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POWER FLOW AND CONTINGENCY ANALYSIS: CASE OF RWANDA
HIGH VOLTAGE POWER SYSTEM

BY

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Declaration

I, **Mudasingwa Alex**, hereby declare that this thesis is my original work. To the best of my knowledge, the work presented here has not been presented for a degree in any other Institution of Higher Learning.

MUDASINGWA ALEX

30/07/2015

This thesis has been submitted for examination with my approval as university supervisor.

Prof. M.K MANGOLI

.....

Name of supervisor

Date

Dedication

This work done is dedicated to:

My late Father **KABERUKA J. Bosco** and my living mother **MUKAFERESI Languida**. They both played an immeasurable role to shape and make my humanitarian nature and to scale up my life status. The inspiration and navigation that they perpetually injected in me during my childhood have all contributed a lot to make my dream alive.

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Acronyms

AC	Alternating Current
ANN	Artificial Neural Network
AV	Average Value
CA	Contingency Analysis
CEPGL	Communauté Économique des Pays des Grands Lacs (Economic community for Great lakes states)
DC	Direct Current
DRC	Democratic Republic of Congo
EARP	Electricity Access Roll-out Program
EWSA	Energy Water Sanitation Authority
FDM	Fast Decoupled Method
GA	Genetic Algorithm
GS	Gaus Seidel
KCL	Kirchoff's Current Law
kVA	Kilovolt Ampere
kV	kVAR- Kilovotl Ampere, Reactive
kV	Kilovolt
MATLAB	Matrix Laboratory
MVA	Megavolt Ampere
MVar	Megavolt Ampere, Reactive
MW	Megawatt
NR	Newton Raphson

PI	Performance Index
PSO	Particle Swarm Optimization
SCADA	Supervisory Control and Data Acquisition

Abstract

This thesis uses power flow and contingency analysis to investigate operating conditions of Rwanda High Voltage Power System and evaluate the impact of branch outage on its operational status. We utilize contingency analysis and performance indices to assess if the system can withstand the impact of transmission outage in relation to available load demand and load demand increase scenarios.

AC load flow method by Newton Raphson algorithm in MATLAB environment are used to determine voltage magnitude and phase angle of each busbar in the system, real and reactive power flowing on the network branches. They are also applied to reveal line outage impacts on the transmission lines transfer capacity in terms of thermal rating, buses prescribed voltage margins and rank their severity influence on the remaining system elements. It is known that element outage in the power system is caused by loadability in the network, specific technical and operational failure of the system elements including scheduled maintenance for a particular part of the system. This is done and attained by the power system operators on the power dispatching centres by the use of on-line analysis of supervisory control and data acquisition (SCADA). They eventually detect and control system hazards to provide defensive measures for reliable service. However, in this research we adhere to offline study to classify sabotages by referring to the buses accepted voltage margins and thermal ratings in the system branches. In doing so, we rank sequentially the highest value of Performance Index(PI) as the first critical sabotage and lowest value as the minor hazard subjected to the network. This informs the system planner which system transmission lines can be put in the first phase of transmission lines expansion. Therefore, it provides the overriding pathway to maintain power system security in order to have the expectable reliability in the power network.

CHAPTER ONE

1.0 Introduction

Rwanda is the Central-East African country whose power system presently has four sources of power generation; hydro power plant, thermal (diesel), methane gas and solar. It is also made up of fifteen 110 kV major buses which interconnect fourteen high voltage transmission lines to cover 412 km and reach various distribution substations in order to serve the entire national grid demand [1-2]. The government in its bid to increase electricity access in the community, established electricity access roll-out program to scale up electricity access in the rural areas. Consequently, Rwanda's house hold power demand has exponentially increased from 6% in 2004 to the 17% in 2013 connections [2-3]. Electricity power generation projects were initiated to support the agenda and to continuously boost the country's economy in terms of power satisfaction and cater for demand forecast . The increase in power demand and power generation projects has led to the need of assessing the existing system's operation in relation to the available demand and load increase on its PQ buses. This study is performed by applying three key techniques namely; Power Flow, Contingency Analysis and Performance Index.

Power flow (load flow) is addressed as the flow of electrical power from one or more sources through transmission lines and distribution branches to end users consuming power. In other words, power flow analysis is the backbone of the power system which facilitates the evaluation of electrical power sources and how they are shared into various network branches in accordance to their respective demands. Power flow analysis has the great impact to forecast future power demand, power economic scheming and power sharing between utilities, countries or regions. It is also an important numerical tool used to calculate or determine the magnitude and phase angle of voltage at each node (bus) in the system and to reveal, real and

reactive power flowing from bus to bus within the entire power system network or partly as required [3-4].

1.1 Contingency Analysis

It is a hybrid of two words, i.e Contingency and Analysis. Contingency in power system is termed as a disturbance resulting from the outage of one or more element(s) such as generators, transmission lines, transformers and circuit breakers. However, Contingency Analysis is the study of the power system element outage and it reveals its influence to the line flow overload and bus voltage profile in the system. It is a useful measure for power system security assessment, particularly to reveal which system element outage leads to the line flow overloads and bus voltage margin's violation. Performance index is used to evaluate and rank contingency impact on the remaining system elements in such way as to identify which critical system element outage sabotages its operational status.

Therefore power flow information incorporated with contingency analysis and performance index are applied to Rwanda High Voltage Power System in order to detect its behaviour under any branch outage [5]. This will enable us to know which contingency may harm the steady state stability of the system in terms of branch thermal ratings and bus voltage profile.

1.2 Power Generation Status in Rwanda

Presently, Rwanda has a power generation of total installed capacity 102 MW under which total available capacity is 92 MW including 18 MW from regional projects of Rusizi I and Rusizi II under umbrella of CEPGL (Communauté Économique des Pays des Grands Lacs) for Rwanda, Burundi and Democratic Republic of Congo (DRC) shared to meet national peak demand of 87MW [6].

1.3 Conceptual Power Supply in Rwanda

Electricity power demand has been exponentially increasing from 46 MW in 2007 to 78 MW in 2011, 85 MW in August 2012 and 87 MW in 2013. This electrical power is transported via 110 kV High Voltage Transmission Lines covering total distance of 412 km to reach the various distribution substations. The Power Supply System of Rwandan High Voltage Power System is made up of fifteen 110 kV major buses, five for generation and ten for loads to serve the entire national supply [6-7]. Therefore, transmission network pathways are divided into three corridors named as:

- i. South- western axis which is made up of Rusizi II, Mururu II, Karongi, Kibuye, Nyabarongo, Kilinda, Kigoma and including national dispatching centre.
- ii. Northern axis which consists of Ntaruka, Mukungwa Jabana HF and Jabana including national dispatching centre.
- iii. Eastern axis which is composed of Birembo, Musha and Rwinkwavu.

The above mentioned power transmission corridors are shown by the blue sketch lines on the map of Rwanda shown below:



Figure 1.1 Map of Rwanda indicating transmission lines pathways

Source: Rwanda Energy Water and Sanitation Authority

By considering Rwanda transmission network, this research aims to know its behavior by determining the power flowing through transmission lines besides their losses, voltage magnitude and phase angle of the major system buses. It also determines voltage magnitudes on the system buses when a certain transmission line is outaged from the system with respect to the available demand and load demand increase scenarios.

1.4 Problem Statement

Different literature provide several theories and practical works of how power flow analyses facilitate investigation of working conditions of electrical power system using different models. They also address how contingency events affect the reliability and efficiency of power services and emphasize on how if not well handled contingency can lead to the total collapse of the power system network. This enables us to do an offline study of branch outage by considering present load demand and load demand increase conditions of the power system transmission network. This study is enormously focused on Rwanda High Voltage power system in order to investigate which system transmission line outage can be a driving force for a system's limit violations, and where if not well managed can lead to the total collapse of the entire network. This is a paramount factor to be utilised in determining which transmission line(s) can be prioritized in the first phase of the system expansion plans and different phases schemed out when economic and environmental challenges can not allow all necessary system expansion or rehabilitation to be done at once.

1.5 Objectives

The general objective of this research is to perform an offline study to investigate the operating conditions of Rwandan High Voltage Power System in relation to the available load demand and load demand increase perspectives. This is done by analyzing its behaviour under sequential single transmission outage and rank its severity impact to the system security status.

- **Specific Objectives**

The specific objectives are precisely limited to :

- a. Investigate and determine voltage magnitude and phase angle at the major power system buses, and power flow in the network branches including their losses under normal operating conditions with respect to the available demand and load demand increase.
- b. Assess the behaviour of the power system status under each transmission line outage, and reveal its severity on the power flow of the remaining network branches and voltage profile on buses.
- c. Analyse the impact of 50% load demand increase on system buses of existing power network.
- d. Recommend contingency measures to the power system planner in order to eradicate the negative implications faced and thereafter contingency simulation.

1.6 Justification of the Study

In general, electricity access in Rwanda is still on its low level of 17% in 2013, compared to the target of the Economic Development and Poverty Reduction Strategy part two (EDPRS II) with an expected access rate of 70% by 2017 through electricity access roll-out program (EARP) [6]. This incredible milestone will be implemented through the generation expansion plan, which is predicted to add an amount of 563 MW to both on and off- grid systems but its bulk will be transmitted through in the present power network [7]. Thus, this triggers the thought about the behaviour of the present power system under both pre and post contingencies as a tool to assess power system security. The contingency analysis is used to determine whether present transmission branches can be able to carry out such paramount task. If not and referring to the economic constraints, how prioritization of constructing new transmission branches, new

generation plants and system expansion can be considered in accordance to the present system situation.

To achieve this, MATLAB features, AC load flow under Newton Raphson technique are applied to determine load flow of the present load demand and load growth conditions for Rwanda high voltage power system in order to reveal its present operational status and load growth scenarios. The term $N-1$ is considered as the scenario used to test power system security network where one transmission line is outaged from the network and reveals its impacts on the remaining system elements. AC load flow contingency analysis of $N-1$ condition, besides its severity effect ranking, enables us to reveal the post contingency system status so that the system planner can prioritize the system expansion scheme, and help the system operator bear in mind the system profile under contingency scenarios for defensive measures.

In doing so, this will help to resolve the system insecurity for post contingency and therefore this factor makes both utility owner and grid power consumers to benefit from reliable and available power supply.

1.7 Significance of the study

In general, the major contribution of this research is all about predicting (estimating) power system behaviour for both normal operating condition and post contingency scenario for a branch outage in relation to the available load and load growth condition.

- **Specific significances**

- i. It will enable to acquire knowledge of the system status, such as power flow in the system transmission lines and buses voltage profile under normal operating conditions.

- ii. In relation to the present status of transmission lines capability, facilitate the system planner to scheme out the future generation expansion plans regarding the present system behaviour.
- iii. I indicate the effectiveness of the load growth perspective to the present transmission lines so as to help load forecasting referring to the present system security.
- iv. Due to the economic constraints and environmental hinderances, facilitate the system planner to prioritize the urgent transmission lines to be put in the first phase of the system transmission lines expansion plan.
- v. It is among the power system security tools that enable both utility owners and system beneficiaries to gain from the reliability and availability of the power services.

1.8 Scope of Work

This thesis reveals power flow of Rwandan High Voltage Power System by using AC load flow under Newton Raphson technique in a MATLAB environment to determine voltage magnitude and phase angle at the system busbars, real and reactive power flowing into the network branches of the system. This is done as of paramount importance to show its behaviour under normal operating conditions of both available load demand and load growth scenarios. Using contingency analysis and performance index, this reseach determines the implication of the system branch outage relating to the transmission line thermal rating and voltage violation on the buses. In case of a negative implication, this work provides power security recommendations for the negative implications faced, thereafter contingency simulation on both available demand and load growth conditions.

1.9 Work Organisation

The entire structure of this research consists of five chapters, every chapter has subsections.

- Chapter one contains the introductory body of the work such as, power flow analysis and its importance in power system contingency analysis and performance index with their contributions in power system analysis. It has also an other major content which addresses aims and benefits of the study.
- Chapter two is composed of the other authors' thoughts which later give ideas for further work to be tackled. It shows how the conventional and intelligent models are used to maintain power system security. It is all about revealing the weakness and strength of each technique in relation to computational time, convergence and accuracy of attained results.
- Chapter three consists of methods and tools utilized to achieve the objectives of the study. It contains the method applied to give power flow in the transmission lines and voltage profile for both pre and post contingency scenarios with respect to the available load demand and load growth conditions. It also comprises programming steps carried out in MATLAB environment in order to have final outputs for the project.
- Chapter four indicates results for the pre and post contingency load flow including the severity effects of each contingency. It also gives results of analyses made with respect to the case study.
- Chapter five represents a short account of the conclusions and remarks for further works in order to create a conducive environment in power system security regarding the contingency analysis.

CHAPTER TWO

2.0 Literature Review

This chapter reveals the information highlighted by different authors in power flow and contingency studies besides the methods used to overcome challenging factors in the power system security.

2.1 Mode of Power System Security

Electrical power plays a big role in the growth of the economy of any country, more especially in the industrial sector. There is a need therefore to put emphasis on maintaining electrical power system security in terms of generation, transmission and supply for reliability.

Power system security incorporates system monitoring installed capacity at the utility dispatching centre, protective measures put in place along the system network and contingency analysis to necessitate scheduled maintenance outage, abrupt element(s) outage and system expansion plan.

A secure power system is likely to be reliable in terms of economic income for the utility, continuity of supply and technically vibrant in all system elements to withstand system post contingency.

The power system security analysis is performed to create several control strategies to guarantee security and survival of system during emergency conditions and hence operate at its possible lowest cost.

To have secure power system, its elements must operate within their prescribed operating conditions such as voltage variation limits, thermal limits, reactive power limits so as to maximize the avoidance of any hazardous event [8].

It is also useful to have power security assessment under contingency analysis by calculating the system operating indices for both pre and post contingency in order to have pre defensive system operation mechanisms to withstand system emergency conditions. This can be done using the following techniques:

- i). AC load flow
- ii). DC load flow
- iii). Genetic Algorithm
- iv). Particle Swarm Optimization
- v). Tabu Search
- vi). Artificial Neural Network.

The techniques mentioned above were used to determine the severity effect of contingency and rank/screen the effect according to its degree of implication on the power network and to optimize the network performance as efficient and reliable.

2.2 Techniques for Power System Contingency Analysis

2.2.1 DC Load Flow

Direct current (DC) power flow is a common model for power system contingency analysis due to its robust simplicity for computational time in order to reveal only real power flow in the system network branches. Meanwhile full AC load flow is accurate to look at all necessary information required such as system voltage profile, real and reactive power and power losses

within the system network branches but it is constrained by the rate of computational time to reveal necessary information [9].

It is also noted that such DC load flow simplification technique is not always justifiable to give realistic values due to its weak standards to consider power flow controlling devices. Thus, it is basically fast with minimum accuracy compared to full AC load flow.

DC load flow specifically has a shorter computational time due to the impact of linearization of power flow solution with respect to the following assumptions:

- i). Voltage angle difference between two buses is considerably small so that its approximate sine is equal to that angle and its cosine is one.
- ii). All voltage magnitudes are approximately equated to be 1.00 p.u
- iii). The system is an ideal network. i.e lossless network branches.
- iv). The tap settings are ignored.

The above assumptions inspired DC load flow to have some specific advantages over the full AC load flow under Newton Raphson method.

- i). The system impedance matrix is less about half the size of the full problem
- ii). The problem is simplified to be non iterative, just requiring a simple calculation in order to have final solution.
- iii). Impedance matrix is independent to the system network, hence it is calculated once throughout the whole calculation to have a final solution.

The above so called DC flow advantages undermined it in such a way that system network gains a flat voltage profile while in the actual practice of power system, voltage keeps changing within

secure voltage limits in accordance of power network perceptions like end users demand and power generation concepts.

Thus, this gives an emphasis to use full AC load flow technique in the concept of actual practice load flow solution which later applied to contingency analysis for a better approximate solution of the network.

The content of [9], indicates the usefulness of full AC load flow for contingency analysis in comparison with DC load flow under sensitivity factors method. It is important to apply sensitivity factor for studying thousands of possible outages due to its quick calculation of possible lines overloads. This model is mostly recommended to be applied when line loading is a major challenge for the study case because it is able to approximate change in the line flows for changes in generation on the network recovery by DC load flow solution.

There are many ways in which sensitivity factors are being used for contingency analysis but mainly are grouped into two classes [9]:

- i. Generation shift factor
- ii. Line outage distribution factor

- Then generation shift factor is presented as:

$$a_{li} = \frac{\Delta P_l}{\Delta P_i} \dots \dots \dots (2.1)$$

Where, l = line index

i = bus index

ΔP_l = Change in real power flow on line l with respect to the change of real power on bus i .

ΔP_i = change of real power generated at bus i

It is noted that real power generated change at bus i , is virtually recovered by reference bus real power change. i.e Loss in real power generated is equivalent to its change as:

$$\Delta P_i = -P_i^0 \dots \dots \dots (2.2)$$

Thus power flow on each line in power network, should be determined by anticipative factor ‘ a ’ as:

$$P_l = P_l^0 + a_{li}\Delta P_i \dots \dots \dots (2.3)$$

$$P_l = P_l^0 + a_{li}\Delta P_i$$

For $l = 1 \dots n$

Where,

P_l = Post real power flow on line l under generator outage

P_l^0 = Pre real power flow on line l

Thus, when the post outage real power flowing in the line l is about to violate the prescribed limits, the system operator on duty should be attentively able to know what is going wrong in the network.

- The line distribution factors: This is used for the line outage contingency analysis under usage of DC load flow.

The line outage distribution factor has the following definition:

$$d_{n,m} = \frac{\Delta P_n}{P_m^0} \dots \dots \dots (2.4)$$

Where,

$d_{n,m}$ = Line outage distribution factor for monitoring line n under the outage of line m

ΔP_n = Post change in real power flow on line n

P_m^0 = Pre real power flow in line m

If both cases power flow on lines n and m before outage of line m are well known, the post real power flow in line n can be determined by the line outage distribution factor as:

$$P_n = P_n^0 + d_{n,m} P_m^0 \dots \dots \dots (2.5)$$

where,

P_n^0 and P_m^0 are pre outage flows of line n and m respectively

P_n = Post real power flow on line n under line m outage.

Hence, before calculating the line outage distribution factors, it is advisable to introduce a fast technique for load flow solution in order to monitor all lines in the network for overload under outage of each particular line. Thereafter, line outage distribution factor will facilitate to examine if post line real power flow is bound within the line limits factors i.e. $-P_n^{max}$ as well as P_n^{max} . This is a worthy notepoint that, line flow can be either negative or positive.

2.2.2 AC Load Flow Contingency Analysis

AC load flow facilitates to make analysis of the system behaviour due to its paramount outputs revealed on the system buses and network corridors such as voltage magnitude and phase angles, real and reactive power besides corridors losses. On the system buses, voltage magnitudes and phase angles are determined in order to justify any change due to system element failure and this gives immediate significance to know what is going on the system corridors. In other words , it gives information of both real and reactive power in the system network corridors and voltage magnitudes on the system buses [9]. Thus AC load flow method reveals the system overloads and voltage bounds violation accurately but it takes a long time to give online information for any system failure since it performs Y-bus for each iteration to give a finite solution. Therefore the total time to compute consecutive lines outages will be too long. Similarly checking the entire system operation will also be time-consuming. In most cases of models applied in power systems have the conflict of accuracy and computational speed; here it is recommended to use AC load flow when the predominate factor is the accuracy.

2.2.3 Artificial Neural Network

This is a model of information processing that is referred to the functionality of the biological brain preferably the human brain. It is useful in modern computer evolution to perform engineering applications in order to have estimate solution of the complex problem. This is done based on its ability to have logical output from the complex or raw data and can also be used for classification of partners, trends that are complex to be recognized by any other computer feature. In its architecture it can either perform as a single layer or multi-layers artificial neural networks

which in common use are composed of input signals and interconnection layer(s) to provide a solution depending on the processing time domain.

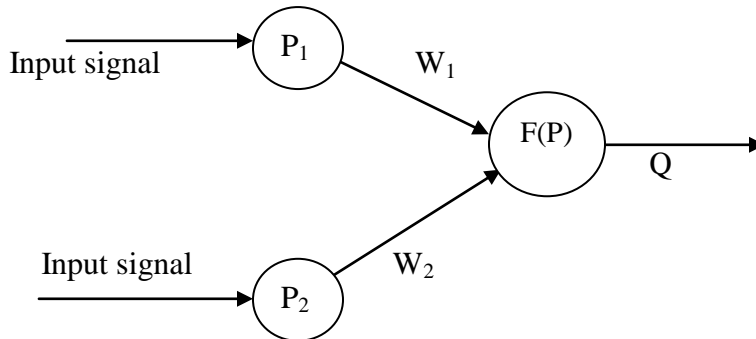


Figure 2.1 Simple neural network architecture

According to its robustness and fast speed to converge, it is widely applied in various areas of the study. In power systems it provides explicit solutions from the complex constraints mainly in power network design and modelling, on line application for power flow study, power system security monitoring and energy management system etc..

Artificial neural networks are also able to assess the effect of contingencies on power system security, and to predict the critical contingencies that can lead to the violation of the system operational limits. This is practised through manoeuvring two occasions, i.e. Contingency ranking and contingency selections. Referring to different literature contents, contingency ranking is made based on the scalar performance index while screening method is practised based on the power sensitivity factors. Artificial neural networks are able to deal with the subject of contingency ranking or screening under online monitoring with less computational time and better quality of standardized accuracy compared to other conventional techniques. However, its performance is limited by the technique applied besides intensive computational training process and no global method exists predicting when to stop this problem of overtraining function [10].

2.2.4 Tabu Search

The historical background of this paradigm relies on the word ‘Tabu’; language of Polynesian used by Aborigines to identify and consider the raw materials to be used and leave those expected to be naturally correct.

This paradigm is considered as meta-heuristic algorithm that is applied to work on and evaluate the combinatorial optimization problem.

It has a wide range of present application in the engineering field, for instance power system planning to optimize objective and constraint functions, pattern classification and molecular engineering.

In its combinatorial optimization, it applies neighbourhood search technique to iteratively move forward from one level solution to an improved subjected solution.

Tabu search has an advantage in terms of large number of iterations, and in every iteration there exists a single random pair change in the sequence. It gains perfect change only when the exchange improves the objective function and in doing so is able to check and neglect any repetitions of same exchanges that have occurred in the previous stages [11].

Even if this technique is able to work on the given task efficiently and converge in due time, in power system contingency analysis and ranking, faces a drawback of basing on the conventional techniques so that it must face the misranking error faced by the conventional model used in load flow solution [11].

2.2.5 Genetic Algorithm Model

The philosophy of Genetic algorithm was formulated by Goldberg and was inspired by Darwin’s theory of evolution which states that the survival of an organism is affected by the principle that states “ the strongest species survive”. Darwin also stated another principle which says that the

survival of an organism can be maintained through the process of reproduction, crossover and mutation [12]. This statement was adopted to computational algorithm to optimize objective function for a specific problem to have a perfect estimate of proper solution.

It is in this regard, Genetic Algorithm is briefly defined as the technique or paradigm used for solving both constrained and unconstrained optimization problems under basis of natural selection with respect to the logic of natural and biological evolution. In other words, it is an optimization and stochastic tool used basing on the principles of genetics and natural selection. This occurs in terms of continuous sequence to modify a population of individual solution.

At each step, the Genetic Algorithm selects the individuals at random from the perfect population to be parents and uses them to produce the children of the next generation.

This replication of successive generations, continues ahead to evolve until it gains an optimum solution (offspring).

Therefore, Genetic Algorithm applies above scenario to have a computational evolution to address a diverse problem to a better optimized solution, and it is done on the basis of three genetic operators to create the next generation form the present parent population.

The genetic operators named as:

- i. Selection: This is a scenario that makes a choice of which perfect parents to create a population of the next generation.
- ii. Crossover: This operator refers to the combination of two parents to reproduce children of the future generation.
- iii. Mutation: This is a regard of random changes to individual parents to produce children.

Genetic algorithm in its optimization operation faces a specific drawback of deciding fitness solution basing on the local optimal positions and this grants not to have an optimal solution. The

[13], proposed a novel power system stabilizer techniques using Advanced Genetic Algorithm approach to enhance genetic algorithm drawbacks of low convergence and misranking based fittest function.

Therefore as this based declaration, genetic algorithm is not the perfect algorithm to study power contingency analysis and ranking in order to avoid misranking of severe or critical contingencies that can affect the system profile violation.

2.2.6 Particle Swarm Optimization (PSO)

It is the swarm intelligent paradigm for solving an optimization problem and it is basically inspired by biological group work such like fish schooling, bird flocking, bees swarming and human behaviour in social classes.

The PSO algorithm is mostly developed with regard to the simulation of bird flocking to search for food in an optimal scenario with respect to their velocity and positions.

It is in this process that it is considered to be an optimization tool that has a major advantage of fast convergence as it is a population based technique rather than other models of computational evolution such as Simulation Annealing, genetic algorithm, tabu searching and so on.

Recent reseachers identified that PSO suffers from a general drawback of performing several iterations to achieve an optimal solution besides premature convergence that can be caused by the local optima localization.

The [14], proposed a hybrid of Particle Swarm Optimization and Tabu Search to select high order contingencies in order to mitigate the pre-mature convergence of PSO that can cause the misranking error of the contingency scenarios that can lead to the power system limits violations.

2.3 Power System Contingency Analysis

Contingency is briefly defined as any disturbance in the network while contingency analysis is defined as the study of the outage of the elements such as transmission lines, transformers and generators, and investigating of the resulting effects on line power flows and bus voltages of the remaining system. It is an utmost important tool to explore the behaviour of the system under an unexpected or planned system outage to detect the weakness that the network will bear [15].

2.3.1 Outages of the System Elements

Most of the system outages are probably considered as the result of elements loadability besides specific technical and operational failure [16].

Contingencies preferably exist as the result of the single or multiple outages of the system elements such as: generator, network transmission lines and system transformer where each of these elements has its specific outage characteristics such as:

- a) Generator: Overload due to consumption demand, temperature limit and technical failure
- b) Transmission line: Line loadability will cause a challenge of thermal limit, voltage drop limit and steady state stability limit.
- c) Transformer: outage of the system transformer will depend on the challenge of the thermal limit and any other technical failure.

2.4 Background on the Power Flow Aspects

The power flow is the major pillar in power systems to reveal information necessary for steady state operation, operation economic scheduling, planning and power exchange between states/ utilities. Power flow studies are normally performed to reveal real power and reactive power in the transmission lines, losses in the network corridors, magnitude and phase angle of the voltage at the system busbars and to investigate if the power network is operating within normal operating limits.

2.4.1 Concept of Power Flow Techniques

The power flow analysis information is determined using three common techniques named as Newton Raphson, Gauss Seidel and Fast-Decoupled solution method. Among these methods each one has its merits and drawbacks depending on the four paramount features; accuracy of the method, speed for solution, convergence of the method for the solution and computational memory required for the applied technique [17-18].

i. Newton Raphson Merits and Drawbacks for Power Flow Solution

- **Merits**

- The rate of convergence is fast and requires less number of iterations to converge and obtain the solution.
- It is important to set the system reference bus in order to define voltage and angular reference for load flow solution. Therefore, for Newton Raphson techniques, slack bus is selected arbitrarily.
- It is more accurate and reliable for medium and large systems.

- **Its Drawbacks**

- The elements of the Jacobian are computed in each iteration, hence it is tedious and takes much time for load flow solution.
- It requires more memory space in order to accommodate all parameters encountered for a complete operation for the solution.

ii. Merits and Demerits for Gauss Seidel Techniques

- **Merits**

- It requires the fewest number of arithmetic operations to complete an iteration. Therefore, it takes less time per iteration as its computational status is proportional to the number of branches and buses in the system.
- It requires less memory for the complete load flow solution.

- **Demerits**

- The rate of convergence is slow and required more number of iterations to obtain the solution.
- Number of iterations increase as the number of buses increase in the power system. Hence, it is complex to use it in large system.
- Convergence is affected by the selection of the slack bus. Thus, slack bus is not selected arbitrarily.
- In large system, it is less accurate and unreliable.

iii. Merits and Demerits for Fast Decoupled Solution Method

- **Merits**

- It is an alternative strategy for improving computational efficiency and reducing computer storage requirements.

- It requires considerably less time per iteration than Newton Raphson and a power flow solution is obtained very rapidly.
- **Demerits**
- It depends on the use of an approximate version of Newton Raphson procedure.
- It requires more iterations than Newton Raphson method to have power flow solution.

As in [19], all methods mentioned above are applied in power flow analysis by depending on the number of busbars and their classifications. The four major variables necessary for power flow analysis include:

- Voltage magnitude and phase angle, $|V|$ & δ .
- Real and reactive power, P & Q.

Among these four variables only two can be specified on each busbar, the other remaining two are determined by the use of power flow solution. With respect to the above load flow techniques mentioned, each is applied to give a load flow solution by depending on the characteristics of the output required. All stated above conventional techniques are contradictive on the rate of computation, accuracy and rate of convergence but in case of accuracy, Newton Raphson method is highly recommended [19].

2.4.2 Load Flow and its Concepts in Power System

Generally, power system network is made up of the following major components: generators, transformers, transmission lines and loads. They are recognized to obtain power flow solution of the system. In order to have power flow solution, the variables of the above mentioned components are considered to be in units and have the common MVA as system. Then, it is very important to know admittance matrix of the given power network. For n- network branches, we

build n - admittance matrix which is the common principal used to have admittance matrix of any given number of busbars in the power network [19-20].

2.4.3 Formation of the Bus Admittance Matrix

Generally, elements of admittance matrix are obtained by considering parameters of transmission lines connected between system buses. For example, a single transmission line connected between bus a and b has the following variables:

R = Resistance,

X = Reactance,

G = Conductance and

B = Susceptance,

I_a = Current at bus a ,

I_b = current at bus b

V_a = voltage at bus a , and also V_b = voltage at bus b .

Then, a single line diagram representing a transmission line connected between two buses is shown below:

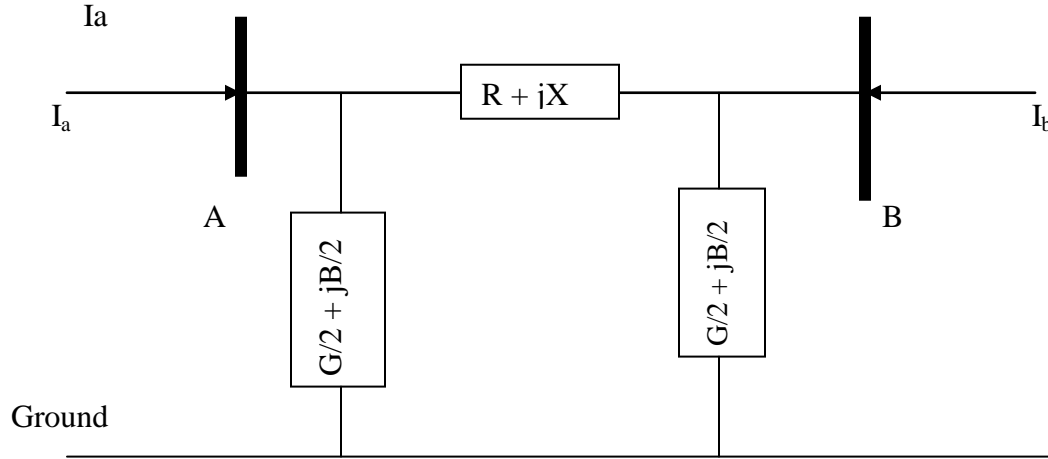


Figure 2.2 Representation for a transmission line connected between two buses

Hence, self admittance of the above line at bus a is equivalent to

$$Y_{aa} = \frac{1}{R+jX} + \left(\frac{G}{2} + j\frac{B}{2}\right) = \frac{R}{R^2+X^2} + \frac{G}{2} - \frac{jX}{R^2+X^2} + j\frac{B}{2} \dots\dots\dots(2.6)$$

Mutual admittance between bus a and b is

$$Y_{ab} = -\frac{1}{R+jX} = -\frac{R}{R^2+X^2} + \frac{jX}{R^2+X^2} \dots\dots\dots(2.7)$$

And it is noted that $Y_{ab} = -Y_{ba}$

It is recognized that when a shunt component is connected to the bus , its admittance value is added to its corresponding self admittance. Then, shunt connected to bus a in fig 2.2 given above, generates the following equivalent admittance value:

$$Y_{aa} (shunt) = \frac{1}{R_{sh} + jX_{sh}} = \frac{R_{sh}}{R_{sh}^2 + X_{sh}^2} - j \frac{X_{sh}}{R_{sh}^2 + X_{sh}^2} \dots\dots\dots (2.8)$$

Therefore, admittance matrix of the above system is

$$Y_{bus} = \begin{bmatrix} Y_{aa} & Y_{ab} \\ Y_{ba} & Y_{bb} \end{bmatrix} \dots\dots\dots(2.9)$$

Therefore, basing on the above expressions, admittance matrix of the n- busbars system is formulated as :

$$Y_{bus} = \begin{bmatrix} Y_{11} & Y_{12} \dots & Y_{1n} \\ Y_{21} & Y_{22} \dots & Y_{2n} \\ \vdots & \vdots & \vdots \\ Y_{n1} & Y_{n2} \dots & Y_{nn} \end{bmatrix} \dots\dots\dots(2.10)$$

2.4.4 Power Network Performance Equations

Using Nodal Voltage Method, the current injected at bus *a* is expressed in terms of *V_a* and *V_b* as follow:

$$I_a = Y_{a0}V_a + Y_{ab}(V_a - V_b) = (Y_{a0} + Y_{ab})V_a - Y_{ab}V_b = Y_{aa}V_a + Y_{ab}V_b \dots\dots\dots(2.11)$$

but $Y_{aa} = Y_{a0} + Y_{ab}$ and $Y_{ab} = -Y_{ba}$

Also at bus b,

$$I_b = I_{b0}V_b + Y_{ba}(V_b - V_a) = (Y_{b0} + Y_{ba})V_b - Y_{ba}V_a = Y_{bb}V_b + Y_{ba}V_a \dots\dots\dots(2.12)$$

But also $Y_{bb} = Y_{b0} + Y_{ba}$ and $Y_{ba} = -Y_{ab}$

The above two equations can form a matrix of the network performance equation as:

$$\begin{bmatrix} I_a \\ I_b \end{bmatrix} = \begin{bmatrix} Y_{aa} & Y_{ab} \\ Y_{ba} & Y_{bb} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \end{bmatrix} \dots\dots\dots(2.13)$$

From equation 2.13, we introduce $\begin{bmatrix} I_a \\ I_b \end{bmatrix} = I$, $\begin{bmatrix} Y_{aa} & Y_{ab} \\ Y_{ba} & Y_{bb} \end{bmatrix} = Y$ and $\begin{bmatrix} V_a \\ V_b \end{bmatrix} = V$ so as to to have a simple expression of the current injected on the power system buses.

$$I = YV$$

2.4.5 Transmission Line Power Flow Equations

Referring to figure 2.2, we define

$Y = \frac{1}{R+jX}$ and $Y/2 = G + jB$, Then, real and reactive power in the transmission line connected

from bus a to b is given by:

$$P_{ab} - jQ_{ab} = V_a^* \left[Y_{ab}(V_a - V_b) + V_a \left(\frac{Y'_{ab}}{2} \right) \right] \dots \dots \dots (2.14)$$

Similarly, the expression of real and reactive power flow from bus b to a is determined as:

$$P_{ba} - jQ_{ba} = V_b^* \left[Y_{ba}(V_b - V_a) + V_b \left(\frac{Y'_{ab}}{2} \right) \right] \dots \dots \dots (2.15)$$

2.4.6 Power Balance Equations

In the real concept, power system network can be operating under balanced or unbalanced conditions but in power flow analysis, we assume and consider power network to be balanced.

Recalling Kirchoff's current Law, current injected on bus a is equivalent to the current flow in the network. So,

$I_a = I_{Ga} - I_{Da} = \sum_{k=1}^n I_{ak}$ and it is well expressed that $I = YV$, Then

$$I_a = I_{Ga} - I_{Da} = \sum_{k=1}^n Y_{ak} V_k \dots \dots \dots (2.17)$$

It is also recognised that complex power on bus a in the system is $S_a = V_a I_a^*$

$$\text{Then } S_a = V_a I_a^* = V_a (\sum_{k=1}^n Y_{ak} V_k) = V_a \sum_{k=1}^n Y_{ak}^* V_k^* \dots \dots \dots (2.18)$$

By considering, V_a as the phase voltage magnitude with the angle, $V_a = |V_a| \angle \theta_a$ and Y_{ab} is the transmission admittance and is a complex element defined by G_{ab} and B_{ab} as the real and

imaginary parts of the admittance matrix parameter of the transmission line connected between two buses. Indeed, $Y_{ab} = G_{ab} + jB_{ab}$. From this expression, Equation (2.18) is rewritten as

$$S_a = V_a \sum_{k=1}^n Y_{ak}^* V_k^* = |V|_a < \theta_a \sum_{k=1}^n (G_{ab} + jB_{ab})^* (|V|_b < \theta_b)^*$$

The above equation is expressed as:

$$\begin{aligned} S_a &= |V|_a < \theta_a \sum_{k=1}^n (G_{ab} - jB_{ab})(|V|_b < -\theta_b) \\ &= \sum_{k=1}^n |V|_a < \theta_a (|V|_b < -\theta_b) (G_{ab} - jB_{ab}) \end{aligned}$$

Thus,

$$S_a = \sum_{k=1}^n (|V|_a |V|_b < (\theta_a - \theta_b)) (G_{ab} - jB_{ab})$$

Recalling, Euler's complex number expression,

$$e^{j\theta} = \cos\theta + j\sin\theta$$

Exact power flow equation will be:

$$S_a = \sum_{k=1}^n |V|_a |V|_b (\cos(\theta_a - \theta_b) + j\sin(\theta_a - \theta_b) (G_{ab} - jB_{ab})) \dots \dots \dots (2.19)$$

Multiplying parameters of equation (2.19), we formulate an equation of the real and imaginary parts which related to $S_a = P_a + jQ_a$. Therefore, the output equations are expressed as:

$$\begin{aligned} P_a &= \sum_{k=1}^n |V|_a |V|_b (G_{ab} \cos(\theta_a - \theta_b) + B_{ab} \sin(\theta_a - \theta_b)) \text{ and} \\ Q_a &= \sum_{k=1}^n |V|_a |V|_b (G_{ab} \sin(\theta_a - \theta_b) - B_{ab} \cos(\theta_a - \theta_b)) \dots \dots \dots (2.20) \end{aligned}$$

The above two equations are the power flow expressions used to determine basic procedure for power flow problem evaluation. They are applied to determine power flow solution of nonlinear algebraic equations by iterative process [20].

2.4.7 Newton Raphson Technique for Power Flow Solution

Power flow equations are non linear algebraic equations which solved by the method of numerical iterations. Newton Raphson technique is considered as the best and successful iterative method for a large system power flow solution compared to other conventional power flow solution techniques. Its performance is less number of iterations to reach convergence and its convergency is certain [20-21].

Taylor's series expansion for a function of two or more variables, is the mother step to get a general expression for the Newton Raphson technique which is used to obtain power flow solution.

Let z_1, z_2, \dots, z_n be the specific functions and f_1, f_2, \dots, f_n be the number of functions whose unknown variables are x_1, x_2, \dots, x_n , responsible to be solved.

Also,

$$z_1 = f_1(x_1, x_2 \dots x_n)$$

$$z_2 = f_2(x_1, x_2 \dots x_n)$$

$$\vdots \quad \vdots \quad \vdots$$

$$z_n = f_n(x_1, x_2 \dots x_n)$$

We estimate the initial variables $x_1^0, x_2^0 \dots x_n^0$ to get the solutions of z_1, z_2, \dots, z_n , but it is normally recognized that estimation does not bear the exact solution, for which $\Delta x_1^0, \Delta x_2^0 \dots \Delta x_n^0$ are said to be slight different to the actual solution. Thus, they added on the initial estimated values to bear the corrective values for the solution.

Considering the expansion of Taylor's series around the initial values, we get a major function of:

$$Z = F(X) = F(X^{(0)}) + J(X^{(0)})\Delta x_1^0 + \text{high- order terms}.....(2.21)$$

Where $J(X^{(0)})$ is a matrix of first-order partial derivatives of $F(X)$ with respect to X and it is called Jacobian Matrix.

When we apply Taylor's series expansion on the equation (2.21) and referring to the equation of z_1 , it reflects the following expansion form:

$$z_1 = f_1(x_1^0, x_2^0, \dots, x_n^0) + \left[\Delta x_1^0 \left(\frac{\partial f_1}{\partial x_1} \right)^0 + \Delta x_2^0 \left(\frac{\partial f_1}{\partial x_2} \right)^0 + \dots + \Delta x_n^0 \left(\frac{\partial f_1}{\partial x_n} \right)^0 \right] +$$

higher order terms (2.22)

If this expansion model is applied to the entire equations of Z and we neglect their higher derivatives terms as they are relatively closed to zero. Finally, by linearizing all equations and arranging them in matrix form, we get:

$$\begin{bmatrix} z_1 - f_1(x_1^0, x_2^0, \dots, x_n^0) \\ z_2 - f_2(x_1^0, x_2^0, \dots, x_n^0) \\ \dots \\ z_n - f_n(x_1^0, x_2^0, \dots, x_n^0) \end{bmatrix} = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \dots & \frac{\partial f_1}{\partial x_n} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \dots & \frac{\partial f_2}{\partial x_n} \\ \dots & \dots & \dots & \dots \\ \frac{\partial f_n}{\partial x_1} & \frac{\partial f_n}{\partial x_2} & \dots & \frac{\partial f_n}{\partial x_n} \end{bmatrix} \begin{bmatrix} \Delta x_1^0 \\ \Delta x_2^0 \\ \dots \\ \Delta x_n^0 \end{bmatrix}(2.23)$$

If we consider two equations with respect to the two variables, we get:

$$\begin{bmatrix} z_1 - f_1(x_1^0, x_2^0, \dots, x_n^0) \\ z_2 - f_2(x_1^0, x_2^0, \dots, x_n^0) \end{bmatrix} = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} \end{bmatrix} \begin{bmatrix} \Delta x_1^0 \\ \Delta x_2^0 \end{bmatrix} (2.24)$$

Where $\begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} \end{bmatrix}$ is called Jacobian of square matrix and $f_1(x_1^0, x_2^0 \dots x_n^0)$ represents the initial

estimate value of z_1 but they are not equal as well as similar to z_2 .

$$\text{Then, } \begin{bmatrix} z_1 - f_1(x_1^0, x_2^0 \dots x_n^0) \\ z_2 - f_2(x_1^0, x_2^0, \dots, x_n^0) \end{bmatrix} = \begin{bmatrix} \Delta z_1^0 \\ \Delta z_2^0 \end{bmatrix},$$

$$\text{Thus, } \begin{bmatrix} \Delta z_1^0 \\ \Delta z_2^0 \end{bmatrix} = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} \end{bmatrix} \begin{bmatrix} \Delta x_1^0 \\ \Delta x_2^0 \end{bmatrix} \dots\dots\dots (2.25)$$

This is the general form of the Newton Raphson which is harmonized to form:

$$\begin{bmatrix} \Delta z_1^0 \\ \Delta z_2^0 \end{bmatrix} = J_1^0 \begin{bmatrix} \Delta x_1^0 \\ \Delta x_2^0 \end{bmatrix} \dots\dots\dots (2.26)$$

The above equation 2.26 is used to determine the intended values of Δx_1^0 and Δx_2^0 in the use of the inverse of the Jacobian matrix to determine the new estimate values equivalent to:

$$x_1^1 = x_1^0 + \Delta x_1^0 \text{ and } x_2^1 = x_2^0 + \Delta x_2^0 \dots\dots\dots (2.27)$$

If the process is repeated, we shall have the iterative solution which is very small relatively to the accepted minimum value.

2.4.8 Application of Newton-Raphson Technique for the Power Flow Solution

Newton Raphson technique has two common options in its parameters arrangement (rectangular and polar) to determine power flow solution. Polar form is used more in practice than rectangular form due to its small and simplified equations compared to those equations involved in rectangular form [21-22].

When we intend to use polar form, bus voltage and line admittance must appear in polar format. Then, by considering a branch power network connected from bus a to b, we are able to have the following respective polar variables.

$$V_a = |V_a| \angle \theta_a, V_a^* = |V_a| \angle -\theta_a, V_b = |V_b| \angle \theta_b \text{ and } y_{ab} = |y_{ab}| \angle \delta_{ab}$$

Also referring to the complex power injected at the bus a:

$$S_a = P_a + jQ_a = V_a I_a^* ,$$

we preferably consider, the conjugate of injected power at bus a as:

$$S_a^* = P_a - jQ_a = V_a^* I_a \dots\dots\dots (2.28)$$

In the power system of n busbars, current injected at the bus a is :

$$I_a = \sum_{b=1}^n Y_{ab} V_b \text{ and when it is substituted in equation (2.17), we get:}$$

$$S_a^* = P_a - jQ_a = V_a^* \sum_{b=1}^n Y_{ab} V_b \dots\dots\dots (2.29)$$

In equation (2.29) above, we consider its real part as the real active power and its imaginary part as the reactive power to get:

$$P_a = \text{Re}\{V_a^* \sum_{b=1}^n Y_{ab} V_b\} \dots\dots\dots (2.30)$$

$$Q_a = -\text{Im}\{V_a^* \sum_{b=1}^n Y_{ab} V_b\} \dots\dots\dots (2.31)$$

In polar form, equations of (2.30) and (2.31) will become:

$$P_a = \sum_{b=1}^n |V_a| |V_b| |Y_{ab}| \cos(\delta_{ab} + \theta_b - \theta_a) \dots\dots\dots (2.32)$$

$$Q_a = -\sum_{b=1}^n |V_a| |V_b| |Y_{ab}| \sin(\delta_{ab} + \theta_b - \theta_a) \dots\dots\dots (2.33)$$

Newton Raphson technique is applied to determine power flow solution by relating power flow equations to the nonlinear equation $Z = f(x)$, to be reflected on equation $Z = f(x)$. Power flow equations are nonlinear, as Z is also assumed to be a nonlinear equation whose solution is obtained by using iterative process. Then, assuming initial value of $x = x^{(0)}$ and $\Delta x^{(0)}$ be a slight difference from the actual value of x .

$$f(x) = f(x^{(0)} + \Delta x^{(0)}) = z$$

Applying Taylor's series expansion on Z equation, we get,

$$f(x^{(0)}) + \frac{df}{dx} \Delta x^{(0)} + \frac{1}{2} \frac{d^2 f}{dx^2} (\Delta x^{(0)})^2 + \dots + \frac{1}{n!} \frac{d^n f}{dx^n} (\Delta x^{(0)})^n = z$$

Higher order terms are neglected

to remain with:

$$f(x^{(0)}) + \frac{df}{dx} \Delta x^{(0)} = z \dots\dots\dots (2.34)$$

From equation 2.34 $\Delta x^{(0)} = \frac{z - f(x^{(0)})}{\frac{df}{dx}}$

Thus, new estimate value for x is:

$$x^1 = x^{(0)} + \Delta x^{(0)} \dots\dots\dots (2.35)$$

we consider, real power (P) and reactive power (Q) with variable of voltage (V) and its phase angle (δ) be related to the Z solution.

$$Z = \begin{bmatrix} P_{inj}^{sch} \\ Q_{inj}^{sch} \end{bmatrix}, \quad x^{(n)} = \begin{bmatrix} \delta^{(n)} \\ V^{(n)} \end{bmatrix} \text{ and } f(x^{(n)}) = \begin{bmatrix} P_{inj}(x^{(n)}) \\ Q_{inj}(x^{(n)}) \end{bmatrix},$$

New estimate,

$$x^{(n+1)} = x^{(n)} + \frac{z - f(x^{(n)})}{\left(\frac{df}{dx}(x^{(n)})\right)} \dots\dots\dots (2.36)$$

It is noted that $\left(\frac{df}{dx}(x^{(n)})\right)$ is the first derivative function applied to the power flow equations in order to determine slight difference for voltage and phase angle that will be added to the initial estimated values in order to have approximated iterative solution.

Then, $\left(\frac{df}{dx}(x^{(n)})\right)$ is reflected to power equation as:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial |V|} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial |V|} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \dots\dots\dots(2.37)$$

From equation (2.37), change in phase angle and voltage magnitude are determined when power mismatch values are known.

Then, $\Delta P_a^{(n)} = P_a^{sch} - P_a^{cal}$ as well as

$$\Delta Q_a^{(n)} = Q_a^{sch} - Q_a^{cal}$$

Subsequently, $\Delta \delta$ and $\Delta |V|$ are determined. when both real and reactive power mismatch are less or equal to the prescribed accuracy.

Therefore, we deliver new iterative estimates for voltage magnitude and phase angle.

$$\delta_a^{(n+1)} = \delta_a^{(n)} + \Delta \delta_a^{(n)} \dots\dots\dots(2.38)$$

$$|V_a^{(n+1)}| = |V_a^{(n)}| + \Delta |V_a^{(n)}| \dots\dots\dots(2.39)$$

Power flow solution is dermined by the iterative solution. Thus, it is a repeatable process for which real and reactive power mismatch reflected to be less or equal to the prescribed accuracy condition [22-23].

CHAPTER THREE

3.0 Methodology and Materials

3.1 Overview

In this Research Thesis, we have used data collected from the dispatching centre of Rwanda state owned power utility company, in order to assess operational status of Rwanda high voltage (110 kV) power system. We coherently apply AC load flow under Newton Raphson model in MATLAB environment to compute voltage magnitude and phase angle for each system bus, real and reactive power flow in the network branches. Newton Raphson technique is chosen from other conventional models due to its successful iterative accuracy and convergence for the solution. A sequential line outage is applied to test if the system is designed with enough redundancy to withstand the influence of a such disturbance. Using performance indices, contingency ranking is applied to reveal the effect of each transmission line outage in the system operational status. We therefore assess such influence by referring to the thermal ratings of the system transmission lines and buses voltage limits. In doing so, we rank sequentially the highest value of PI as the first critical sabotage and lowest value as the minor hazard subjected to the network. We finally intend to know the system voltage profile under 50% load increase on each PQ bus under normal operating conditions, and when there is contingency in the network.

3.2 Data Collection

Data used in this reasearch were gathered from Rwanda state owned power utility company named “Energy, Water and Sanitation Authority”. Data collected were targeting to match simulation inputs of the algorithm employed. As far as load flow and contingency analysis are concerned, we gathered information corresponding to real and reactive power injected on generation buses and load buses, real and reactive power demand and transmission parameters.

Detailed data parameters for this research are annexed on the back pages of this report. The Utility Data Centre and Power National Dispatching Centre were consulted to get comprehensive data required for the study.

3.2.1 Challenges Experienced During Data Collection

- i. Time was a major constraint to allow in charge person to sort out the information required from data set of entire network. It was his ambition and courages to assist in data collection otherwise it would not happen as it was really the extra work added to his usual planned activities.
- ii. Availability of personnel was an other challenge to make it happen. Specific employees with their daily duties were responsible to facilitate me in conducting data collection activities. However, their daily responsibilities such as technical interventions, official deligation and duty management could not allow them to satisfy my request on time.

3.3 Materials for Case Study Simulation

AC load flow using Newton Raphson technique under MATLAB software applied to obtain load flow solution for both available demand and load increase conditions. They are used to reveal the impact of each transmission line outage to the Rwanda High Voltage power system. They are also necessary to give out the post outage information of which critical branch in the sytem and load buses voltage profile in the entire network. Therefore, this helps to plan and put in place interim measures for maintaining the power network security.

3.3.1 Contingency Ranking

In power system security analysis,contingency ranking is practiced in order to identify the effect of contingencies on the system operation and to experience which critical contingencies violate

the bounds of the system operational conditions. In this study, contingency ranking is done to identify which critical branch outage that leads the power system network to be under stress in terms of real power ratings and voltage magnitudes. In this research, we do contingency ranking by utilizing the thermal rating and reactive performance indices.

3.3.2 Performance indices used

These include:

- Thermal ratings limit testing; $\frac{(P_{max}-P_{ilineflow})}{MVA_{systembase}} \dots \dots \dots (3.1)$

Where P_{max} = Maximum real power ratings of the system branches

$P_{ilineflow}$ = Power flow on line i after contingency

$MVA_{systembase}$ = 100 MVA system base.

- **PI av Thermal Rating overload under single outage:** $\frac{\sum_{i=1}^n f(x)}{t} \dots \dots \dots (3.2)$

Where, PI av = Average value performance index for thermal ratings encountered when more than one lines are overloaded due to branch outage.

$f(x)$ = Post line outage thermal rating overload for each transmission line.

t = Total number of lines overloaded due to a certain single line outage.

- **Voltage Performance Index**

$$PI_V = \sum_{i=1}^{N_{PQ}} \left[\frac{2(V_i - V_{i\text{norm}})}{V_{i\text{max}} - V_{i\text{min}}} \right]^2 \quad [9] \dots \dots \dots (3.3)$$

Where, V_i = Voltage at bus i after contingency,

$V_{i\text{max}}$ = Maximum voltage limit of bus i,

$V_{i\text{min}}$ = Minimum voltage limit of bus i,

$V_{i\text{norm}}$ = Average of voltage maximum and minimum limits of bus i,

N_{PQ} = Total number of load buses in the system

3.4 Necessary information required for the Solution

In order to simulate the case study model, the following parameters must be put in place, namely Bus data and system line data.

The other specific parameters to be clarified are power system MVA base, power mismatch accuracy, maximum iterations and correction factor.

The network to be simulated has the following actual bus names that are replaced by the bus numbers indicated on the single line diagram.

Table 3.1: Actual bus names of the network

Bus numbers	Bus Names
1	Ntaruka
2	Mukungwa
3	Jabana
4	Jabana heavy fuel
5	Birembo
6	Musha
7	Rwinkwavu
8	Gikondo
9	Kigoma
10	Kilinda
11	Nyabarongo
12	Karongi
13	Kibuye
14	Mururu II
15	Rusizi II

users. The system transmission line numbers and actual names of their interconnected buses are represented in the following table.

Table 3.2 System Transmission lines

Number of branches	Interconnection buses		Actual names of interconnections buses	
	From	To	From	To
1	1	2	Ntaruka	Mukungwa
2	2	3	Mukungwa	Jabana
3	3	4	Jabana	Jabana Heavy Fuel
4	3	5	Jabana	Birembo
5	5	6	Birembo	Musha
6	6	7	Musha	Rwinkwavu
7	3	8	Jabana	Gikondo
8	8	9	Gikondo	Kigoma
9	9	10	Kigoma	Kilinda
10	10	11	Kilinda	Nyabarongo
11	10	12	Kilinda	Karongi
12	12	13	Karongi	Kibuye
13	12	14	Karongi	Mururu II
14	14	15	Mururu II	Rusizi I

3.7 Steps Tabulated for Case Study Contingency Analysis

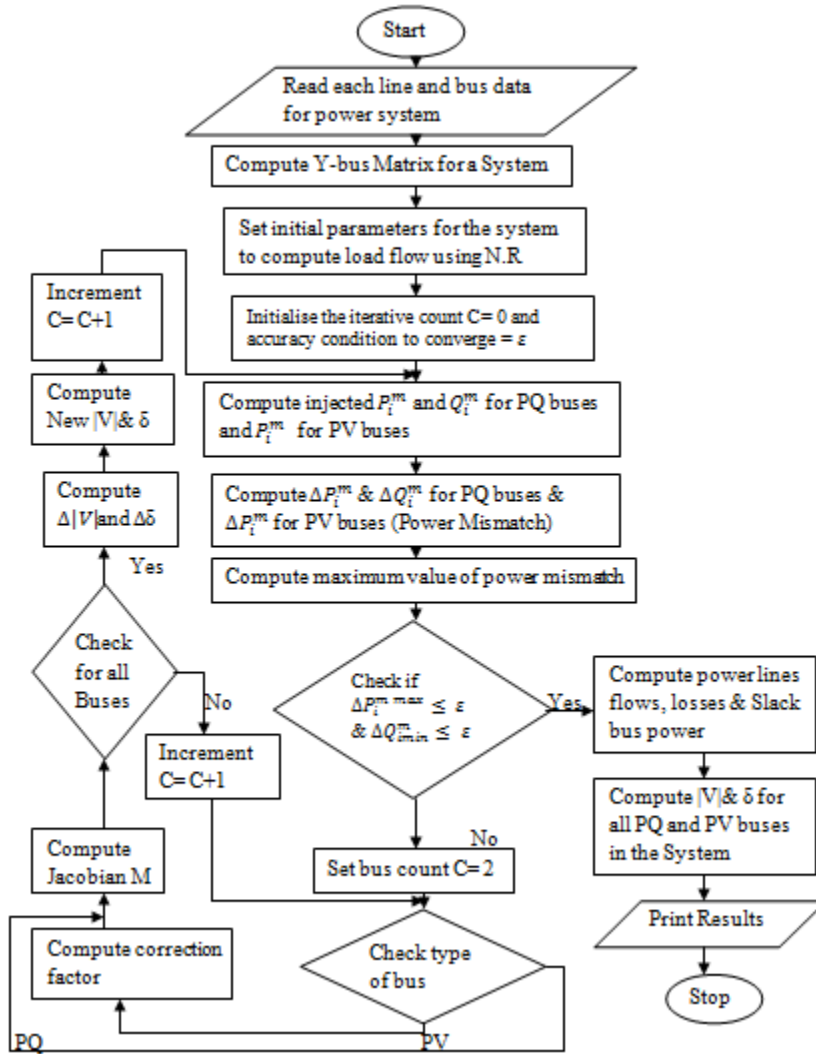


Figure 3.2. Flowchart for AC load flow using Newton Raphson model

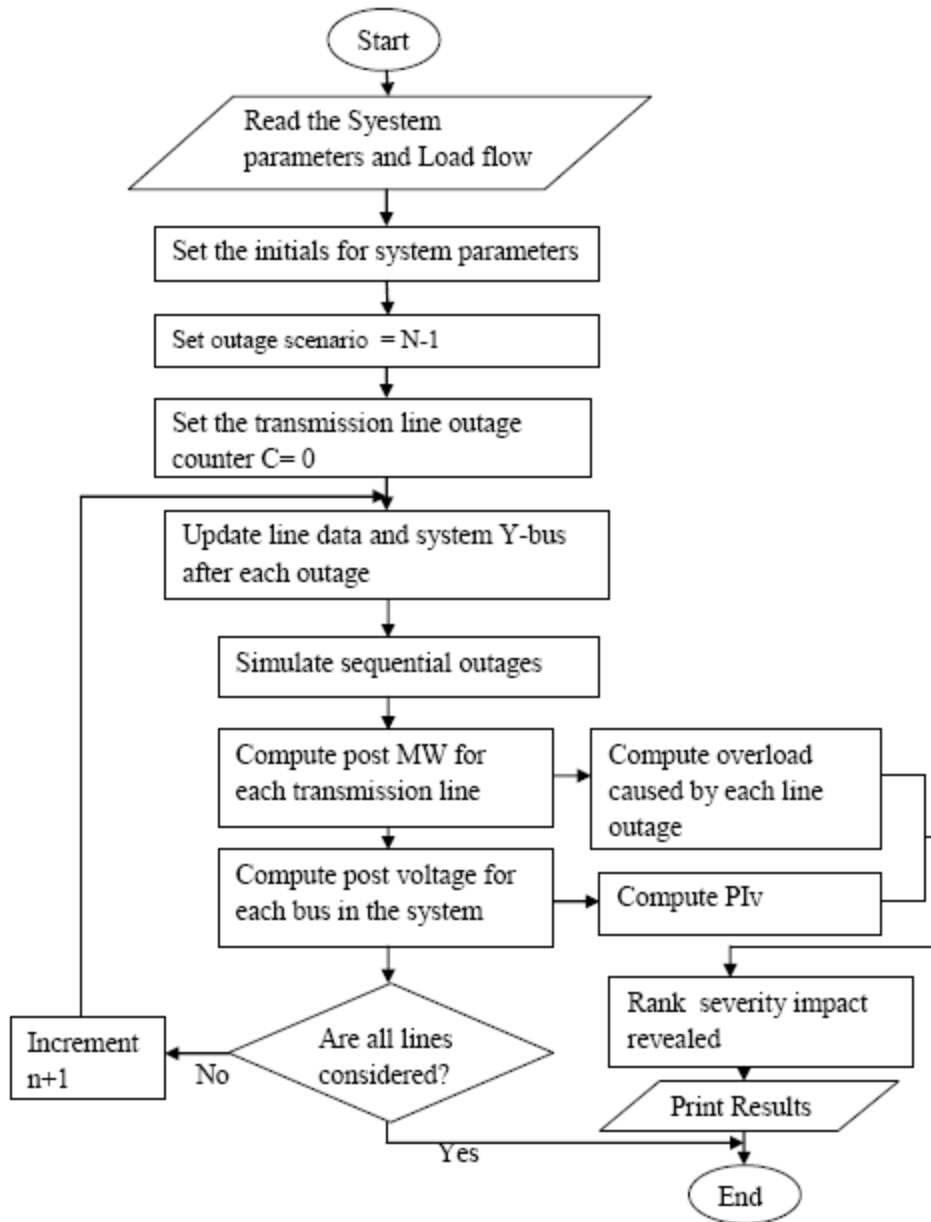


Figure 3.3. Flowchart for contingency analysis of available demand

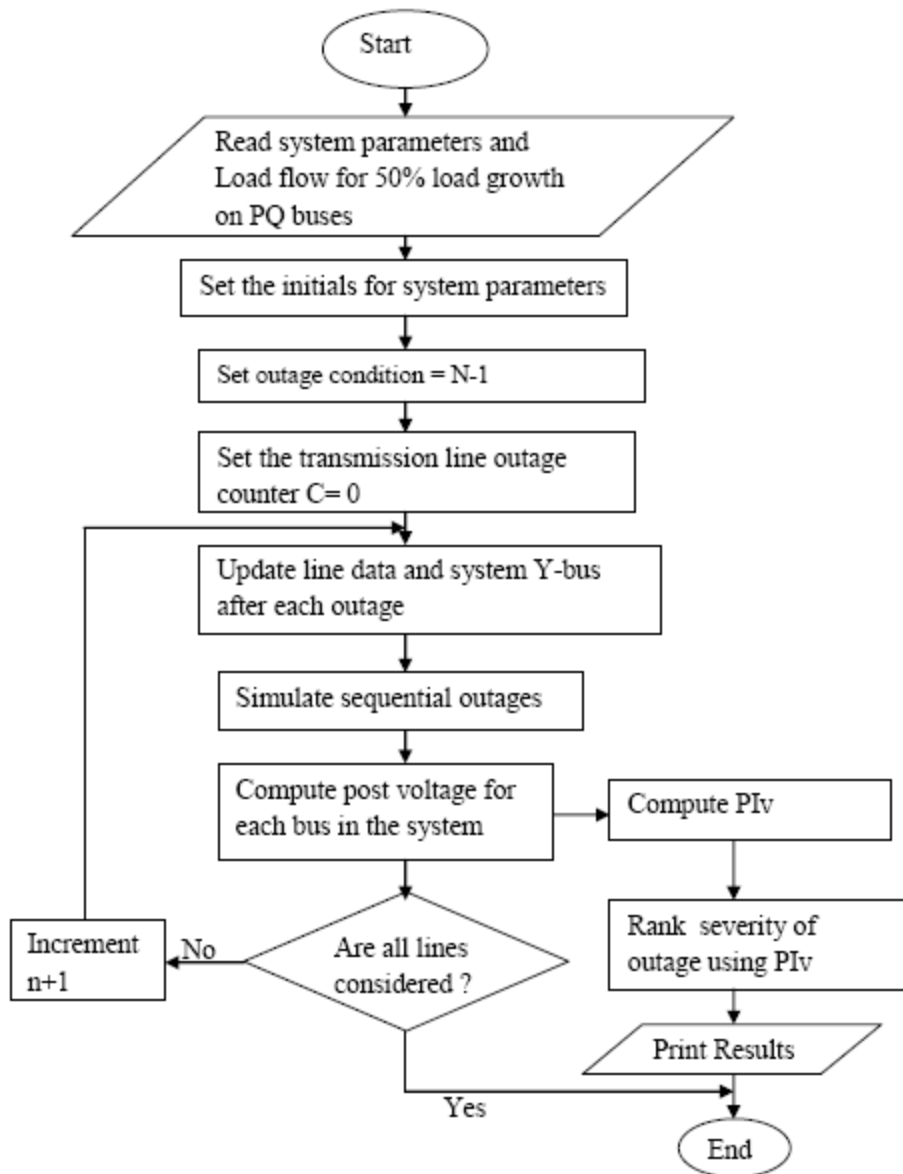


Fig.3.4 Flowchart for contingency analysis for 50% load demand increase

3.7.1 Algorithmic Steps attained in the above Flowcharts

The first flowchart represents the steps encountered to get AC load flow solution by Newton Raphson for the given case study.

- i. Input the system buses and transmission lines parameters.

- ii. Layout initial conditions for the system parameters. For instance, initial conditions for reference bus are set to be $|V| = 1.0$ and phase angle to be equal to zero, initial parameters for load buses recommended to be equal to the reference initials. However, for the generator buses, phase angle is initially set to zero so long as initial voltages are recognized.
- iii. System bus admittance matrix is formulated.
- iv. Calculation for power injected on the system buses. Real and reactive power injected are determined for load buses, where real power is determined for the generator buses. Thus, power mismatches are calculated.
- v. In relation to the power equations with respect to the voltage magnitudes and phase angles, Jacobian matrix is formulated, subsequently to calculate the voltage magnitude and phase angle differences to the actual solutions.
- vi. Thereafter, new iterative values for voltage magnitudes and phase angles are determined.

The important point to consider is, the process of power flow is terminated when power mismatches are less or equal to the specified accuracy.

The second flowchart represents the steps considered to attain power system security by contingency analysis.

- i. Read system parameters with respect to the initial conditions.
- ii. Set initial transmission outage counter and outage condition ($N-1$)
- iii. Update transmission lines data after each contingency and bus admittance matrix is formulated.

- iv. Compute post real power flow on each remaining transmission line
- v. We use equations (3.1) and (3.2) to compute and rank severity impacts (thermaloverloads) caused by a certain transmission line outage.
- vi. Using equation (3.3), we compute reactive performance index to rank severity impact of each transmission line outage to the system voltage profile.
- vii. We stop the process if all transmission lines are considered for contingency analysis

The third flowchart represents the steps considered to attain power system security by contingency analysis when there is 50% load demand increase for available load demand of the case study. Therefore, the solution is obtained by maintaining steps in flowchart of figures (3.2) and (3.3) without considering steps of thermal rating condition.

CHAPTER FOUR

4.0 Results and Interpretation

The flowcharts of figures (3.2), (3.3) and (3.4) are considered to provide results of load flow and contingency analysis for Rwanda High Voltage Power System, referring to the scenarios of available load demand and 50% load increase on PQ buses in the System network. By considering available load demand condition, AC load flow under Newton Raphson model are used to determine magnitude and phase angle of voltage and power flow in each transmission line.

Equations (3.1) and (3.2) are used to reveal the sequential severity influence of each transmission line outage. From equation (3.1), maximum thermal rating of each branch is provided in the line data, while P_i is a real power flowing on branch i after contingency, and is determined by using load flow power equations.

The expression $P_{max} - P_{lineflow}$ in the same equation, is set and considered in MATLAB under no overload condition and vice-versa to present overload numerical values for any line flow exceeding system thermal rating specified ($P_{max}=0.572$ p.u). Using equation (3.2), we rank severity impact for each transmission outage in terms of thermal ratings. Equation (3.3) determines existence of any bus voltage limit violation, relating to the system voltage margins of $\pm 10\%$, i.e. 0.9 and 1.1. Finally, we only consider outage of line five in the network under both available load demand and load growth scenarios, to reveal and analyse its impact by relating pre- and post-voltage profile of each system bus. Thus, computed results are shown below.

Table 4.1: Load Flow Outputs for Available Load Demand

Bus No	Voltage Magnitude	Angle Degree	Load		Generation		Injection
			MW	Mvar	MW	Mvar	Mvar
1	1.000	0.000	0.000	0.000	1.667	-9.108	0.000
2	1.008	-0.232	0.000	0.000	6.600	6.287	0.000
3	0.999	-1.217	5.338	1.816	0.000	0.000	0.000
4	1.000	-1.192	0.000	0.000	13.500	11.738	0.000
5	0.997	-1.419	8.154	1.997	0.000	0.000	0.000
6	0.988	-2.372	5.397	1.168	0.000	0.000	0.000
7	0.989	-2.435	0.160	0.020	0.000	0.000	0.000
8	0.996	-1.211	28.439	10.159	0.000	0.000	0.000
9	1.007	1.403	13.278	2.628	0.000	0.000	0.000
10	1.047	2.060	0.160	0.000	0.000	0.000	0.000
11	1.050	3.301	0.000	0.000	24.000	-9.624	0.000
12	1.044	3.065	0.923	0.170	0.000	0.000	0.000
13	1.044	3.046	0.731	0.145	0.000	0.000	0.000
14	1.025	6.731	4.161	1.064	0.000	0.000	0.000
15	1.024	7.617	0.000	0.000	24.150	-14.163	0.000
Total			66.741	19.167	69.917	-14.870	0.000

Table 4.2: ElectricPower Flow on the Transmission Lines

Lines		Transmission Lines Power Flow			Line losses	
From	To	MW	Mvar	MVA	MW	Mvar
1	2	1.667	-9.108	9.259	0.020	-1.922
2	1	0.066	0.063	0.091	0.020	-1.922
2	3	8.246	-0.899	8.295	0.069	-1.814
3	2	-8.177	-0.915	8.228	0.069	-1.814
3	4	-13.496	-11.807	17.932	0.004	-0.068
3	5	13.788	1.270	13.846	0.028	-0.402
3	8	2.547	9.636	9.967	0.010	-0.586
4	3	13.500	11.738	17.890	0.004	-0.068
5	3	-13.760	-1.672	13.862	0.028	-0.402
5	6	5.606	-0.325	5.616	0.049	-0.707
6	5	-5.557	-0.383	5.570	0.049	-0.707
6	7	0.160	-0.785	0.802	0.000	-0.805
7	6	-0.160	-0.020	0.161	0.000	-0.805
8	3	-2.538	-10.221	10.532	0.010	-0.586
8	9	-25.901	-0.062	25.901	0.339	-2.190
9	8	26.240	-2.253	26.337	0.339	-2.190
9	10	-39.518	-0.375	39.520	1.671	-16.721
10	9	41.189	-16.346	44.313	1.671	-16.721
10	11	-23.739	8.580	25.242	0.261	-1.044
10	12	-17.609	7.766	19.246	0.097	-1.683
11	10	24.000	-9.624	25.858	0.261	-1.044
12	10	17.706	-9.448	20.069	0.097	-1.683
12	13	0.731	-0.779	1.068	0.000	-0.924
12	14	-19.360	10.057	21.816	0.428	-4.638
13	12	-0.731	-0.145	0.745	0.000	-0.924
14	12	19.788	-14.695	24.648	0.428	-4.638
14	15	-23.949	13.631	27.557	0.201	-0.532
15	14	24.150	-14.163	27.997	0.201	-0.532
Total losses					3.176	-34.037

Table 4.3: Overload Results in Terms of Thermal Ratings for Available Demand under N-1 Outage

Line Outage		Overloaded lines		Thermal Limit Rating (Overload pu)	Outage Severity	Severity Ranking
From Bus	To Bus	From Bus	To Bus			
1	2	9	10	1.75701	1.75701	14
2	3	1	2	6.710864	4.228935	4
		9	10	1.747006		
3	4	1	2	6.738844	2.739043	12
		2	3	0.023527		
		9	10	1.454758		
3	5	1	2	7.023440	25.759664	1
		5	6	93.308699		
		6	7	0.940891		
		9	10	1.765627		
5	6	1	2	6.638257	3.142395	8
		6	7	1.023302		
		9	10	1.765627		
6	7	1	2	6.751966	4.254419	3
		9	10	1.756872		
3	8	1	2	6.771814	4.265907	2
		9	10	1.760001		
8	9	1	2	6.979815	3.389185	7
		9	10	2.893290		
		10	11	0.294452		
9	10	1	2	6.800396	2.502387	13
		8	9	0.316805		
		10	11	0.389961		
10	11	1	2	6.080157	3.695534	6
		9	10	1.310912		
10	12	1	2	6.717834	2.902575	9
		9	10	1.857371		
		12	14	0.132520		
12	13	1	2	6.751317	2.878937	11
		9	10	1.752974		
		12	14	0.132520		
12	14	1	2	6.589815	4.161193	5
		9	10	1.732572		
14	15	1	2	6.659762	2.890558	10
		9	10	1.836312		
		12	14	0.175600		

4.1 The graph Representing Outage Severity on Transmission Lines Thermal Rating

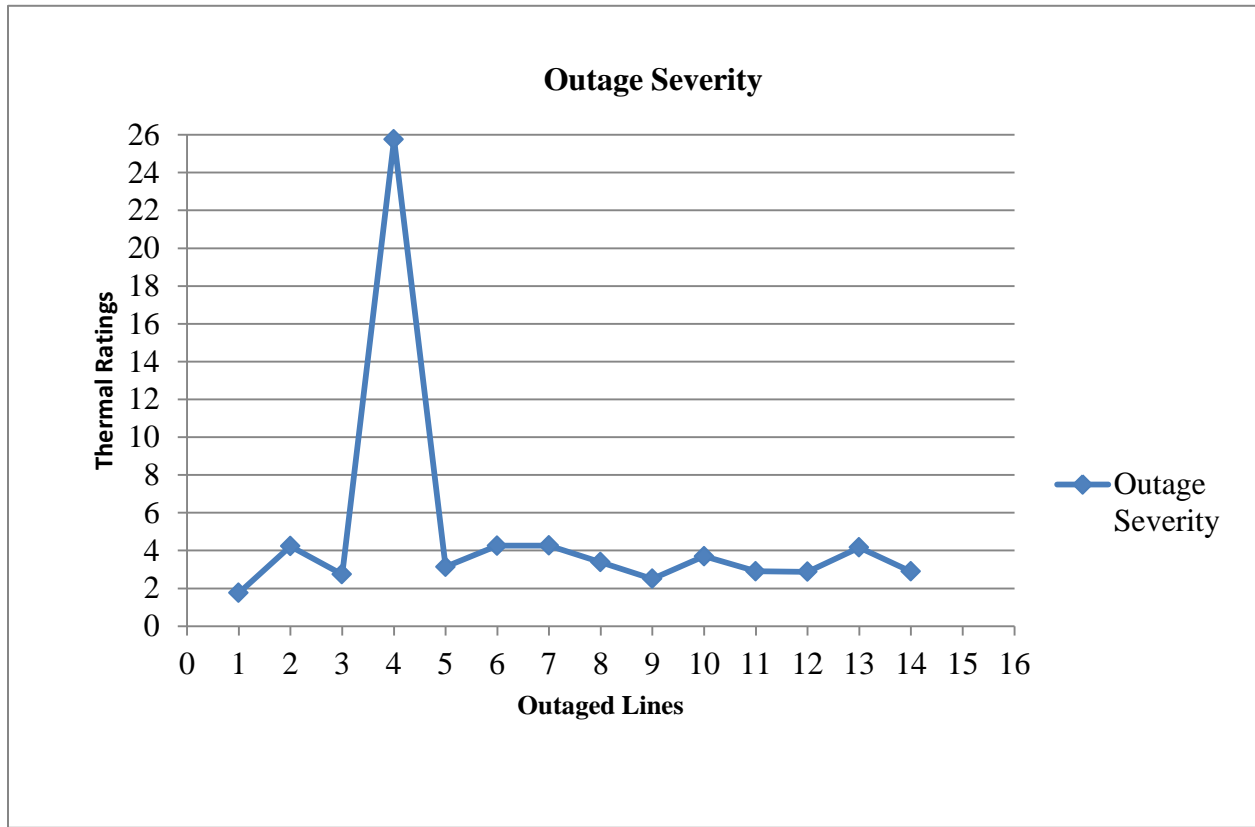


Figure 4.1, Graph representing thermal rating overload in transmission lines

This graph is clearly identifying that each transmission line outage violates the transporting limits of the remaining system corridors. Further more, it indicates that transmission line outage of the line extended from Jabana to Birembo is the most severe due to, it has the largest connected load. This has the potential of highest thermal rating stability of the system as indicated in the results of table (4.3). Therefore, it requires a greatest attention during operation for maintaining provision of continuous power delivery services.

Table 4.4: PIV Outputs for Available Load Demand

Lines Outages		PI _v Value	Severity Ranking
From	To		
1	2	0.00000	00
2	3	0.00000	00
3	4	0.02018	9
3	5	0.00000	00
5	6	0.02505	8
6	7	0.04458	5
3	8	0.04014	7
8	9	0.04443	6
9	10	0.18759	2
10	11	0.01067	10
10	12	0.00000	00
12	13	0.08578	3
12	14	0.08504	4
14	15	1.02931	1

4.2 Graph for PIV Outputs for Available Load Demand

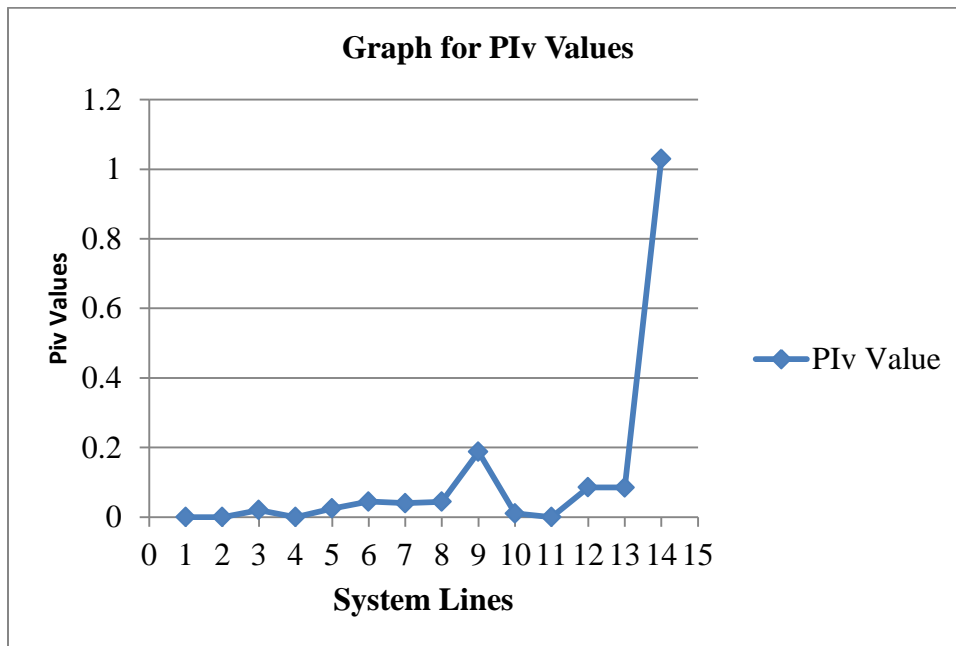


Figure 4.2, Graph representing PIV outputs for available load demand

Table 4.5: Load Flow Outputs for 50% Load Increase for Available Load Demand

Bus No	Voltage	Angle	Load		Generation		Injection
	Magnitude	Degree	MW	Mvar	MW	Mvar	Mvar
1	1.000	0.000	0.000	0.000	37.053	-18.414	0.000
2	1.008	-2.440	0.000	0.000	6.600	7.678	0.000
3	0.989	-8.247	8.007	2.724	0.000	0.000	0.000
4	0.990	-8.235	0.000	0.000	13.500	29.321	0.000
5	0.985	-8.550	12.231	2.996	0.000	0.000	0.000
6	0.969	-9.965	8.096	1.752	0.000	0.000	0.000
7	0.970	-10.043	0.240	0.030	0.000	0.000	0.000
8	0.983	-8.677	42.658	15.239	0.000	0.000	0.000
9	0.996	-7.038	19.917	3.942	0.000	0.000	0.000
10	1.034	-6.668	0.240	0.000	0.000	0.000	0.000
11	1.040	-5.490	0.000	0.000	24.000	-5.724	0.000
12	1.031	-5.799	1.385	0.256	0.000	0.000	0.000
13	1.031	-5.826	1.097	0.217	0.000	0.000	0.000
14	1.014	-2.439	6.241	1.569	0.000	0.000	0.000
15	1.014	-1.563	0.000	0.000	24.150	-12.373	0.000
Total			100.111	28.751	105.303	0.488	0.000

Table 4.6: ElectricPower Flow in the Transmission Lines under 50% Load Increase on PQ Buses

Transmission Lines		Transmission Lines Power Flow			Line losses	
From	To	MW	Mvar	MVA	MW	Mvar
1	2	37.053	-18.414	41.376	0.493	-0.282
2	1	0.066	0.077	0.101	0.493	-0.282
2	3	43.160	-10.454	44.408	1.980	2.121
3	2	-41.180	12.575	43.057	1.980	2.121
3	4	-13.487	-29.356	32.306	0.013	-0.035
3	5	20.747	3.125	20.981	0.065	-0.321
3	8	25.913	10.932	28.124	0.076	-0.342
4	3	13.500	29.321	32.279	0.013	-0.035
5	3	-20.683	-3.447	20.968	0.065	-0.321
5	6	8.452	0.451	8.464	0.116	-0.556
6	5	-8.336	-1.008	8.396	0.116	-0.556
6	7	0.240	-0.744	0.782	0.000	-0.774
7	6	-0.240	-0.030	0.242	0.000	-0.774
8	3	-25.837	-11.274	28.190	0.076	-0.342
8	9	-16.821	-3.964	17.282	0.149	-2.767
9	8	16.970	1.197	17.012	0.149	-2.767
9	10	-36.887	-5.139	37.243	1.442	-16.343
10	9	38.329	-11.204	39.933	1.442	-16.343
10	11	-23.756	4.681	24.213	0.244	-1.042
10	12	-14.813	6.523	16.185	0.071	-1.723
11	10	24.000	-5.724	24.673	0.244	-1.042
12	10	14.884	-8.246	17.015	0.071	-1.723
12	13	1.097	-0.684	1.292	0.000	-0.901
12	14	-17.365	8.674	19.411	0.351	-4.765
13	12	-1.096	-0.218	1.118	0.000	-0.901
14	12	17.716	-13.439	22.237	0.351	-4.765
14	15	-23.957	11.843	26.725	0.193	-0.529
15	14	24.150	-12.373	27.135	0.193	-0.529
Total Losses					5.192	-28.263

Table 4.7: PIV Outputs for 50% Load Demand Increase on PQ Buses

Lines Outages		PIv Value	Severity Ranking
From	To		
1	2	0.00000	00
2	3	0.00000	00
3	4	0.00033	10
3	5	0.00000	00
5	6	0.00296	7
6	7	0.03930	3
3	8	0.03650	4
8	9	0.01256	7
9	10	0.05273	2
10	11	0.01990	5
10	12	0.00000	00
12	13	0.00077	8
12	14	0.00076	9
14	15	0.44190	1

4.3 The Graph of PIV Outputs for 50% Load Demand Increase on PQ Buses

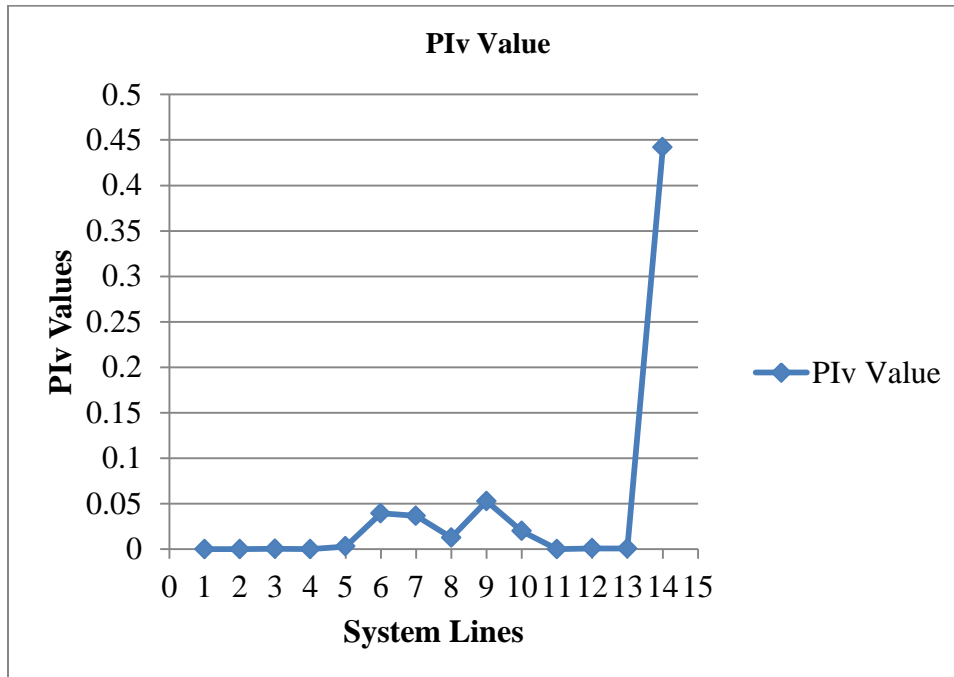


Figure 4.3, Graph representing PIV outputs for 50% load demand increase on PQ buses

Table 4.8: Voltage Magnitudes for Pre and Post Contingency on Buses for line 5 outage in the System

Bus Number	Voltage profile of the system under available demand		Voltage profile under 50% increase of available demand on PQ buses	
	Pre-Contingency Voltage	Post-Contingency Voltage	Pre-Contingency Voltage	Post-Contingency Voltage
1	1.000	1.000	1.000	1.000
2	1.008	1.014	1.008	1.022
3	0.999	0.986	0.989	0.998
4	1.000	0.986	0.990	1.000
5	0.997	0.984	0.985	0.995
6	0.988	0.979	0.969	0.980
7	0.989	0.980	0.970	0.981
8	0.996	0.979	0.983	0.989
9	1.007	0.957	0.996	0.977
10	1.047	0.990	1.034	1.014
11	1.050	0.981	1.040	1.015
12	1.044	0.971	1.031	0.977
13	1.044	0.971	1.031	0.977
14	1.025	0.899	1.014	0.934
15	1.024	0.898	1.014	0.793

4.4 System Voltage Profile for Pre and Post Line five outage under Available Demand

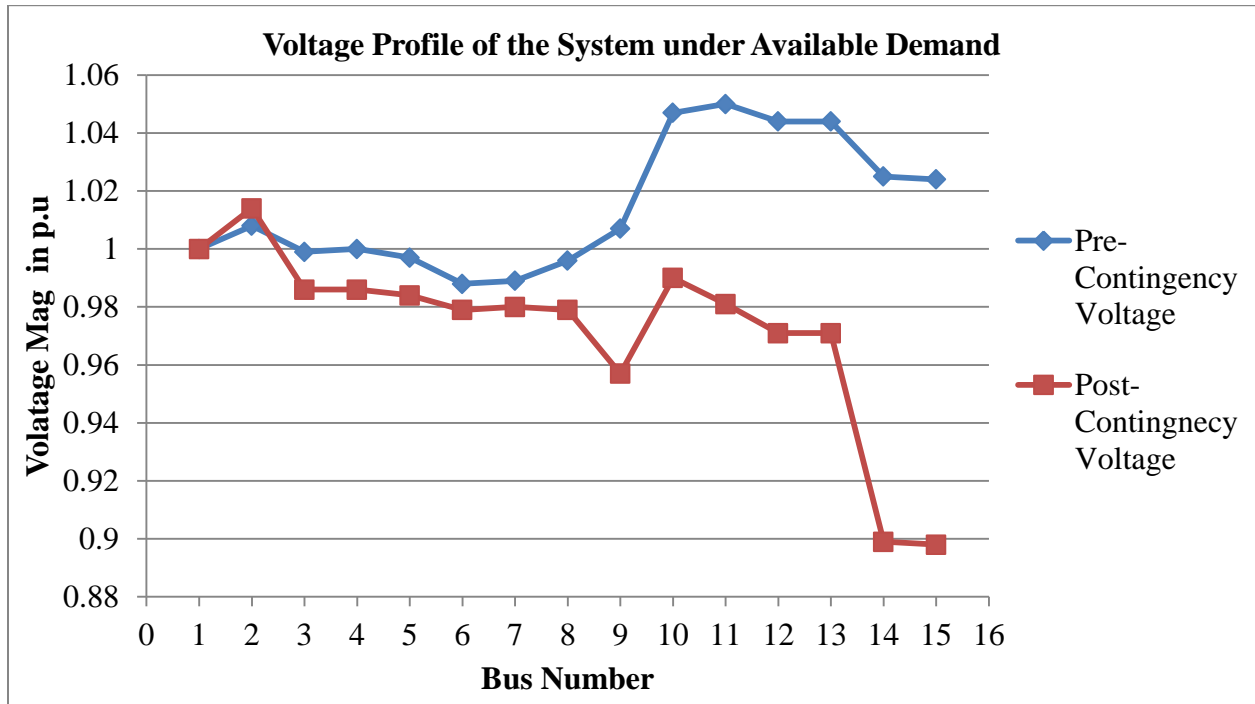


Figure 4.4, Graph that shows system voltage profile for pre and post line five outage under available demand indicated in Table 4.8

The graph shown above is the pre and post voltage magnitudes on each system bus when line five is outaged from the network with respect to the available demand.

4.5 System Voltage Profile for pre and post Line Five Outage under 50% Load Increase of Available Demand

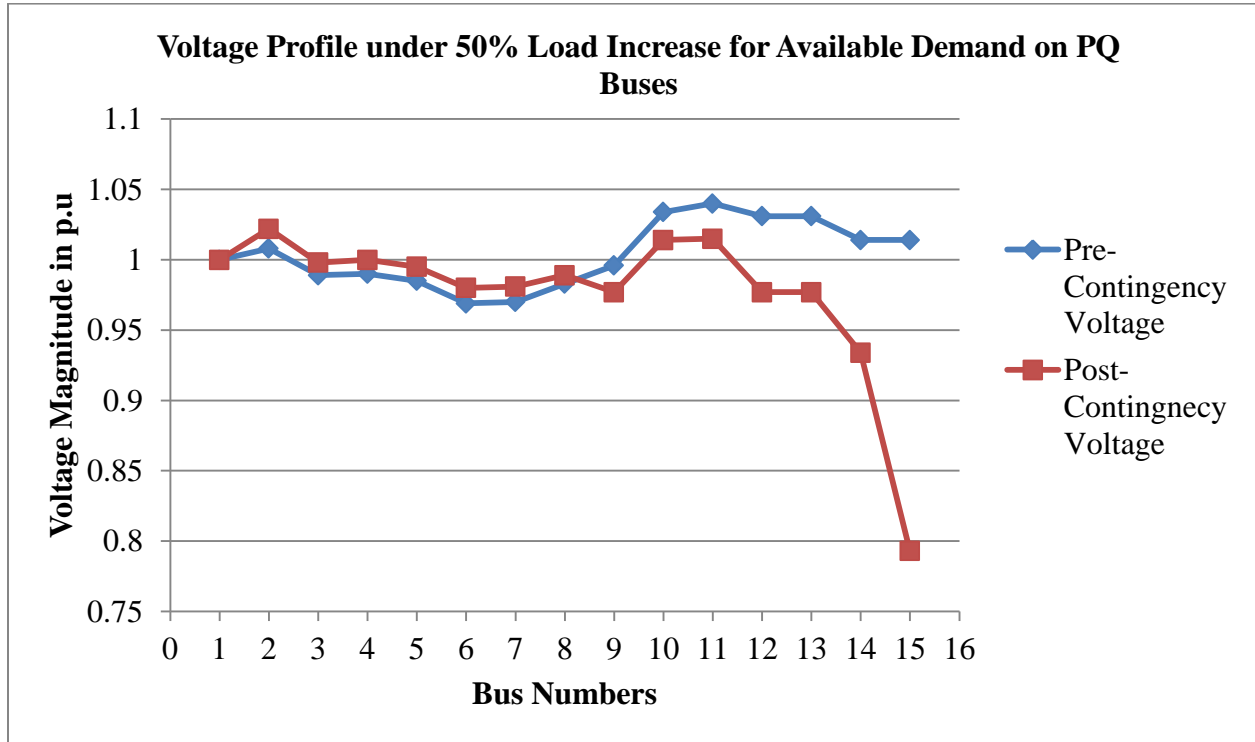


Figure 4.5, Graph representing system voltage profile for pre and post line five outage under 50% load increase of available load demand

The graph indicated above is clarifying the voltage profile for fifty per cent increase of available demand under pre and post line five contingency.

4.1 Discussion of Results Analysis

4.1.1 Introduction

This subsection explains and presents findings from the case study tabulation outputs. In line with results displayed, this subsection presents results analysis and discussion basing on the tabulation made up on the case study with respect to the both available demand and load increase scenarios. Major concern to look at is the power system security under normal operational status and contingency implication on each transmission line thermal rating and voltage variation on system buses.

4.1.2 Results Analysis for Available Load Demand

Table (4.1) available demand scenario, indicates the system numerical values for bus magnitudes and phase angles, real and reactive power of both injected and load demand. It reveals that bus voltage magnitudes are within accepted voltage margins of $\pm 10\%$, but there exists voltage increase on the buses like Nyabarongo (1.05 p.u), Kilinda (1.047 p.u), Karongi (1.044) and Kibuye (1.044) due to either less or no load reactive power demand on the mentioned buses. However, there is voltage drop on buses Musha (0.988 p.u), Rwinkwavu (0.989 p.u), Gikondo (0.996 p.u) and Birembo (0.997 p.u) as a result of the high reactive power demand required by the end users connected to the mentioned buses.

Table 4.2 (available demand) determines the power flow on the transmission lines and power losses experienced in each line. In normal circumstances, any power system network incurs tolerable technical losses that can be caused by the energy dissipated in the network and other internal or external factors. In our case study, Table (4.2) indicates that the transmission line from Kigoma to Kilinda has critical power losses which expected to be caused by the long

distance covered by the aforesaid transmission line. Subsequently, it requires the specific power loss investigation in order to reveal the reason behind this situation.

Therefore, simulation outputs indicated that under normal operating conditions, thermal ratings of transmission lines are within accepted margins and no voltage limit violations were encountered on buses.

4.2 Assessing System Security by N-1 Contingency

In line with *N-1* contingency condition, we have assessed its implications on system security in terms of system transmission thermal rating and buses voltage variations. The simulation results in Table (4.3) show that the system does not have enough redundancy to withstand any transmission line outage. It is observed that each transmission line outage harms the steady state operations of the system network. However, outage of line from Jabana to Birembo is the most critical outage which overloads other four transmission lines from Ntaruka to Mukungwa, Birembo to Musha, Musha to Rwinkwavu and Kigoma to Kilinda. Second line which needs much more attention is extended from Jabana to Gikondo. Its outage overloads transmission lines of Ntaruka to Mukungwa and Kigoma to Kilinda with high thermal rating implication. General notepoint on this investigation is that transmission lines of Ntaruka to Mukungwa and Kigoma to Kilinda are very vulnerable to the extent that they are almost being affected by any other outage of the transmission line from the network.

Using Reactive Power Performance index, Table (4.4) provides the post contingency outputs for voltage profile corresponding to each line outage from the system. Generally, reactive power performance index determines the severity impact of transmission line outage to violate bus voltages in the power network. Therefore, the highest value of PIV inferred critical outage to

violate system bus voltages and its lowest to be marked as tolerable instability in the network. Results in Table (4.4) imply that each transmission line of two thirds of the total transmission line violates the voltage profile. However, it is remarked that outage of system line extended from Mururu II to Rusizi II is the most critical line to be given a high attention regarding to the system voltage margins. Meanwhile, outage of each transmission line for the lines extended from Ntaruka to Mukungwa, Mukungwa to Jabana, Jabana to Birembo and Kilinda to karongi does not harm the system operational stability in regard to the voltage margin violation.

4.3 Results Analysis for 50% Load Increase of Available Load Demand

This subsection presents results analysis and discussion based on the tabulation made up on the case study with respect load increase in the power network. Major concern to look at is the power system security status when there is load increase. Here I intended to reveal implication of load increase on the case study network under normal operational status and contingency.

It is in this line, Table (4.5) provides load flow outputs under 50% load increase on PQ Buses. It is observed that under normal system operating conditions, 50% load growth does not affect system security status. Subsequently, there exists a slight voltage drop on some buses which do not violate the system voltage margins. According to the analysis made, the reason behind the voltage drop on system buses was due to the reactive power demand increase which allows phase shift that consequently resulted into voltage alleviation on the particular part of the power system. An other observation made is about the generation expansion required to cater amount of energy demand exceeding to the total available generation demand in the network of the case study. It is also observed that there is increase of reactive power generated to be injected in the network. This may cause excess of real power losses in the transmission lines.

Table (4.6) reveals the power flow on the transmission lines and power losses experienced in each line under load increase in the system. From the outputs displayed, it is generally revealed that under normal operating conditions, the system incurs tolerable technical losses, but transmission lines from Kigoma to Kilinda and Mukungwa to Jabana experience excess power losses. Therefore, they need further investigation to reveal the reason behind such implication.

4.3.1 System Security by *N-1* Contingency for Load Increase

Reference made to the outputs of the available load demand indicated that each transmission line outage makes thermal rating of the system transmission lines to exceed their prescribed thermal rating limits. It is in this context, we preferably investigated implication of transmission line outage on the bus voltage profile excluding thermal rating condition.

Using Reactive Power Performance index, Table (4.7) provides the post contingency outputs corresponding to the voltage profile on system buses under load increase in the network. Generally, it implies that transmission line outage of each one of the transmission lines extended from Jabana to Jabana Heahy Fuel, Birembo to Musha, Musha to Rwinkwavu, Jabana to Gikondo, Gikondo to Kigoma, Kigoma to Kilinda, Kilinda to Nyabarongo, Karongi to Kibuye, Karongi to Mururu II and Mururu II to Rusizi II violates system voltage accepted limits. Therefore, the high attention is mandatory in operation of the case study power system.

In Table (4.8), show the voltage outputs for voltage magnitude of each system bus during pre and post contingency of line from Birembo to Musha. It was a matter of random selection to display voltage profile for line five outage. This was considerably made to indicate and compare system behaviour corresponding to the voltage profile under pre and post scenarios. The observation made indicates that under steady state operation, the voltage magnitudes are normally within

accepted voltage margins for both available load demand and load increase. However, the outage of the line from Birembo to Musha, there exists severe voltage limits violations on the buses Mururu II and Rusizi II incorporating voltage drops on some other buses.

CHAPTER FIVE

5.0 Conclusion, Recommendations and Further Investigations

This chapter presents the notepoints for conclusion and recommendations for policy and technical aspects to maintain steady state operation of the case study network.

5.1 Conclusion

The work done revealed critical line outages that violate the prescribed and accepted system limits in terms of thermal ratings in transmission lines and voltage boundaries on the system buses. Therefore, referring to the above simulated results, we conclude that there is a need to expand transmission network in order to put in place enough redundancy to maintain system security against instability caused by the overload and overheating contingency. The results can also assist the system planner to better understand what to do in case of financial and environmental constraints so as to choose which transmission lines to be put in the first phase of transmission lines expansion, and make reactive power compensation on weak buses for maintaining voltage stability. The results reveal weak transmission lines in the system so that during the implementation of planned power generation projects, the system planner may recognize need of the present power network to uphold and transport the new incoming power generated in the longer radial lines including an other generating system in the radial network.

It is therefore a paramount factor that can greatly help to execute the implementation of planned electricity generation projects and maintain genuineness of the present operational power network in relation to meet the future power demand growth.

5.2 Recommendations

This thesis determines case study voltage magnitude and phase angle for system buses besides real and reactive power flow on the transmission lines during steady state operation of the network. It also reveals the influence of sequential transmission line outage on the thermal rating of remaining transmission lines and system buses voltage profile referring to the available load demand and 50% load demand increase in the network.

In line with the study made, the thesis has come up with the following recommendations:

1. It has been revealed that the Rwanda Power System does not have enough capacity to withstand a transmission outage. This calls for urgent expansion of the transmission lines due to increased capacity.
2. Compensations of Power System operations by allocating power system reactive power compensators on the known weak buses in order to maintain voltage magnitudes within the prescribed levels and also minimize power losses in the network.

5.3 Suggestions for Further Work

The work done in my research uses Newton Raphson method to assess power system security under transmission contingency analysis for Rwanda high voltage power system in relation to the available load demand and 50% load demand increase of available demand. In line with the study made, I suggest that further work can give better results if it incorporates new technologies such as Artificial Neural Networks, Fuzzy logic control, Chaos Theory which have the capability to include human intuition and other environmental consideration such as work condition of the operators.

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Research Paper Published out of my MSc Thesis Report

1. Mudasingwa Alex and M.K Mangoli. Power flow and contingency analysis: “Case of Rwanda high voltage power system”. www.icastorindia.org, ICASTAR Journal of Engineering. Vol.8, Issue No.1, January, 2015

APPENDIX I: DATA COLLECTION FORM

**UNIVERSITY OF NAIROBI
SCHOOL OF ENGINEERING
DATA COLLECTION FORM**

RE: MSc Thesis Data Collection

My name is MUDASINGWA Alex, I am persuing Master of Science in Electrical Engineering in the Department of Electrical and Information Engineering. I am conducting academic research for my Masters and it is a part of my studies to fulfill academic requirements for graduation.

It is in this concern, I kindly request you to allow me to collect data from EWSA which will provide a great support of partial fulfilment of my MSc thesis entitled as “ **Power Flow and Contingency Analysis: Case of Rwanda High Voltage Power System**”.

This MSc research is a paramount importance to analyse and investigate power system security of Rwanda power systems by assessing impact of each transmission outage in the network. It is a great measure to facilitate the system planner to initiate the way forward of the power system expansion plan.

I indeed remain with positive attitude for your response.

Regards.

Data Collection Form

Single Line Diagram of the power Network.

Current installed capacity of the system in MW :

Available capacity in MW

Expected power capacity by 2017 in MW:

Expected peak demand by 2017 in MW:

Recorded peak demand in MW:

I. Generator Buses Data

Bus Names	Voltage p.u	Angle degree	P _G MW	Q _G Mvar	P _L MW	Q _L Mvar	Q _G max Mvar	Q _G Min Mvar
Ntaruka								
Mukungwa								
Jabana HF								
Nyabarong								
Rusizi II								
Gikond ag								

II. Load Buses Data

Bus Names	Voltage p.u	Angle degree	P _G MW	Q _G Mvar	P _L MW	Q _L Mvar	Q _G max Mvar	Q _G Min Mvar
Jabana								
Kilinda								
Kibuye								
Birembo								
Gikondo								
Kigoma								
Karongi								
Musha								
Rwinkwavu								
MururuII								

III. Transmission Lines Data

T-line No	Frm bus	To Bus	R p.u	X p.u	B p.u	P_{Max}p.u
1	Ntaruka	Mukungwa	0.029378	0.101986	0.009882	0.572
2	Mukungwa	Jabana	0.173012	0.21097	0.099708	0.572
3	Jabana	Jabana HF	0.00122	0.004235	0.00041	0.572
4	Jabana	GikondoII	0.00925	0.032113	0.003112	0.572
5	Jabana	Birembo	0	0.0001	0	0.572
6	Birembo	Musha	0.049911	0.17327	0.01679	0.572
7	Musha	Rwinkwavu	0.104456	0.010122	0.079993	0.572
8	Jabana	Gikondo	0.043909	0.083066	0.006991	0.572
9	Kigoma	Kilinda	0.027446	0.095281	0.009233	0.572
10	Kilinda	Nyabarongo	0.012605	0.043759	0.00424	0.572
11	Kilinda	Karongi	0.085083	0.295371	0.028621	0.572
12	Karongi	Kibuye	0.000764	0.001445	0.000122	0.572
13	Karongi	Mururu II	0.0273	0.051645	0.004347	0.572
14	Mururu II	Rusizi II	0.014318	0.027087	0.00228	0.572

APPENDIX II: Power Network Data Collected

I. Buses Data

Bus no	Volt magni	Angle degr	Load MW	Load MVA R	Gen MW	Gen MVA R	Gen Qma X	Gen Qmin	Injec MVA R
1	1.0248	-33.36	0.0	0.0	8.6	0.5	7.9	-4.7	0.0
2	1.0278	-34.01	0.0	0.0	6.6	0.5	7.9	-4.7	0.0
3	1.00	-35.72	5.338	1.816	0.0	0.0	0.0	0.0	0.0
4	1.00	-35.69	0.0	0.0	13.5	8.9	15.3	-9.9	0.0
5	1.00	-35.96	8.154	1.997	0.0	0.0	0.0	0.0	0.0
6	1.00	-39.11	5.397	1.168	0.0	0.0	0.0	0.0	0.0
7	1.00	-39.52	0.16	0.02	0.0	0.0	0.0	0.0	0.0
8	1.00	-35.79	28.4386	10.159	0.0	0.0	0.0	0.0	0.0
9	1.00	-38.87	13.278	2.628	0.0	0.0	0.0	0.0	0.0
10	1.0081	-38.9	0.16	0.0	0.0	0.0	0.0	0.0	0.0
11	1.02	-34.25	0.0	0.0	24	1.8	17.4	-9.2	0.0
12	1.0087	-38.19	0.923	0.1704	0.0	0.0	0.0	0.0	0.0
13	1.0088	-38.19	0.731	0.145	0.0	0.0	0.0	0.0	0.0
14	1.0046	-35.73	4.161	1.064	0.0	0.0	0.0	0.0	0.0
15	1.014	-34.67	0.0	0.0	24.15	1.5	18	-13.08	0.0

II. Transmission Lines Data

T-line No	Frm bus	To Bus	R p.u	X p.u	B p.u	Tap set
1	Ntaruka	Mukungwa	0.029378	0.101986	0.009882	1
2	Mukungwa	Jabana	0.173012	0.21097	0.099708	1
3	Jabana	Jabana HF	0.00122	0.004235	0.00041	1
4	Jabana	Birembo	0.014318	0.027087	0.00228	1
5	Birembo	Musha	0.155572	0.294306	0.004062	1
6	Musha	Rwinkwavu	0.157928	0.298765	0.004123	1
7	Jabana	Gikondo	0.00925	0.032113	0.003112	1
8	Gikondo	Kigoma	0.049911	0.17327	0.01679	1
9	Kigoma	Kilinda	0.104456	0.010122	0.079993	1
10	Kilinda	Nyabarongo	0.043909	0.083066	0.006991	1
11	Kilinda	Karongi	0.027446	0.095281	0.009233	1
12	Karongi	Kibuye	0.012605	0.043759	0.00424	1
13	Karongi	MururuII	0.085083	0.295371	0.028621	1
14	MururuII	RusiziII	0.0273	0.051645	0.004347	1

APPENDIX IV: Main Program for Load Flow and Contingency Analysis of AvailableLoadDemand

```

clear all
clc
basemva=100;
tolerance =0.000001;
maxiter=1000;
busd=busdata;
Linedata=linedata;
j=sqrt(-1);
i = sqrt(-1);
nl = Linedata(:,2);
nr = Linedata(:,3);
R = Linedata(:,4);
X = Linedata(:,5);
Bc = j*Linedata(:,6);
a = Linedata(:, 8);
Pmax=Linedata(:,7);
nbr=length(Linedata(:,1));
nbus = max(max(nl), max(nr));
Z = R + j*X;
y= ones(nbr,1)./Z;
i = 1;
[S,Sa,Sol,Ol,ST,converge,Ybus,npq,tech,maxtolerance,iter,Vm,deltad,Pd,Qd,Pg,Qg,Qsh,P,Q]=pf
ac5(Linedata,busd);
busdata(:,3)=Vm';
busdata(:,4)=deltad';
Pgt = sum(Pg);
Qgt = sum(Qg);
Pdt = sum(Pd);
Qdt = sum(Qd);
Qsht = sum(Qsh);
%%%%%%%%%%%%%%
%%%%%%%%%%%%%%
%%N-1 considerations in line outages
Col =0;
pI=0;
converge=1;
Sol=0;
i=1;
while i <= maxiter && converge == 1
[Col,PI,Ol,ULD,UBD,Old,pI,Volt]=contgen1(Linedata,nbr,Sa,S,Ybus,Sol,npq);
if converge ~= 1
converge = 1;
end
i=i+1;

```

```

end
% PROGRAM FOR THE RESULTS DISPLAY
%clc
disp(tech)
fprintf('\n\n\n***** NORMAL ');
fprintf('CONDITION *****');
fprintf('\nmaxtolerance = %g \n', maxtolerance)
fprintf('Number of iterations = %g \n\n', iter)
fprintf(' Bus Voltage Angle -----Load----- ---Generation--- Injected\n')
fprintf(' No. Mag. Degree MW Mvar MW Mvar Mvar \n')

for n=1:nbus
    fprintf(' %5g', n),
    fprintf(' %7.3f', Vm(n)),
    fprintf(' %8.3f', deltad(n)),
    fprintf(' %9.3f', Pd(n)),
    fprintf(' %9.3f', Qd(n)),
    fprintf(' %9.3f', Pg(n)),
    fprintf(' %9.3f', Qg(n)),
    fprintf(' %8.3f\n', Qsh(n))
end
fprintf(' \n'),
fprintf(' Total ')
fprintf(' %9.3f', Pdt),
fprintf(' %9.3f', Qdt),
fprintf(' %9.3f', Pgt),
fprintf(' %9.3f', Qgt),
fprintf(' %9.3f\n\n', Qsht)

fprintf('\n')
fprintf(' *****POWER FLOW ANALYSIS FOR BUS AND LINE***** \n\n')
fprintf(' LINE POWER AT BUS&LINE FLOW LINE LOSSES\n\n')
fprintf(' TRANSFORMER\n')
fprintf(' from to MW Mvar MVA MW Mvar tap\n')

for n = 1:nbus
busprt = 0;
for L = 1:nbr;
if busprt == 0
fprintf(' \n'),
fprintf('%6g', n),
fprintf(' %9.3f', P(n)*basemva)
fprintf(' %9.3f', Q(n)*basemva),
fprintf(' %9.3f\n', abs(S(n)*basemva))

busprt = 1;

```

```

else
end
if nl(L)==n
    k = nr(L);

elseif nr(L)==n
k = nl(L);

else
end
if nl(L)==n || nr(L)==n
fprintf('%12g', k),
fprintf('%9.3f', real(S(n,k))),
fprintf('%9.3f', imag(S(n,k)))
fprintf(' %9.3f', abs(S(n,k))),
fprintf(' %9.3f', real(Sa(L))),
if nl(L) ==n || a(L) ~= 1
fprintf(' %9.3f', imag(Sa(L))),
fprintf(' %9.3f\n', a(L))
else
fprintf(' %9.3f\n', imag(Sa(L)))
end
else
end
end
end
end
fprintf(' \n'), fprintf('          TOTAL LOSSES          ')
fprintf(' %9.3f', real(ST)),
fprintf(' %9.3f\n', imag(ST))
clear IkInSLSLTsknSnk
%% overload display in normal condition
if Sol == 0
fprintf('\n*****\n');
fprintf('\n*** No overload in normal condition***\n');
else
nl = size (Linedata,1);
fprintf('\n*** Overload at normal***:');
fprintf('\n Total overload of normal condition is');
fprintf(' %3.5f pu\n',Sol);
fprintf('*****');
fprintf('*****');
fprintf('\n***** Power flow and overload');
fprintf(' values of branches *****\n');
fprintf('*****');
fprintf('*****\n');
fprintf('-----\n');

```



```

fprintf('      Fbus   Tbus      Smax      flow   Overload \n');
fprintf('      ----   ----      ----      ----   -----');
for i = 1 : nl
fprintf('\n %1.0f %14.0f %15.0f %20.5f %20.5f\n'...
, Ol(i,:));
end
end
%%

%% N-1 condition
% overload calculation in N-1 condition
fprintf('\n
          \n');
fprintf('\n
          ***** N-1 condition*****\n');
fprintf('*****');
fprintf('*****');
if(Col == 0)
fprintf('\n No overload in N-1 condition\n');
fprintf('\n*****\n');
else
fprintf('\n*****');
fprintf('*****');
fprintf('*****\n');
LCOL=Old{size (Col,1),1};
fprintf(' Overload values of ');
fprintf('branches in N-1 condition\n');
fprintf(' following lines are overloaded in');
fprintf(' this outage\n');
fprintf(' \n');
fprintf('\n  OUTAGES          overloaded busses are\n');
fprintf('  From bus  To bus      From Bus   To Bus   Overload (pu)\n');
fprintf('  *****  *****      *****      *****      *****');
for i = 1 : size (Old,1)
iOLD = Old{i,1}; iL = iOLD(1,:);
fprintf('\n   %3.0f      %3.0f\n',iL(1:2))

for j = 2 : size (iOLD,1);
fprintf('          %5.0f %10.0f      %0f\n',iOLD(j,1),iOLD(j,2),iOLD(j,4));
end
end
end
% calculation of performance index under N-1 condition
fprintf('\n\n\n')
fprintf('  *****performance index for each bus for N-1 condition***** \n\n' );
fprintf('\n
          ***** N-1 condition*****\n');
fprintf('*****');
fprintf('*****');

```

```

nl = size(Linedata,1);
fprintf('\n*****');
fprintf('');
fprintf('\n');
fprintf(' Performance index for outage of line\n: ');
fprintf(' From Bus   To Bus     PIv         PImva\n');
fprintf(' *****   *****   *****   *****');
for i = 1:nl
fprintf('\n %5.0f   %10.0f %18.5f %18.5f \n',...
PI(i,:));
end
fprintf('\n\n voltage on busses after contingency\n');
fprintf('\n bus no         Volts \n');

for n=1: nbus
fprintf('%6g', n),
fprintf('          %0.3f \n', Volt(n));
end

```

APPENDIX V: Main Program for Load Flow and Contingency Analysis of Load Demand Increase

```
clear all
clc
basemva=100;
tolerance =0.000001;
maxiter=100;
slstep = 0.0005; % Small step
llstep = 0.005;% max step
busd=busdata;
Linedata=linedata;
j=sqrt(-1);
i = sqrt(-1);
nl = Linedata(:,2);
nr = Linedata(:,3);
R = Linedata(:,4);
X = Linedata(:,5);
Bc = j*Linedata(:,6);
a = Linedata(:, 8);
Pmax=Linedata(:,7);
nbr=length(Linedata(:,1));
nbus = max(max(nl), max(nr));
Z = R + j*X;
y= ones(nbr,1)./Z;

i = 1;
converge = 1;
LR=0;
while i <= maxiter && converge == 1
LR = i*llstep;
[S,Sa,Sol,Ol,ST,converge,Ybus,npq,tech,maxtolerance,iter,Vm,deltad,Pd,Qd,Pg,Qg,Qsh,Pl,Ql,P,
Q,Ph,Qh]=pfac4(Linedata,busd,LR);
busdata(:,3)=Vm';
busdata(:,4)=deltad';
Pgt = sum(Pg);
Qgt = sum(Qg);
Pdt = sum(Ph);
Qdt = sum(Qh);
Qsht = sum(Qsh);
if converge ~= 1
converge = 1;
LR = (LR-llstep);
j = 0;
j = i+j;
while converge==1
LR=LR+slstep;
```

```

[S,Sa,Sol,OI,ST,converge,Ybus,npq,tech,maxtolerance,iter,Vm,deltad,Pd,Qd,Pg,Qg,Qsh,PI,QI,P,
Q,Ph,Qh]=pfac4(Linedata,busd,LR);
busdata(:,3)=Vm';
busdata(:,4)=deltad';
Pgt = sum(Pg);
Qgt = sum(Qg);
Pdt = sum(PI);
Qdt = sum(QI);
Qsht = sum(Qsh);
    j=j+1;
end
end
    i=i+1;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%N-1 considerations in line outages
Col =0;
pI=0;
converge=1;
Sol=0;
i = 1;
converge = 1;
LR=0;
while i <= maxiter && converge == 1
LR = i*llstep;
[Col,PI,OI,ULD,UBD,Old,pI,fOld,Volt]=contgen(Linedata,nbr,Sa,S,Ybus,Sol,npq,LR);
if converge ~= 1
converge = 1;
LR = (LR-llstep);
j = 0;
j = i+j;
while converge==1
    LR=LR+slstep;
[Col,PI,OI,ULD,UBD,Old,pI,fOld,Volt]=contgen(Linedata,nbr,Sa,S,Ybus,Sol,npq,LR);
    j=j+1;
end
end
    i=i+1;
end
% PROGRAM FOR THE RESULTS DISPLAY
%clc
disp(tech)
fprintf('\n\n\n***** NORMAL ');
fprintf('CONDITION *****');
fprintf('\nmaxtolerance = %g \n', maxtolerance)

```

```

fprintf('Number of iterations = %g \n\n', iter)
fprintf(' Bus Voltage Angle -----Load----- ---Generation--- Injected\n')
fprintf(' No. Mag. Degree MW Mvar MW Mvar Mvar \n')

for n=1:nbus
    fprintf(' %5g', n),
    fprintf(' %7.3f', Vm(n)),
    fprintf(' %8.3f', deltad(n)),
    fprintf(' %9.3f', Ph(n)),
    fprintf(' %9.3f', Qh(n)),
    fprintf(' %9.3f', Pg(n)),
    fprintf(' %9.3f', Qg(n)),
    fprintf(' %8.3f\n', Qsh(n))
end
fprintf(' \n'),
fprintf(' Total ')
fprintf(' %9.3f', Pdt),
fprintf(' %9.3f', Qdt),
fprintf(' %9.3f', Pgt),
fprintf(' %9.3f', Qgt),
fprintf(' %9.3f\n\n', Qsht)

fprintf('\n')
fprintf(' *****POWER FLOW ANALYSIS FOR BUS AND LINE***** \n\n')
fprintf(' LINE POWER AT BUS&LINE FLOW LINE LOSSES\n')
fprintf(' TRANSFORMER\n')
fprintf(' from to MW Mvar MVA MW Mvar tap\n')

for n = 1:nbus
    busprt = 0;
    for L = 1:nbr;
        if busprt == 0
            fprintf(' \n'),
            fprintf('%6g', n),
            fprintf(' %9.3f', P(n)*basemva)
            fprintf(' %9.3f', Q(n)*basemva),
            fprintf(' %9.3f\n', abs(S(n)*basemva))

            busprt = 1;
        else
            end
        if nl(L)==n
            k = nr(L);

        elseif nr(L)==n
            k = nl(L);

```

```

else
end
if nl(L)==n || nr(L)==n
fprintf('%12g', k),
fprintf('%9.3f', real(S(n,k))),
fprintf('%9.3f', imag(S(n,k)))
fprintf(' %9.3f', abs(S(n,k))),
fprintf(' %9.3f', real(Sa(L))),
if nl(L) ==n || a(L) ~= 1
fprintf(' %9.3f', imag(Sa(L))),
fprintf(' %9.3f\n', a(L))
else
fprintf(' %9.3f\n', imag(Sa(L)))
end
else
end
end
end
end
fprintf(' \n'), fprintf(' TOTAL LOSSES ')
fprintf(' %9.3f', real(ST)),
fprintf(' %9.3f\n', imag(ST))
clear IkInSLSLTsknSnk
%% overload display in normal condition
if Sol == 0
fprintf('\n*****\n');
fprintf('\n*** No overload in normal condition***\n');
else
nl = size (Linedata,1);
fprintf('\n*** Overload at normal***:');
fprintf('\n Total overload of normal condition is');
fprintf(' %3.5f pu\n',Sol);
fprintf('*****');
fprintf('*****');
fprintf('\n***** Power flow and overload');
fprintf(' values of branches *****\n');
fprintf('*****');
fprintf('*****\n');
fprintf('-----\n');
fprintf(' Fbus Tbus Smax flow Overload \n');
fprintf(' ---- ---- ---- ---- -----');
for i = 1 : nl
fprintf('\n %1.0f %14.0f %15.0f %20.5f %20.5f\n'...
, Ol(i,:));
end
end

```

```

%%
%% N-1 condition
% overload calculation in N-1 condition
fprintf('\n\n');
fprintf('\n ***** N-1 condition*****\n');
fprintf('*****');
fprintf('*****');
if(Col == 0)
fprintf('\n No overload in N-1 condition\n');
fprintf('\n*****\n');
else
fprintf('\n*****');
fprintf('*****');
fprintf('*****\n');
LCOL=Old{size (Col,1),1};
fprintf(' Overload values of ');
fprintf('branches in N-1 condition\n');
fprintf(' following lines are overloaded in');
fprintf(' this outage\n');
fprintf(' \n');
fprintf('\n OUTAGES          overloaded busses are\n');
fprintf(' From bus To bus From Bus To Bus Overload (pu)\n');
fprintf(' ***** ***** ***** ***** *****');
for i = 1 : size (Old,1)
iOLD = Old{i,1}; iL = iOLD(1,:);
fprintf('\n %3.0f %3.0f\n',iL(1:2))

for j = 2 : size (iOLD,1);
fprintf(' %5.0f %10.0f %0f\n',iOLD(j,1),iOLD(j,2),iOLD(j,4));
end
end
end
% calculation of performance index under N-1 condition
fprintf('\n\n\n')
fprintf(' *****performance index for each bus for N-1 condition***** \n\n ');
fprintf('\n ***** N-1 condition*****\n');
fprintf('*****');
fprintf('*****');
nl = size (Linedata,1);
fprintf('\n*****');
fprintf("");
fprintf('\n');
fprintf(' Performance index for outage of line\n: ');
fprintf(' From Bus To Bus PIV \n');
fprintf(' ***** ***** ***** ');

```

```
for i = 1:nl
fprintf('\n %5.0f   %10.0f %18.5f %18.5f \n',...
PI(i,:));
end
fprintf('\n\n voltage on busses after contingency\n');
fprintf('\n bus no      Volts \n');

for n=1: nbus
fprintf('%6g', n),
fprintf('      %0.3f \n', Volt(n));
end
```