV, the distribution level. The load demand determines the voltage at which power is to be supplied. The loads may be residential, industrial or commercial which brings about the peak load and off peak load hours. Power is transmitted from low demand areas to high load demand in the grid network. The control of generation, transmission, distribution and area exchange is performed from a centralized location. In order to perform the control functions satisfactorily, the steady state power flow must be known. The entire system is modelled as an electric network and a solution is simulated using a digital program. Such a problem solution practice is called power flow analysis.

The power flow analysis (also known as the load flow problem) is a very important and fundamental tool involving numerical analysis applied to a power system. The results play a major role in the day to day operation of any system for its control and economic schedule. The analysis is also employed during power system design procedures, planning expansion and development of control strategies. The purpose of any load flow analysis is to compute precise steady-state voltages and voltage angles of all buses in the network, for specified load, generator real power and voltage conditions. Once this information is known, the real and reactive power flows into every line and transformer, as well as generator reactive power output can be analytically determined. Due to the nonlinear nature of this problem, numerical methods are employed to obtain a solution that is within an acceptable tolerance.

Unlike in traditional circuit analysis, where voltages and currents through branches of direct current (d.c) circuits, the load flow study uses simplified notation such as the one line diagram, per unit representation and focuses on various forms of AC power (Real and Reactive), rather than voltage. It is normally assumed that the system is balanced and the common use of the term implies a positive sequence solution only.

A power flow analysis for a system operating under actual or projected normal operation conditions (base case) give the results which constitute a benchmark for comparison of changes in the network flows and voltages under abnormal conditions. The principal information obtained from power flow analysis, also known as the load flow study is the magnitude and phase angle of the voltage at each bus and real and reactive power flowing in each line.

The load flow problem non-linear relationships are given which involve the real and reactive power consumption at a bus, or the generated real power and scheduled voltage magnitude at a generator bus. As such, the load flow gives the electrical response of the transmission system to a particular set of loads and generators unitsô outputs.

Before the development of large digital computers, load flow analysis were carried out on AC calculating boards which provided small scale single phase replicas of the actual systems by interconnecting circuit elements and voltage sources. The whole process of setting connections, making adjustments, and reading the data was tedious and time consuming. Hence the use of digital computer load flow programs to routinely run for systems of up to 5000 or more buses and also to study in power systems control centres, the unique operating problems of power systems.

Electric utility companies worldwide use conventional elaborate programs to perform power flow analysis aimed at evaluating the adequacy of complex interconnected network. Important information is obtained concerning the design and operation of systems that have not yet been built and effects of changes on existing systems.

The solution to the power-flow problem is of fundamental importance in power system analysis, design and for starting points of other system studies such as transient stability analysis, economic analysis and fault analysis in power systems which demand solutions to a power-flow problem as a first step in the analysis. In particular, some programs use linear programming to find the optimal power flow (OPF), Security Constrained Optimal Power Flow (SCOPF) and State Estimation (ES), the conditions which give the lowest cost per kilowatt (kW) generated.

In this paper, the purpose of power flow analysis is to determine Kenyan Power transmission grid systems power flows. The analysis is performed by simulation of the Kenyan power transmission Network under MATLAB Environment as a substitute to Power System Simulator for Engineers software (PSS/E), commercial based software which is normally used by Kenya Power and Lighting Company. The software is used to determine the reliability of the transmission system under normal and emergency operating conditions.

The rest of the paper is organised as follows: A brief account of Kenya power sector (Generation and Transmission) is given in chapter2. Theory and background on the operation states of Power Systems and methodology of power flow analysis is given in chapter 3. The power flow problem and simulation of the Network in chapter 4. Results, Analysis and Discussion of project are given in chapter 5.The Conclusion and Recommendation in chapter 6.

CHAPTER 2: THE KENYA POWER SECTOR

2.1 The Existing System

The Kenyan power transmission and distribution network is owned and operated by KPLC. The main public sector generator is Kenya Electricity Generating Company (KenGen) which supplies 80% of the national electricity demand, with the balance being supplied by Independent Power Producers (IPPs). KPLC and the Uganda Electricity Transmission Company Limited (UETCL) have an electricity exchange contract currently with net power export to Uganda. Mumias Sugar Company is the only local co-generator supplying the grid and currently injects up to 2 MW from its sugar factory in Western Kenya. The capacity will be increased to 25 MW by the end of 2008.

The current national installed interconnected capacity is 1,296 MW comprising of 737 MW hydroelectric, 279 MW thermal, 128 MW geothermal, 150 MW emergency diesels, 2 MW cogeneration, and 0.4 MW wind. Table 2.1 gives a summary of the installed and effective generation capacity including the Governmentôs off-grid power stations.

POWER STATION	**CAPACITY (MW)**	
	Installed	**Effective**
Hydro		
Tana	14.4	10.4
Wanjii	7.4	7.4
Kamburu	94.2	90
Gitaru	225	216
Kindaruma	40	40
Masinga	40	40
Kiambere	144	144
Small Stations	6.3	5.6
Turkwel	106	106
Sondu	60	60
Total Hydro	**737.3**	**719.4**
Geothermal		

Olkaria I (KenGen)	45	45
Olkaria II (KenGen)	70	70
Olkaria III (IPP)	13	13
Total Geothermal	**128**	**128**
KenGen Wind		
Ngong	0.4	0.4
KenGen Thermal		
Kipevu Steam	0	0
Kipevu I Diesel	75	60
Kipevu GT1 and GT2	60	60
Nairobi Gas Turbine	13.5	10
Total KenGen Thermal	**148.5**	**130**
IPP Thermal		
Iberafrica Diesel	56	56
Tsavo Power Diesel	74	74
Mumias Cogeneration	2	0
Total Thermal	**132**	**132**
Emergency Power Producers		
Aggreko Power	150	146
Imports		
UETCL (Imports)	0	0
TANESCO	0	0
Total Interconnected System	**1,246**	**1,254**
Isolated Stations		
KenGen Diesel Stations	5.2	4.6
REF Diesels and Wind Off-grid Stations	6.1	5.1
Total Off-grid Capacity	**11.3**	**9.7**

Gross Capacity	**1,257**	**1,263**
Kenya Interconnected System Peak Demand		**1,044**

Table 2.1: Breakdown of Existing Generation Capacity

2.2 The Kenyan Transmission Network

The Kenya Power and Lighting Company (KPLC) own transmission and distribution lines of different voltage capacities scattered all over the country. The transmission system as of June 2007 comprise of 1,323 km of 220 kV and 2,122 km of 132 kV lines and the distribution system comprise of , 632km of 66kV 29 km of 40 kV, 11,163 km of 33 kV and 21,918 km of 11 kV lines. Table 2.2 shows the transmission and distribution lines as of June 2007.

Voltage capacity	Length (km)
220 kV	1,323
132 kV	2,122
66 kV	632
40 kV	29
33 kV	11,163
11 kV	21,918
Total	**37,186**

Table 2.2: Transmission and distribution lines

The 220 kV and 132 kV transmission lines of the Kenyan network are shown in the figure 2.1 below.

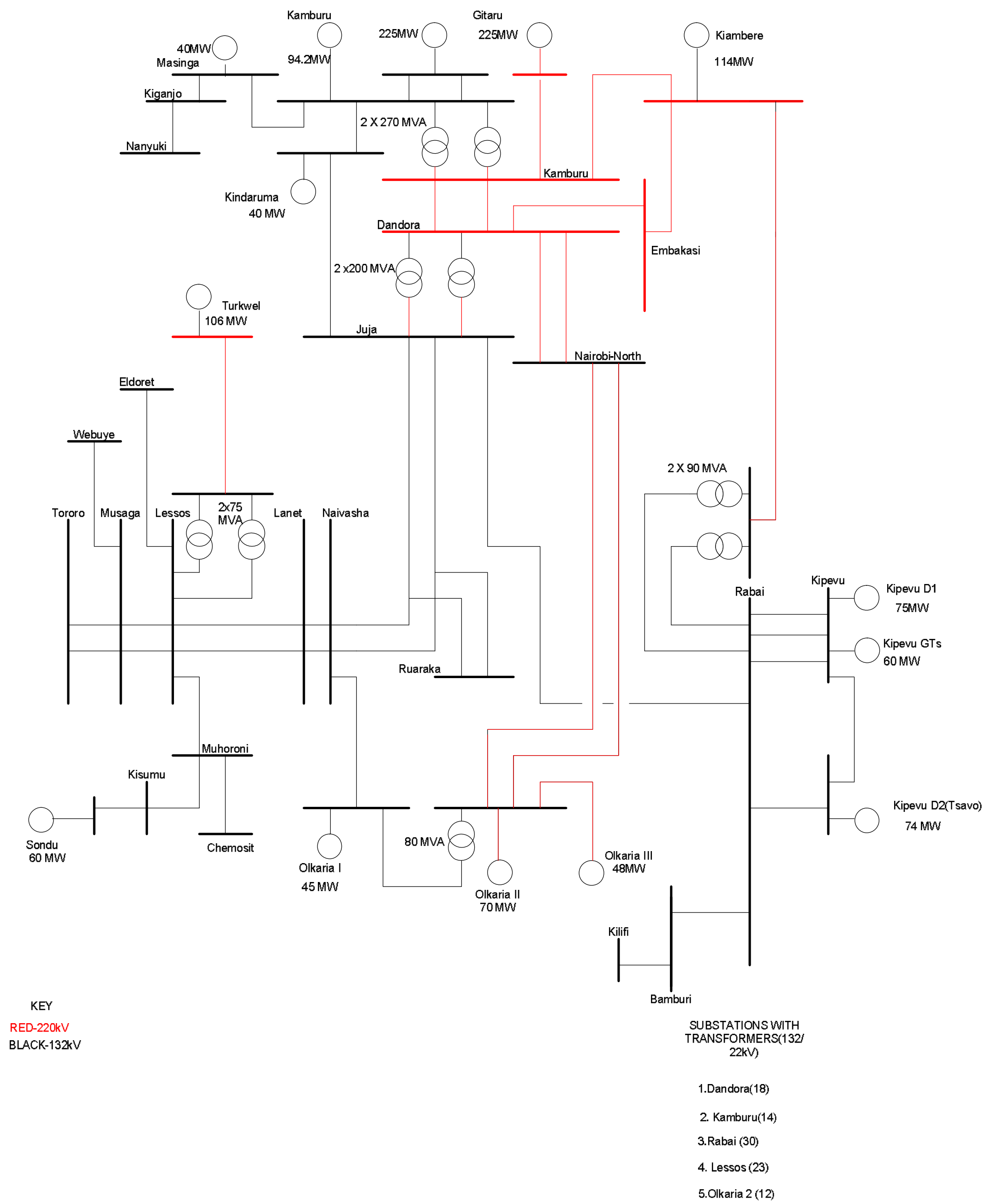

Figure 2.1: 220kV and 132kV transmission lines of the Kenyan network

Supply to the Nairobi-North region is sourced from the Olkaria transgrid 11/220/132 kV substation via two 220 kV lines both of 66.3 km, which connect to the Nairobi- North 220/66 kV substation. There is a 220kV connection from the Kamburu generating station to Dandora through two 220kV transmission lines of 107.5 km and 109.5 km. There is a 220kV main supply from the Kiambere generating station connecting to the Embakasi 220/66 kV transmission substation which is 152.5 km to the Country Energy 132/66 kV Juja substation located in Dandora township.

There is also a 132Kv connection from the Kindaruma generating station to Juja substation of 119km. from the Kipevu generating stations a 132kV transmission line connects to the Juja substation.

2.3 Power Demand

The total energy purchased increased from 5,697 (Giga Watt Hours) GWh in 2005/06 to 6,169 GWh in 2006/07 corresponding to a growth of 8.3%. The number of customers increased to 924,520 2006/07 from 802,249 in 2005/06 equivalent to a growth of 12.3% compared to 7.7% in 2005/06. Customers under the Rural Electrification Programme (REP) increased by 22,323 to reach 133,047 in 2006/07, representing a 20% growth from the previous year. KPLC sales increased by 8.7% while REP sales increased by 33.9%. This was achieved mainly through strategies initiated to enhance customer growth under the Energy Sector Recovery Project (ESRP) and the Rural Electrification Programme. The power sector targets to grow the customer base by 200,000 annually in the next five years through an enhanced customer connection campaign programme and the intensive Rural Electrification Programme being implemented by the Government countrywide. This will translate into a rise in power demand especially due to the large number of domestic customers.

Peak power demand increased from 920 MW in 2005/06 to 987 MW in 2006/07 and rose to 1,035 MW by November 2007. Intensive measures being implemented through the system improvement work under the (Energy Sector Recovery Project) ESRP and (Kenya Power and Lighting Company) KPLCös own targets to reduce outages considerably are expected to enhance both peak demand and consumption.

2.4 CURRENT GENERATION OPERATION PLANNING IN KENYA

2.4.1 Feasibility Study for interconnecting the Ethiopian and Kenyan power Systems

Recently Ethiopian Electric Power Corporation (EEPCo) and Kenyan Ministry of Energy (MOE) carried out a feasibility study for interconnecting the Ethiopian and Kenyan power systems via a high voltage transmission line starting from Wolayta /Sodo on the Ethiopian side and ending in the Nairobi area on the Kenyan side so as to meet the growing demand of electricity in the country. The target capacity for cross-border exchanges considered generation expansion planning and load forecasts over the 2007-2030 planning horizon, covered by the EEPCo Master Plan Update and Kenyaǒs Power Development Plan. The review of the short, medium and long term planning of hydropower capacity development in Ethiopia was subject to particular attention, as this is the key regional resource to be shared through the Kenya interconnection. Under various assumptions on energy exchanges with Sudan, Egypt and Djibouti as well as on the hydrological risks in Ethiopia, a two-stage development of the interconnection capacity to Kenya were defined:

- **Phase 1**

1000 MW transfer capacity by 2012, the year scheduled for availability of hydropower from Gilgel Gibe III in Ethiopia

- **Phase 2**

2000 MW transfer capacity by 2020, up to the planning horizon 2030.

2.4.2 Load Forecast and Generation Planning Review between Ethiopia and Kenya

Ethiopia

The Target Load Forecast prepared in 2006 assumes an economic growth of 12% and 150,000 new connections annually over the entire planning horizon, reflecting the Government's commitment to economic development and poverty eradication. The Target Forecast results in net generation requirements of 71,570 Giga Watt hour(GWh) and a peak demand of 14,330 MW in the 2030 financial year (FY), at an average annual demand growth rate of 14.3%. The Moderate Forecast for FY 2030 is about 50% lower (34,030 GWh and 6,814 MW, average growth rate 10.9%). In agreement with EEPCo, the Moderate/Reference Forecast was adopted for generation expansion planning and power system analysis, considering that an economic growth rate above 12% per annum as assumed by the Target Forecast may be difficult to sustain over the relatively long planning period of this study.

Kenya

The Reference Forecast prepared in 2007 assumes an economic growth of 6.5% p.a., which is in line with short term World Bank and IMF projections, and an additional 120,000 connections for the next four years. The forecast results in net generation requirements of 30,999 GWh and a peak demand of 5,282 MW in FY 2030, with an average annual growth rate of 7.3%. The results of the Low Forecast in 2030 are about 10% lower, and the results of the High Forecast are about 25% higher. In agreement with KPLC, the Reference Forecast was taken for generation expansion and optimization of interconnection capacity.

2.4.3 Conceptual Design

Due to the long interconnection distance of up to 1200 km, the choice of the voltage level and AC or DC technologies plays a decisive role for the technical and economic feasibility of the Project. A consensus was reached in the early stages of the conceptual design that the interconnection shall fully or partially include an HVDC (High Voltage Direct current) link for following reasons:

· cost-effective for long distances (lower overhead line construction costs, as compared to the HVAC)

· conventional technology (line commutated converters)

· robust dynamic performance (stability enhancer and firewall, no propagation of disturbances between the interconnected systems)

· reduced overall losses and Rights of Way.

· no need for power system control enhancement to harmonize generation reserve requirements.

· electrical performances practically insensitive to line length.

On both sides of the interconnection, the study investigated the optimal voltage level for integration in the existing national transmission systems. On the Ethiopian system side, the selection of 400 kV as HVAC is straightforward since it is already established as standard transmission voltage. On the Kenyan side, it is possible to use initially, after conversion to AC, the existing 220 kV transmission voltage level. However, as indicated in the East African Power System Master Plan, all regional cross-border interconnections are planned at voltages higher than 220 kV. Especially the committed interconnection to Tanzania (Arusha) and the future interconnections around Lake Victoria (Uganda) speak for including 400 kV switchgear at the termination point in the Nairobi area. The adopted ±500 kV voltage corresponds to the commonly offered line commutated converter for long distance HVDC links and power ranges in excess of 250 MW.

2.4.4 Power System Analysis

Dynamic simulations showed that the options with DC links are robust for the power transfer targets of Phases 1 and 2 and shall be preferred from the electrical performance viewpoint. Mitigation measures were tested on the Kenyan side, aiming at restoring the generationï demand balance after permanent blocking of a DC pole. These include among others multi-stage under-frequency load shedding and a continuous overload capability of each DC pole.

CHAPTER 3: THEORY AND BACKGROUND

3.1 THE POWER SYSTEM STRUCTURE

Since the beginnings of commercial electric power in the 1880s, the systems for its delivery from production sites to end users(customers) has become increasingly large and interconnected. In the early days, the standard ñpower systemò consisted of an individual generator connected to an appropriately matched load. The trend since the early 1900s has been to interconnect these isolated systems with each other, in addition to expanding them geographically to capture an increasing number of customers. Due to the large number of interconnections and continuously increasing demand, the size and complexity of the present day power systems, have grown tremendously.

The continuing geographical expansion and interconnection of power systems over the course of the last century has been motivated by a variety of technical, social, and economic factors. These include cultural progress associated with a connected grid, economies of exchange, or opportunities for sales of electricity. The main technical justifications for expansion and interconnection are improvement of the load factor, and enhancement of reliability by pooling generating reserves.

The load factor relates to the ratio of a loadôs actual energy consumption over a period of time to the maximum amount of power it demands at any one instant. From the supply standpoint, the ideal customer would be demanding a constant amount of power 24 hours a day, this however does not match the actual usage profile of real customers; nevertheless, a smoother consumption profile can be accomplished by aggregating loads, that is, combining a larger number and different types of customers within the same supply system whose times of power demand does not coincide.

Enhancement of reliability by pooling generating reserves is the ability to provide greater service reliability in relation to cost. The basic idea is that when a generator is unavailable for whatever reason, the load can be served from another generator elsewhere. To allow for unexpected losses of generation power or outages, electric power utilities and Independent Power Producers (IPPôs) maintain a reserve margin of generation, standing by in case of need.

More extensive interconnection of power systems also provides for more options in choosing the least expensive generators to dispatch, or, conversely, for utilities with a surplus of inexpensive generating capacity to sell their electricity.

As the distance spanned by transmission lines has increased, so has the significance of energy losses due to resistive heating. Therefore, high voltage is desirable for power transmission in order to reduce current flow and resistive losses in the lines. As systems have grown in geographical extent, there has been an increasing incentive to operate transmission lines at higher voltages. In addition, the transmission system is a highly integrated system; that is, a change in the status of any one component can significantly affect the operation of the entire system. The transmission system is therefore one of the key factors in maintaining a constant, reliable, power flow.

3.2 <u>Power System Operation Analysis</u>

Bulk power in Kenya is generated at 11kVand is stepped up to high voltages of 132kV and 220 kV for transmission. The load centres are usually located away from generating stations. The power is transmitted to the load centres and is stepped down to distribution level.

The power flow solution is used to evaluate the bus voltage, branch current, real power flow, reactive power flow for the specified generation and load conditions. The results are used to evaluate the line or transformer loading and the acceptability of bus voltages. In general the power flow solutions are needed for the system under the following conditions:

ÅVarious systems loading conditions (peak and off peak).
ÅWith certain equipment outages.
ÅAddition of new generators.
ÅAddition of new transmission lines or cables.
ÅInterconnection with other systems.
ÅLoad growth studies.
ÅLoss of line evaluation.

3.3 <u>Operation States of a Power System</u>

The operating condition of a power system may be classified into normal, emergency or restorative. The normal state is one in which the total demand on the system is met by satisfying all the operating constraints.

Contingencies, such as outage of a generating unit, short circuit and subsequent tripping of a line and the loss of transmission can lead to two emergency conditions where in one, the system remains stable but operates within the violation of some of the operating constraints. While the consumerõs demand is met, abnormal voltage and frequency conditions may arise and loading limits of some lines and equipment maybe violated. However, this kind of emergency can be tolerated for a certain period. In the second kind of emergency, the power system becomes unstable, causing a violation of both the loading and operating constraints, and unless a corrective action is taken immediately, the system faces the risk of a total shutdown.

In the restoration state, the corrective action is taken so that the system goes back to either a new normal state or to the previous normal state. This state is characterised by the interruption of the consumers demand, bringing into operation of the rapid start of units.

3.4 General Layout of the System

The transport system by which electric power is conveyed from generation to consumption is divided into two distinct parts that is transmission and distribution (T&D) system. Finally, power is supplied to individual customers. Generation and transmission is exclusively three-phase, 50 Hertz(Hz) at varying voltages, whereas distribution to the ultimate customer maybe three-phase or single phase depending on the requirements of the customer.

In the generation station, power is generated by three phase alternators, at 11 kV. The voltage is then stepped up by suitable 3-phase generation transformers for transmission purposes. Primary or high ï voltage transmission is carried out at 132kV and 220kV. In selecting the transmission voltages, consideration is given to the overall line distance to the substations and the amount of power being transmitted. A rough basis of determining the most economical transmission voltage is to use 650 volt per km of the transmission line. The high voltage transmission is terminated by a step down transformer in a substation known as receiving station which in most cases lies in the outskirts of the intended consumers. Here, the voltage is stepped down to

66 kV. For stability of power supply, transmission system is always designed with redundancy back-ups in place.

From the receiving station, power is next transmitted at 66kV to various substations strategically placed within a load locality for system stability and power loss reduction. This is the distribution section. At the substation, voltage is reduced from 66kV to 33 or 11kV for final distribution depending on the distance. The consumers are then connected to the distribution network at 415/240 V.

3.5 Network Representation

When representing a power system on a large scale, the nodes are called buses, since they represent an actual physical busbar where different components of the system meet. A bus is electrically equivalent to a single point on a circuit, and it marks the location of one of two things: a generator that injects power, or a load that consumes power. At the degree of resolution generally desired on the larger scale of analysis, the load buses represent aggregations of loads (or very large individual industrial loads) at the location where they connect to the high-voltage transmission system. Such an aggregation may in reality be a transformer connection to a sub transmission system, which in turn branches out to a number of distribution substations; or it may be a single distribution substation from which originate a set of distribution feeders .In any case, whatever lies behind the bus is taken as a single load for purposes of the power flow analysis. The buses in the system are connected by transmission lines.

A balanced three-phase system is always solved as a single phase circuit composed of one of the three lines and a neutral return. The circuit diagram is often simplified by omitting the completed circuit through the neutral and by indicating the component parts by standard symbols rather than their equivalent circuits. Circuit parameters are not shown, and a transmission line is represented by a single line between its two ends. Such a simplified diagram of an electric system is called a one-line diagram. The purpose of a one line diagram is to supply in concise form the significant information about the system. Figure 1 shows a simple one-line diagram indicating the generators, circuit breakers, buses, loadings and transformers.

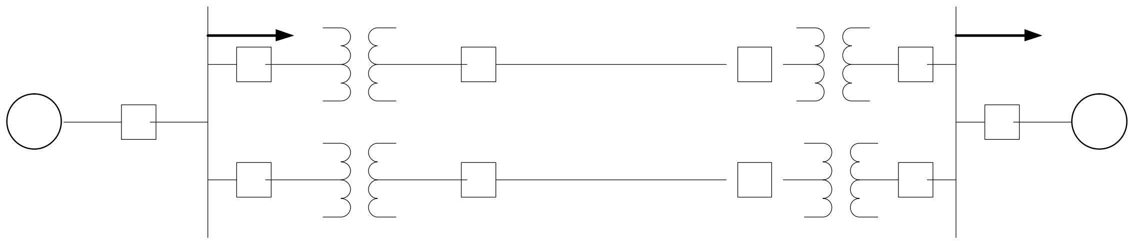

Figure 1: One line diagram representation.

3.5.1 <u>Classification of Buses in the System</u>

In power flow analysis, when considering a large system having *n* buses, the classification of buses based on their actual, practical operating constraints. The two main types are generator buses and load buses. However in power flow analysis, they are classified into three types based on their known variables:

(*i*). Generator bus or PV bus is one at which the total injected active power at a bus is specified and the voltage magnitude is maintained constant at specified value by injected reactive power injection.

(*ii*). Load bus or PQ bus is one at which the total injected power, both real and reactive power is specified at a bus.

(*iii*). Slack bus or swing bus is one of the buses in the system to which generators are connected. At this bus, the voltage magnitude and phase angle of the voltage are specified. The swing bus is a fictitious concept in the load flow study and arises because the system I^2R losses are not known precisely in advance for the load flow calculation. Therefore the total injected power cannot be specified at every bus.

Variables in power flow analysis are shown in the table below.

Type of Bus	Variables given(known)	Variables found (unknown)
Slack	Voltage magnitude(V) Voltage angle (d)	Real power (P) Reactive power (Q)
Generator	Real power (P) Voltage magnitude (V)	Voltage angle (u) Reactive power (Q)
Load	Real power (P) Reactive power (Q)	Voltage angle (u) Voltage magnitude (V)

Table: Variables in Power Flow Analysis

3.6 Variables for Balancing Real and Reactive Power

For system balancing, all the generators in the system collectively must supply power in exactly the amount demanded by the load, plus the amount lost on transmission lines, which are the resistive I^2R and reactive I^2X energy losses by maintaining the frequency of the system constant at 50 Hz. This applies for both real and reactive power.

For balancing real power, P, one generator is chosen whose output is allowed to be adjusted, depending on the systemôs needs. The generator is allowed to ñtake up the slackò and generate more power if the system losses are greater than expected, or less if the system losses are smaller. Hence the one generator bus in power flow analysis is called the slack or swing bus. Thus, in power flow analysis, the real power is specified for, one less than the total number of buses. What takes the place of real power will be taken by the voltage angle, which is the requirement that the system remains balanced.

For balancing reactive power, the generator is governed to maintain a certain voltage magnitude at its bus. The voltage is continually and automatically adjusted through the generatorôs field current, and is therefore a straightforward variable to control. Conveniently for power flow analysis, the total amount of reactive power, Q required for the system does not need to be explicitly known since specifying the voltage magnitude is essentially equivalent to requiring a balanced Q. Voltage magnitude instead of reactive power is specified for all generator buses, which are therefore called PV buses. This assignment implies that all generators share the ñreactive slack,ò in contrast to the real slack that is taken up by only a single generator.

Hence system variables in power flow analysis are classified as follows:

ÅReal and Reactive power from the generators injected into generator (PV) buses and are control or independent variables. Real power from PV buses affects bus voltage angles while reactive power from PV buses affects bus voltage magnitudes.

ÅReal and Reactive loads tapped from the load (PQ) buses and are determined by the consumers, hence are beyond control. They are termed as disturbance or uncontrollable variables.

ÅVoltage magnitude and voltage angle are dependent or state variables.

3.6.1 <u>Constraints on System Variables</u>

System variables have constraints that are looked at in carrying out power flow analysis.

Constraints on state variables are:

(*i*). The voltage at any bus should be within tolerable limits, ranges between ±5% to ± 10% of the value specified. That is:

$|V_p|_{min} < |V_p| < |V_p|_{max}$ for p = 1, 2, é , n

(*ii*). The voltage angle ŭ state variable must satisfy the constraints:

$|\delta_p - \delta_q| < (\delta_p - \delta_q)_{max}$; the maximum power angle between bus p and bus q being specified.

Constraints on control variables are:

$P_{p,min} < P_p < P_{p,max}$

$Q_{p,min} < Q_p < Q_{p,max}$

3.7 Per-Unit Method of Representing Quantities

The quantities involved in power system calculations are kVA, voltage, current and impedance of the equivalent circuits of the different components of the system. The equivalent circuits are at different voltages and are connected together in the system by means of transformers and interconnections. Each apparatus is rated in kVA and its impedance is given in actual ohms or in percentage values referred to its rated kVA and rated voltage. To facilitate the solution of the power system quickly, the component ratings are expressed in values common to the same reference base, by expressing the quantities in ñper-unitò values. For common representation, base kVA and base voltage are to be chosen. Then the base current and the base impedance can be expressed as follows:

$$\text{Base current} = \frac{\text{Base kVA}}{\text{Base kV}}$$

$$\text{Base impedance} = \frac{\text{Base voltage in volts}}{\text{Base current in amperes}}$$

$$= \frac{\text{Base k}V^2}{\text{Base MVA}}$$

$$\text{Per unit impedance} = \frac{\text{Actual impedance}}{\text{Base impedance}}$$

3.8 DATA FOR LOAD – FLOW ANALYSIS

The following are steps implemented in the collection of system data for load-flow (or power flow) analysis:

(*i*). Draw a single-line diagram of the system.

(*ii*). Assuming a balanced three phase system, the transmission system is represented by its positive-phase sequence network of linear lumped series and shunt branches. The linear impedances and shunt admittances in per-unit values are then found, including transformer impedances, shunt capacitor ratings and transformer ratings and transformer tappings.

(*iii*). Node or bus self and mutual admittances are found, using the nodal analysis.

(*iv*). The operating conditions of the system are selected. The static operating state of the system is then specified by the constraints on power and/or voltage at the network buses.

After getting the above type of data, a suitable mathematical model of the system, adequately describing the relationships between the voltages and powers in the interconnected system is formed. Power and voltage constraints at various buses in the network are then specified and the load flow equations are solved numerically. When various bus voltages are determined, actual load flow in all transmission lines is computed.

The mathematical formulation of the load flow problem results in a system of algebraic non-linear equations. The equations can be established by using either the bus or loop frame of reference. The coefficients of the equations depend on the selection of the dependent variables that is voltages or currents. Thus either the admittance or impedance network matrices are used.

Early approaches to the computer solution of load flows employed the loop frame in admittance form. Later approaches used the bus frame reference in the admittance form to describe the system, which gained widespread application because of the simplicity of data preparation and ease at which the bus admittance matrix could be formed and modified for network changes. This approach remains the most economical from the computer time and memory requirement point of view.

3.8.1 Iterative Computation of Nonlinear Algebraic Equations

The complexity of obtaining a formal solution for power flow in power systems arises due to the differences in the type of data specified for the different kind of buses. Although the formulation of sufficient equations is not difficult, the closed form of solution is not practical. To solve simultaneous non-linear algebraic equations in power flow analysis follow a numerical iterative processes. Estimated values to the unknown bus voltages are assigned and a new value for each bus voltage from the estimated values at the other buses, the real power specified, and the specified reactive power or voltage magnitude. A new set of values for voltage is thus obtained for each bus and used to calculate still a new set of bus voltages. Considering an *n*-bus system and *p* and *q* buses linking transmission line.

Forming the bus admittance matrix:

$$Y_{pp} = \sum_{q=1}^{n} y_{pq} \quad ; p \neq q$$

(1)

$$Y_{pq} = Y_{qp} = - y_{pq}$$

(2)

The total current entering the p_{th} bus of *n* bus system is given by:

$$I_p = Y_{p1}V_1 + Y_{p2}V_2 + é \ + Y_{pn}V_n = \sum_{q=1}^{n} Y_{pq}V_q$$

$$= \frac{P_P - jQ_P}{(V_P)^*}$$

(3)

Where Y_{pq} is the admittance of the line between buses *p* and *q* and V_q is the voltage at bus *q*.

In polar coordinates:

$$V_p = V_p \angle \delta_p$$

$$V_q = V_q \angle \delta_q$$

$$Y_{pq} = Y_{pq} \angle \theta_{pq}$$

Here ŭ is the angle of the bus voltage and ɗ is the bus admittance angle. At bus *p*, the complex conjugate of apparent power is given by:

$$S^*_p = P_p - jQ_p = V_p^* I_p$$

(4)

$$= V_p^* \left(\sum_{q=1}^{n} Y_{pq}V_q\right)$$

(5)

The static power flow equations are therefore given by:

$$P_p - jQ_p = \sum_{q=1}^{n} |V_p \ V_q Y_{pq}| \angle(\theta_{pq} + \delta_q - \delta_p)$$

(6)

Hence,

$$P_p = \sum_{q=1}^{n} |V_p \ V_q Y_{pq}| \cos(\theta_{pq} + \delta_q - \delta_p)$$

(7)

$Q_p = \sum_{q=1}^{n} | V_p \; V_q Y_{pq}| \sin(\theta_{pq} + \delta_q - \delta_p)$

(8)

The line flow equations are therefore given by:

$i_{pq} = (V_p - V_q) y_{pq} + V_{pq} \frac{y'_{pq}}{2}$

(9)

Where: i_{pq} is the current at bus p in the line connecting bus p to bus q.

y_{pq} is the admittance of the line connecting bus p to bus q.

$V_{pq} \frac{y'_{pq}}{2}$ is the current contribution at bus p due to line charging.

The power flow both real and reactive at bus p, from bus p to bus q is:

$P_{pq} - jQ_{pq} = V_p^{*} i_{pq}$

(10)

$= V_p^{*}(V_p - V_q)\, y_{pq} + V_p^{*} V_p \frac{y'_{pq}}{2}$

(11)

Whereas the power flow both real and reactive at bus q, from bus q to bus p is:

$P_{qp} - jQ_{qp} = V_q^{*} i_{qp}$

(12)

$= V_q^{*}(V_q - V_p)\, y_{qp} + V_q^{*} V_q \frac{y'_{pq}}{2}$

(13)

The power loss in line p - q is the algebraic sum of the power flows determined by equations (9) and (11).

3.9 METHODOLOGY: THE LOAD FLOW SOLUTION TECHNIQUES

There are several standard techniques for solving the load flow problem using the iterative process and the most commonly used are:

(*i*). The Gauss-iterative method.

(*ii*). The Gauss-Seidel method.

(*iii*). The Newton- Raphson method.

(*iv*). The Fast Decoupled method.

The steps in solving the load flow problem by the iterative methods are:

(*i*). Make an initial guess of all unknown voltage magnitudes and angles. Use a ñflat startò in which all voltage magnitudes are set to 1.0 per-unit (p.u) and the voltage angles set to zero.

(*ii*). Solve the power balance using the most recent magnitude values.

(*iii*). Linearize the system around the most recent voltage magnitude and voltage angles.

(*iv*). Solve for voltage magnitude and voltage angle change.

(*v*). Update the voltage magnitude and angle.

(*vi*). Check the stopping conditions that is check for convergence of the solution, if met terminate, else go to step (*ii*).

3.9.1 The Gauss-iterative Method

Computations for this method using the admittance matrix deduce:

$I_p = \frac{P_P - jQ_P}{(V_P)^*}$; p= 1, 2, 3, é , n and p$\neq$slack bus

(1)

By this method, the unknownôs voltage magnitudes and angles are assigned initial values of

1.0

initial voltages using the equation shown. The procedure is repeated until a solution is reached.

$$V_p = \frac{1}{Y_{pp}}\left\{\frac{P_p - jQ_p}{V_p^{\ *}} - \sum_{q=1}^{n} Y_{pq}V_q\right\} \quad ; q \neq p$$

(2)

Gauss-iterative method uses the same set of voltage values throughout a complete iteration, instead of immediately substituting each new value obtained to calculate the voltage at the next bus.

3.9.2 The Gauss-Seidel Iterative Method

The Gauss-Seidel method uses upgraded iterates as soon as they are available and thus has an advantage over the Gauss- iterative method which takes longer. Computations for this method using the admittance matrix deduce:

$$I_p = \frac{P_P - jQ_P}{(V_P)^*} \quad ; p = 1, 2, 3, é \ , n \text{ and } p \neq \text{slack bus}$$

(3)

For a system with *n* total of buses, the calculated voltage at any bus *p* and P_p and jQ_p the real and reactive powers at any bus *p* are given:

$$V_p^{\ K} = \frac{1}{Y_{pp}} \{ \frac{P_p - jQ_p}{V_p^{\ *}} - \sum_{q=1}^{P-1} Y_{pq} V_q^{\ K} - \sum_{q=P+1}^{n} Y_{pq} V_q^{\ K-1} \} \quad ; q \neq p$$

(4)

Where: k is the iteration count.

The Gauss-Seidel method of solution of power flow problems has an excessive number of iterations before the voltage corrections are within and acceptable precision index. The number of iterations required is reduced considerably if the correction in voltage at each bus is multiplied by some constant that increases the amount of correction to bring the voltage closer to the value it is approaching. The multipliers that accomplish this improved convergence are acceleration factors. The difference between the newly calculated voltage and the best previous voltage at the bus is multiplied by the appropriate acceleration factor to obtain a better correction to be added to the previous value. The acceleration factor for the real component of correction may differ from that for the imaginary component. For any system, optimum values for acceleration factors exist, and poor choice of factors may result in less rapid convergence or make convergence impossible. In most cases, an acceleration factor of 1.6 is used in power flow analysis. However, studies may be made to determine the best choice for a particular system.

At a bus where the voltage magnitude rather than reactive power is specified, the real and reactive components of the voltage for each iteration are found by computing a value for the reactive power. Thus from equation (4):

$$P_p - jQ_p = \{ Y_{pp}V_p + \sum_{q=1}^{p-1} Y_{pq} V_q^K + \sum_{q=p+1}^{n} Y_{pq} V_q^{K-1} \} V_p^* \quad ; q \neq p$$

(5)

For $q = p$, then:

$$P_p - jQ_p = V_p^* \sum_{q=1}^{n} Y_{pq} V_q^K \tag{6}$$

The reactive power is then evaluated for the best previous voltage values at the buses.

$$Q_p = -\text{Im}\{ V_p^* \sum_{q=1}^{n} Y_{pq} V_q^K \} \quad)$$

(7)

The new value of reactive power is substituted in equation (4) to find a new value of V_p.

The line flows in line pq is thus:

$$S_{pq} = P_{pq} - jQ_{pq} = V_p I_p^*$$

(8)

$$S_{pq} = V_p(V_p^* - V_q^*) Y_{pq}^* + V_p V_p^* Y_{sh}$$

(9)

Advantages of Gauss-Seidel Method

ÅThe Gauss-Seidel method uses rectangular coordinates when programming.

ÅIt requires the fewest number of arithmetic operations to complete an iteration because of the sparsity of the network matrix and simplicity of the solution technique.

Åt takes less time per iteration.

ÅIt is easy to program and has the most efficient utilisation of core memory.

Disadvantages of Gauss-Seidel Method

ÅGauss-Seidel is characteristically long in solving due to its slow convergence and often difficulty is experienced with unusual network conditions such as negative reactive branches.

ÅIn Gauss-Seidel method, each bus is treated independently. Each correction to one bus requires subsequent correction to all buses to which it is connected.

3.9.3 Newton-Raphson Method

The Newtonï Raphson (N-R)method has powerful convergence characteristics, though computational and storage requirements are heavy. The sparsity techniques and ordered elimination led to its earlier acceptability and it continues to be a powerful load-flow algorithm even in todayõs environment for large systems and optimization. A lesser number of iterations are required for convergence, as compared to the Gaussï Seidel method, provided that the initial estimate is not far removed from the final results, and these do not increase with the size of the system. This method uses the Gaussï Seidel method to obtain good initial voltages as the starting values and the results input into the N-R method as a starting estimate. These voltages are used to calculate real power P at every bus except the swing bus and also reactive power Q wherever reactive power is specified.

To apply the Newton-Raphson method to the solution of load flow equations, bus voltages and line admittances may be expressed in polar form or rectangular form. For polar form representation, then the voltages, line admittances and real and reactive powers are expressed as:

$$V_p = V_p \angle \delta_p$$

$V_q = V_q \angle \delta_q$

$Y_{pq} = Y_{pq} \angle \theta_{pq}$

Where ŭ is the angle of the bus voltage and ɗ is the bus admittance angle. The static power flow is given by:

$P_p - jQ_p = \sum_{q=1}^{n} | V_p \ V_q Y_{pq} | \angle(\theta_{pq} + \delta_q - \delta_p)$

(1)

Hence

$P_p = \sum_{q=1}^{n} | V_p \ V_q Y_{pq} | \cos(\theta_{pq} + \delta_q - \delta_p)$

(2)

$Q_p = - \sum_{q=1}^{n} | V_p \ V_q Y_{pq} | \sin(\theta_{pq} + \delta_q - \delta_p)$

(3)

For rectangular representation, then:

$P_p - jQ_p = V_p^{*} \sum_{\substack{q=1 \\ q \neq p}}^{n} Y_{pq} V_q$

(4)

$V_p = e_p + jf_p$

(5)

$Y_{pq} = G_{pq} - jB_{pq}$

(6)

Using the values of V_p and Y_{pq}, the expression for the power at bus *p* is:

$P_p = \sum_{q=1}^{n} \{ e_p (e_q G_{pq} + f_p B_{pq}) + f_p (f_q G_{pq} - e_q B_{pq}) \}$

(7)

$Q_p = \sum_{q=1}^{n} \{ f_p (e_q G_{pq} + f_q B_{pq}) + e_p (f_p G_{pq} - e_q B_{pq}) \}$

(8)

The changes is bus power are the differences between the scheduled powers and the calculated powers, that is:

$ꝕP_p = P_{p,sched} - P_p$

(9)

$ꝕQ_p = Q_{p,sched} \quad Q_p$

(10)

The Newton-Raphson requires a set of equations expressing the relationship between the changes in real and reactive powers and components of the voltages.

$$
\begin{bmatrix} \Delta P_2 \\ \vdots \\ \Delta P_n \\ \\ \Delta Q_2 \\ \vdots \\ \Delta Q_n \end{bmatrix}
=
\left[\begin{array}{ccc|ccc}
\frac{\partial P_2}{\partial \delta_2} & \cdots & \frac{\partial P_2}{\partial \delta_n} & \frac{\partial P_2}{\partial |V_2|} & \cdots & \frac{\partial P_2}{\partial |V_n|} \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
\frac{\partial P_n}{\partial \delta_2} & \cdots & \frac{\partial P_n}{\partial \delta_n} & \frac{\partial P_n}{\partial |V_2|} & \cdots & \frac{\partial P_n}{\partial |V_n|} \\
\hline
\frac{\partial Q_2}{\partial \delta_2} & \cdots & \frac{\partial Q_2}{\partial \delta_n} & \frac{\partial Q_2}{\partial |V_2|} & \cdots & \frac{\partial Q_2}{\partial |V_n|} \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
\frac{\partial Q_n}{\partial \delta_2} & \cdots & \frac{\partial Q_n}{\partial \delta_n} & \frac{\partial Q_2}{\partial |V_2|} & \cdots & \frac{\partial Q_n}{\partial |V_n|}
\end{array}\right]
\begin{bmatrix} \Delta \delta_2 \\ \vdots \\ \Delta \delta_n \\ \\ \Delta V_2 \\ \vdots \\ \Delta V_n \end{bmatrix}
\qquad (11)
$$

Where the square matrix of partial derivatives is a Jacobian matrix.

The matrix representetation is reduced as thus:

$$
\begin{vmatrix} \Delta P \\ \Delta Q \end{vmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{vmatrix} \Delta \delta \\ \Delta V \end{vmatrix} \qquad (12)
$$

From equation (12) the new bus voltages can be calculated by multiplying the changes of real and reactive power by the inverse of the Jacobian matrix.

Advantages of the Newton-Raphson

(*i*). The Newton-Rsphson method has quadrature convergence characteristics and therefore has fewer iterations. For large systems, it is faster, more accurate and more reliable than the Gauss-Seidel method.

(*ii*). It is used with advantage for large systems.

(*iii*). N-R method is based on calculating the voltage corrections while taking account of all the interactions as compared to the Gauss-Seidel which treats each bus independently and each correction to one bus requires subsequent correction to all the buses connected to it.

Disadvantages of the Newton-Raphson

(*i*). The Newton-Rasphson method takes longer time as elements of the Jacobian are to be computed for each iteration.

3.9.4 Fast Decoupled Method

The Fast Decoupled Power Flow Method (FDPFM) is an approximation (simplification) of Newton-Raphson algorithm (N-R) by using knowledge of physical characteristics of electrical systems. The decoupling principle recognises that in the steady state, active powers are strongly related to voltage angles, and reactive powers to voltage magnitudes. This implies that the load flow problem can be solved separately by two synthetic networks that is P-ŭ and Q-V networks, taking advantage of real power-reactive power (Pï Q) decoupling.

Therefore, the full derivative equation can be decoupled into two equations as:

$$ȹP = \left[\frac{\partial P}{\partial \delta}\right] ȹŭ \qquad (1)$$

$$ȹQ = -\left[\frac{\partial Q}{\partial V}\right] ȹV \qquad (2)$$

Solving for ȹŭ and ȹQ:

$$ȹŭ = \left[\frac{\partial P}{\partial \delta}\right]^{-1} ȹP \qquad (3)$$

$$ȹV = \left[\frac{\partial P}{\partial \delta}\right]^{-1} ȹQ \qquad (4)$$

The sub matrix involved in equation (3) and (4) is only half the size of the Jacobian matrix.

This method due to its calculations simplifications, fast convergence and reliable results became the most widely used method in load flow analysis. However, FDPFM for some cases, where there is high R/X ratios or heavy loading (Low Voltage) at some buses are present, does not converge well and is ineffective. 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, others those with low voltage buses.

However, the methods used in most utility companies are the Gauss-Seidel (G-S) and Newton-Raphson (N-R) method, with the N-R method has becoming the de-facto industry standard. The main reason for this is that the convergence properties of the N-R scheme are very desirable when the initial, guessed solution is quite good that is, when it is chosen close to the correct solution. In this project, the N-R method is used to solve the power flow problem.

CHAPTER 4: THE POWER FLOW PROBLEM

4.1 Software Development

Power system simulation involves a wide range of timeframes, starting at microseconds when simulating fast electromagnetic transients and extending to several years in system planning studies. The same system may have to be modelled and solved in many
different ways, depending upon the studies event of interest. It has been desirable to have a single software platform from which several power system analysis functions can be easily activated from the same power system.

In the last decade, several high-level programming languages, such as Matlab, Mathcad, Mathematica and so on, have become more popular for both research and educational purposes. Any of these languages can lead to good results in the field of power system analysis. From these languages Matlab proved to be the best user choice. The important features of Matlab are the matrix-oriented programming, plotting capabilities and a graphical environment (Simulink), which highly simplified control scheme design.

The power flow problem was simulated using MATLAB which is a high-performance language for technical computing and integration. MATLAB is a numerical computing environment and programming language that provides suitable solutions for computations involving matrices and vectors.

During simulation process, the developed using the 132kV and 220kV transmission system raw data and run under the MATLAB environment. The transmission grid of Kenyan power system network simulated comprises of 35 buses, 12 generators, 46 branches, 9 transmission transformers and 17 general loads. In this single line diagram, all the transformers are assumed to 2-winding transformers.

4.2 <u>The Actual Problem Solution</u>

To simulate the developed model in MATLAB environment, a MATLAB computer program for the solution of power flow problem, has been developed using the Newton-Raphson method. All the calculations during simulation process were done in per unit system. The solution method consists of three function programs namely: busdataproj, linkdataproj and pfaproj.

The Newton-Raphson algorithm is summarised in the following steps and the flow chart is shown in fig.2.

ÅBus admittance matrix is formed.

The diagonal elements forming the bus admittance matrix are computed as:

$$Y_{ii} = \sum_{k=1}^{n} y_{ik} \quad ; i \neq k \tag{1}$$

The off-diagonal elements forming the bus admittance matrix are computed as:

$$Y_{ik} = Y_{ki} = -\, y_{ik} \tag{2}$$

Where i and k are buses.

Å Initial values of voltages and phase angles are assumed for the load (PQ) buses. Phase angles are assumed for PV buses. A ñflat startò is used in which all voltage magnitudes are set to 1.0 per-unit (p.u) and the voltage angles set to zero for the unknown voltage magnitudes and angles.

ÅReal and reactive powers, P and Q, are calculated for each bus.

$$P_i = V_i \sum_{k=1}^{m} V_k \{ G_{ik} \cos(\delta_i - \delta_k) + B_{ik} \sin(\delta_i - \delta_k) \} \tag{3}$$

$$Q_i = V_i \sum_{k=1}^{m} V_k \{ G_{ik} \sin(\delta_i - \delta_k) - B_{ik} \cos(\delta_i - \delta_k) \} \tag{4}$$

ÅReactive power limits are checked for the load (PQ) buses.

ÅReal and reactive power, φP_i and φQ_i mismatches are checked on the basis of the given power at the buses.

$$\varphi P_i = P_{i,sched} - P_i \tag{5}$$

$$\varphi Q_i = Q_{i,sched} - Q_i \tag{6}$$

ÅThe elements of the Jacobian matrix are calculated.

Off-diagonal elements: $i \neq k$

$$\frac{\partial P_i}{\partial \delta_k} = \; G_{ik} V_i V_k \sin(\delta_i - \delta_k) + B_{ik} V_i V_k \cos(\delta_i - \delta_k) \qquad (7)$$

$$\frac{\partial P_i}{\partial V_k} = \; G_{ik} V_i \cos(\delta_i - \delta_k) + B_{ik} \sin(\delta_i - \delta_k) \qquad (8)$$

$$\frac{\partial Q_i}{\partial \delta_k} = \; -G_{ik} V_i V_k \cos(\delta_i - \delta_k) - B_{ik} V_i V_k \sin(\delta_i - \delta_k) \qquad (9)$$

$$\frac{\partial Q_i}{\partial V_k} = \; G_{ik} V_i \sin(\delta_i \delta_k) - B_{ik} V_i \cos(\delta_i \quad \delta_k) \qquad (10)$$

Diagonal elements:

$$\frac{\partial P_i}{\partial \delta_i} = V_i \sum_{k=1}^{m} V_k \; \{ G_{ik} \sin(\delta_i \quad \delta_k) + B_{ik} V_k \cos(\delta_i \quad \delta_k) \} \quad V_i^{2} B_{ii} \qquad (11)$$

$$\frac{\partial P_i}{\partial V_i} = \sum_{k=1}^{m} \{ V_k \; [G_{ik} \cos(\delta_i - \delta_k) + B_{ik} \sin(\delta_i - \delta_k)]\} + V_i G_{ii} \qquad (12)$$

$$\frac{\partial Q_i}{\partial \delta_i} = \; V_i \sum_{k=1}^{m} \{ V_k \; [G_{ik} \cos(\delta_i - \delta_k) + B_{ik} \sin(\delta_i - \delta_k)]\} - V_i^{2} G_{ii} \qquad (13)$$

$$\frac{\partial Q_i}{\partial V_i} = \sum_{k=1}^{m} \{ V_k \; [G_{ik} \sin(\delta_i - \delta_k) + B_{ik} \cos(\delta_i - \delta_k)]\} + V_i B_{ii} \qquad (14)$$

ÅThe voltage corrections, φǔ and φV are computed.

ÅNew bus voltages are calculated from the computed voltage corrections.

ÅThe next iteration is started with these new values of voltage magnitudes and phase angles.

ÅThe procedure is continued until the required tolerance is achieved.

ÅThe bus power injection and line flows are then calculated.

From the power balance equation, that is:

$$S_{G_i} = S_{L_i} + S_{T_i}$$

Where: S_{G_i} is the power flowing from the generator at the *i*th bus.

S_{L_i} is the load power flowing out of the *i*th bus.

S_{T_i} is the complex transmission power flowing out of the *i*th bus.

Figure: 4.2 shows the flowchart for the Newton-Raphson power flow solution method.

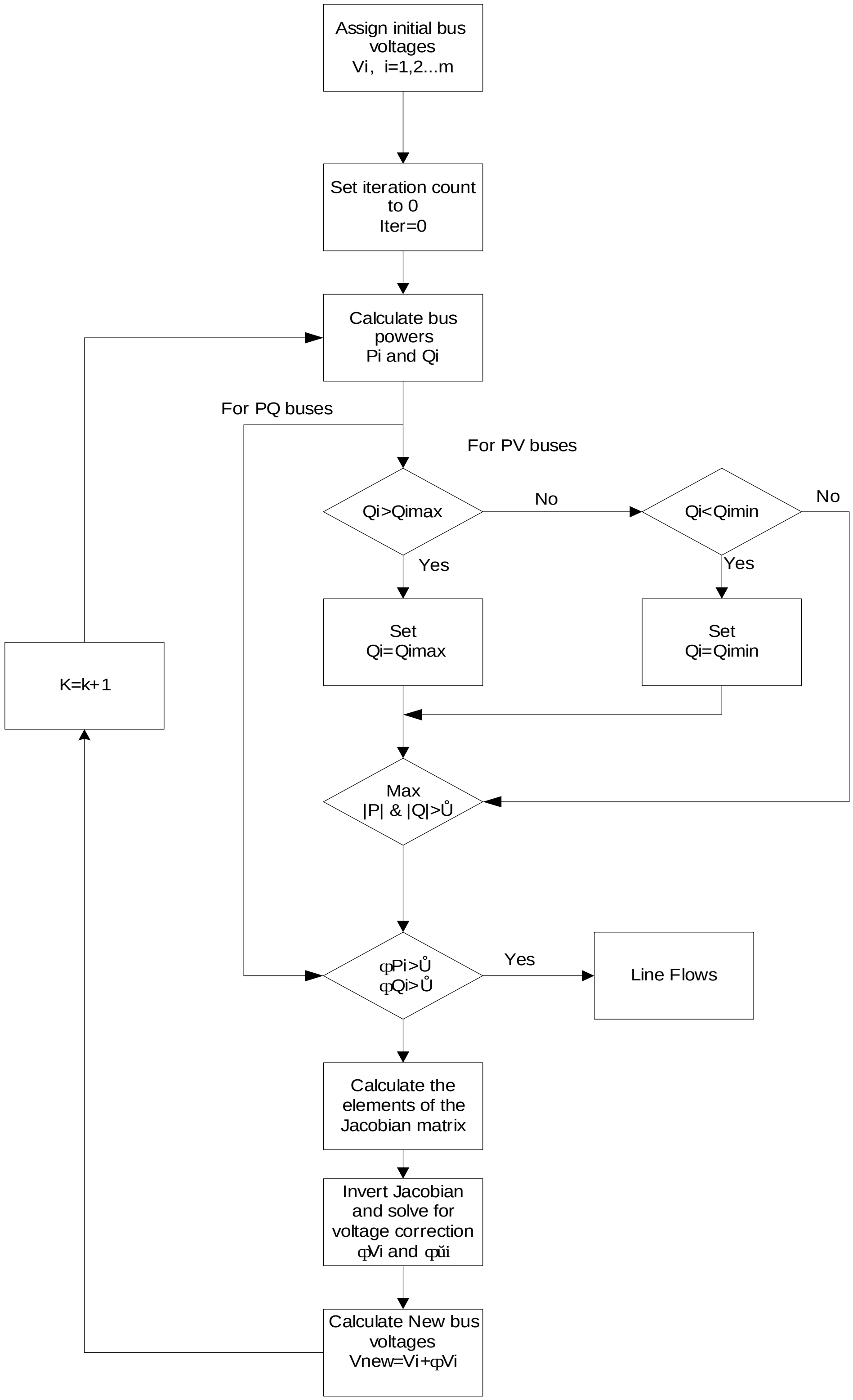

Figure: 4.2 : Algorithm for Newton-Raphson Power flow Solution

CHAPTER 5: RESULTS AND ANALYSIS

5.1: Results of Simulation

The results obtained after simulations of the power system model are presented in both tabular and graphical form. Tabular form of both voltage magnitude and phase angles are given in Table 5.1 while Figures 5.1 and 5.2 shows the corresponding voltage magnitude and angle profiles graphically. The power flows are given in Table 5.2.

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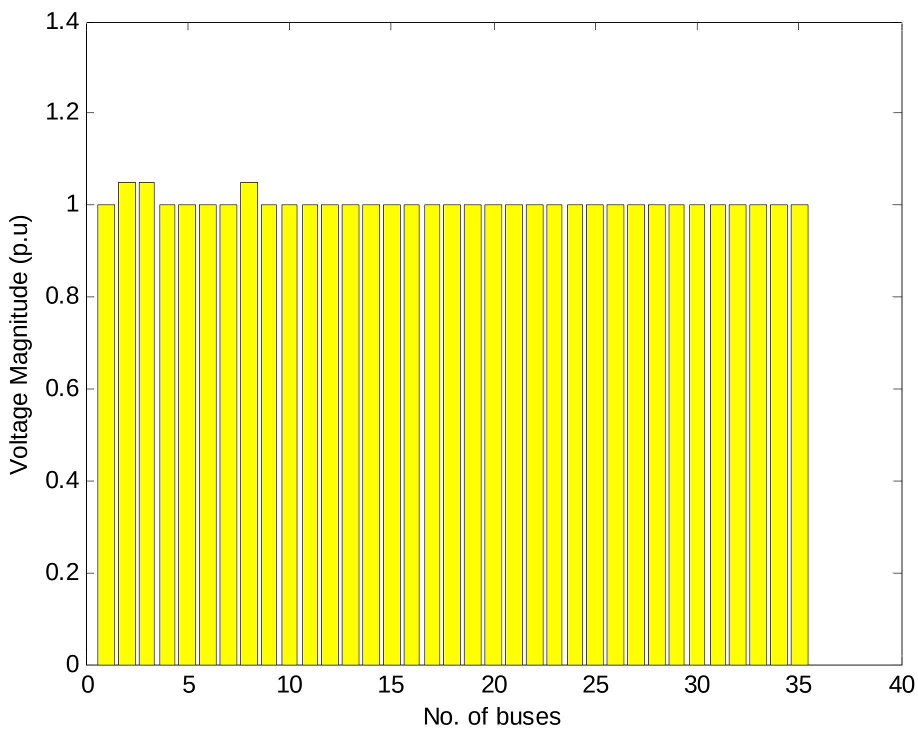

Figure 5.1 : Voltage profile of the transmission system

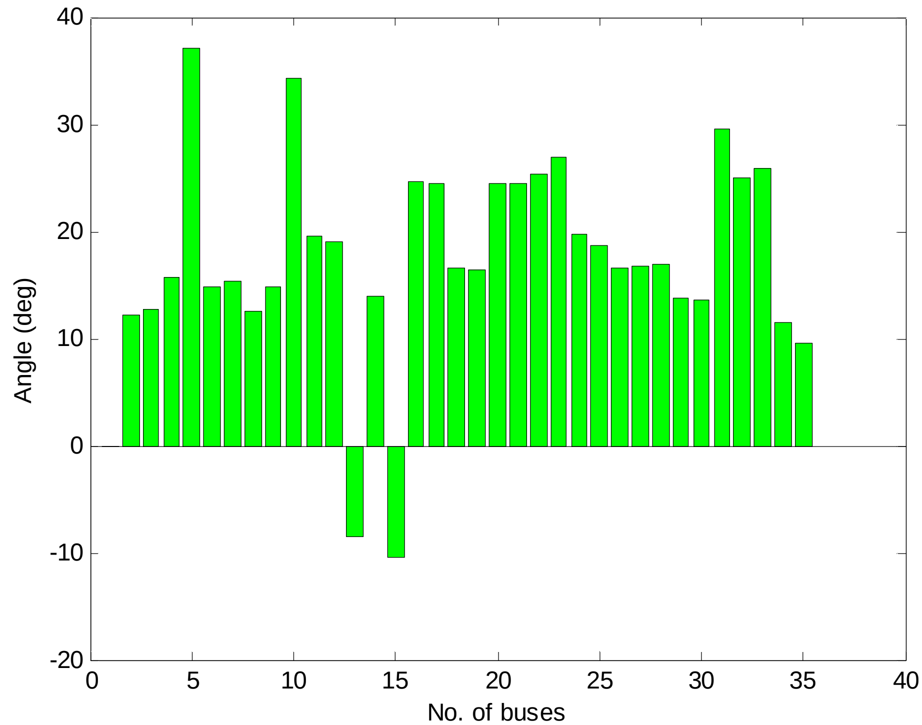

Figure 5.2 : Angle profile of the transmission system

Bus No	V pu	Angle (Degrees)
1	1.0000	0.0000
2	1.0500	12.2598
3	1.0500	12.7518
4	1.0000	15.6751
5	1.0000	37.0307
6	1.0000	14.9056
7	1.0000	15.3236
8	1.0500	12.6277
9	1.0000	14.8446
10	1.0000	34.3638
11	1.0000	19.4804
12	1.0000	19.1006
13	0.9900	-8.4852
14	0.9900	13.9184
15	0.9900	-10.4672
16	0.9900	24.6253
17	0.9900	24.4160
18	1.0100	16.5568
19	1.0100	16.3228
20	1.0100	24.5314
21	1.0100	24.5314
22	1.0100	25.3160
23	1.0100	26.9348
24	0.9900	19.6891
25	1.0100	18.7383
26	0.9900	16.5909
27	1.0100	16.7297
28	1.0100	16.9000
29	1.0100	13.7759
30	0.9900	13.5602

31	0.9900	29.4784
32	0.9900	24.9840
33	0.9900	25.9170
34	0.9900	11.4901
35	0.9900	9.5447

Table 5.1: Voltage magnitudes and angles of the transmission system

From bus	To bus	Real power flow(MW)	Reactive power flow (MVA)
2	1	434.4414	81.5117
1	2	-420.9728	-0.7
13	1	-54.5874	27.4760
1	13	58.6303	-19.3139
3	2	85.1000	-35.5912
2	3	-84.7913	36.3205
6	2	51.0557	-129.6810
2	6	-47.3652	138.4606
14	2	222.9199	-601.9418
2	14	-221.9394	643.6041
14	4	-88.1621	-14.6773
4	14	88.8141	16.1932
23	25	-85.8283	34.6371
5	23	89.6743	-18.8667
26	6	5.8471	-5.7446
6	26	-5.7628	5.9450
14	7	-83.4914	-11.3294
7	14	84.0274	13.5169
19	7	14.3187	5.1952
7	19	-14.2666	-4.8896
30	7	-8.2383	-0.4826
7	30	8.3026	0.7433

From bus	To bus	Real power flow(MW)	Reactive power flow (MVA)
29	8	7.6370	-297.1268
8	29	-1.7480	308.9913
30	9	-52.6706	2.6607
9	30	53.2495	-1.4943
31	10	-60.1872	20.1573
10	31	62.3083	-15.1095
12	11	-9.9993	0.3650
11	12	10.0015	-0.2986
25	11	-19.2 8	21.0074
11	25	19.374	-20.5503
28	12	-100.7847	47.1757
12	28	101.5069	-42.8421
15	13	-21.6602	11.1964
13	15	22.0345	-10.4406
18	14	100.8317	27.05 73
14	18	-99.9637	-21.8865
22	16	22.7726	14.7692
16	22	-22.4946	-14.2066
21	17	22.0650	35.3226
17	21	-21.6977	-34.5795
19	18	-36.4634	6.2631
18	19	36.4889	-6.1128
26	18	-108.2162	-806.9557
18	26	110.9216	823.1880
28	18	106.4262	-16.7774
18	28	-106.3238	17.4146
22	21	14.0740	-6.8340
21	22	-13.9791	7.0261
23	22	87.9369	-1.6836
22	23	-87.8542	4.1671

From bus	To bus	Real power flow(MW)	Reactive power flow (MVA)
24	22	-55.5820	17.4052
22	24	58.1727	-12.1113
33	22	0.4271	-14.5606
22	33	-0.2799	14.8586
25	24	-6.4754	28.2134
24	25	6.8052	-27.5456
27	25	-33.3950	16.7557
25	27	33.9615	-15.5754
27	26	164.6409	257.1391
26	27	-161.9906	-251.6557
30	29	-15.3652	-69.5620
29	30	15.4083	71.0258
34	30	-47.4282	24.6727
30	34	48.2884	-22.9434
33	31	-40.9529	21.8236
31	33	42.2294	-19.2376
33	32	17.2903	-8.3663
32	33	-17.1518	8.6467
35	34	-22.5423	11.6755
34	35	22.9257	-10.9035
		54.4498	279.5993

Table 5.2: Power flows of the transmission system

The angle profile presented in Figure 5.2 reflects the acceptable phase angle/power factor of the transmission system. The power factor ranges between 0.829 and 0.991, and, the voltage magnitudes range between 1.05 and 0.99 p.u. from the power flow solution by Newton-Raphson method and converged after four iterations. The total active and reactive power losses in the system during this particular scenario were 54.44 MW and ï 254.23 MVAr respectively.

The total loading of the system is 282.4 MW and 114.8 MVAr. The slack bus generation is thus 336.8494 MW to maintain the power balance and synchronism within the system.

CHAPTER 6: SUMMARY, RECOMMENDATIONS AND CONCLUSIONS

The aim of this project was to determine the power flows and voltages on the 132kV and 220kV transmission lines of the Kenyan grid to evaluate the current performance of the network. To achieve this objective, a computer program was developed and using the Kenya Power and Lighting Companyôs raw data and used in the program to approximate the power flow within the transmission network. The results will assist the planning engineer in planning for future expansion of the network by estimating the maximum power on the lines and comparing with the capacity of the line.

The power factor ranges and voltage magnitude ranges where within the range of the operating limits of the transmission system, meaning the transmission system has the nominal capacity to meet the demand. However, the losses in the system in some transmission lines are high. With increasing power carried at a given voltage, an increasing fraction of the total power is lost on the lines, making transmission uneconomical at some point. The transmission losses are at the maximum accepted percentage loss of 5.06% .To improve the efficiency of the network, the losses need to be reduced by enhancing design (increasing the number of conductors on the current lines or building more transmission lines). This can be counteracted by reducing the resistance of the conductors, but only at the expense of making them thicker and heavier. The swing generatorôs powers output should also be adjusted and generate more power when the losses are greater than expected.

Recommendation for Further Work

The steady state operating point of the power system network will form the basis for the Optimal Power Flow (OPF) and Security Constrained Optimal Power Flow Analysis (SCOPF) to be extended in the ongoing research work. The objective of the OPF is to identify the operating configuration or solution that best meets a particular set of evaluation criteria that includes the cost of generation, transmission line losses, and various requirements concerning the systemôs security, or resilience with respect to disturbances.

An OPF algorithm is required which consists of numerous power flow analysis runs, one for each hypothetical dispatch scenario that could meet the specified load demand without violating any constraints. The output of each individual power flow run, which is a power flow solution in terms of bus voltage magnitudes and angles, is evaluated according to one or more criteria that can be wrapped into a single quantitative metric or objective function, such as the sum of all line losses in Megawatts or the sum of all generating costs in dollars when line losses are included. The OPF program then devises another scenario with different real and reactive power contributions from the various generators and performs the power flow routine on it, then another, and so on until the scenarios do not get any better and one is identified as optimal with respect to the chosen metric. OPF solutions may then provide guidance for on-line operations as well as generation and transmission planning.

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