UNIVERSITY OF NAIROBI

FACULTY OF ENGINEERING

DEPARTMENT OF MECHANICAL AND MANUFACTURING ENGINEERING

Static Security Assessment of the Kenyan Power System Using Contingency Analysis

By

Chepkemoi Janeth

F56/64671/2010

A Research Project Report Submitted in Partial Fulfilment of the Requirement for the Award of the Degree of Master of Science in Energy Management of the University Of Nairobi

May 2022

DECLARATION

This project is my original work, except where due acknowledgement is made in the text, and to the best of my knowledge has not been previously submitted to University of Nairobi or any other institution for the Award of degree, masters or doctorate.

Signature: 19/02/2022

Name: Chepkemoi Janeth

Reg No: F56/64671/2010

Supervisor Confirmation:

This project has been submitted to the Faculty of Engineering, Department of MME and University of Nairobi with my approval as the supervisors.

Name: Dr. Peter Musau Moses

Signature: .... Date: 21/02/22

Name: Dr. Reuben Mwanza Kivindu

Signature: ..KIVINDU REUBEN MWANZA RKivindu......... Date: 22/02/2022

DEFINITION OF TERMS

- **Contingency –** Refers to an operational outage in one or more devices in a power system, such as transmission lines, generators and transformers.
- **Contingency analysis** - Is the process of anticipating what might happen to a power system in the event of unplanned component outages or topological changes.
- **Post Contingency** - It is the state of the Power System after an outage or a loss of a component has occurred, it is being assumed that this condition has a security violation such as line or transformer are beyond its flow limit, or a bus voltage is outside the limit.
- **Secure Dispatch** – It is the state of the system with no contingency, but with corrections to the operating parameters to account for security violations.
- **Base Case-**refers to the power system in its normal steady-state functioning, with all elements in service that are expected to be in service.

ABBREVIATIONS

CA- Contingency Analysis

AC- Alternating Current

DC-Direct Current

DSA – Dynamic Security Assessment

GSDF- Generator shift distribution factor

KETRACO-Kenya Transmission Co. Ltd

SCADA - Supervisory Control and Data Acquisition

KV- Kilovolt

MVAR-Megavars

KW - Kilowatt

KWh- Kilowatt hours

LODF – Line outage distribution factor

MW- MegaWatts

NR – Newton-Raphson

NRLF- Newton-Raphson Load Flow

PI_p - Real power performance index

PI_v- reactive power performance index

ABSTRACT

Chepkemoi Janeth

F56/64671/2010

Static Security Assessment of the Kenyan Power System using contingency analysis.

The demand for reliable power supply in Kenya has been driven by increased industrialization however, the reliability of the Kenyan Power System recently came into question following frequent blackouts affecting the entire country almost yearly for the past three years. In June 2016, a fault at Gitaru Power Station led to the loss of 180MW which triggered a national blackout that lasted for over ten hours. As recently as 8th January 2017, the Nairobi, Coast and Mt. Kenya regions were plunged into darkness due to a technical fault at the Nairobi North Substation that cut the supply off to Nairobi from Olkaria geothermal fields. Following these rampant outages, there is need to study the security of the system. This project aimed at evaluating the static security of the Kenyan Power System using Contingency analysis and offer recommendations to mitigate the vulnerabilities of the power system. To achieve this, the Kenyan Power System was modelled, and a contingency analysis done for different operating scenarios factoring in generators and transmission lines and considering an outage level of (N-1) using DIgSILENT Power Factory software. AC Load Flow method Newton-Raphson was used to perform the CA since it was able to give information on the reactive energy flows and the bus voltages in the system. The component loading was between 80 -90 percent which operated closer to their loading limit thus limiting the load expansion and ability to withstand loading in case of a contingency. The bus voltages before CA was done ranged from 0.99 p.u. to 1.02 p.u and a loss of transmission line caused them to drop to as low as 0.6 p.u due to a decrease of reactive power injection. There is need to strengthen their loadability through redundancy of the system components. Recommendations to correct these violations without load shedding have been suggested to enable the system handle an outage level of (N-1).

Key Words: Power System Security, Load flow, (N-1) Security, Contingency analysis, load shedding

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE

INTRODUCTION

1.1 Background

Following the increase of power grid interconnections, reinforcements and the penetration of intermittent energy resources such as solar and wind, modern power systems have become increasingly more complex and dynamic. In addition, due to economic reasons and widespread transmission expansion, many power systems have been forced to operate closer to their stability limit. In the event of a violation of the stability limit of a system due to failure of a system component such as a generator or transformer, the system may respond by a cascade of outages or even a system blackout. Hence, security analysis has become an important tool to assess the stability of a power system under component outages and topological changes. [1]

The dramatic expansion of the power grid and the penetration of intermittent energy resources in the country in a relatively short time; the power system has become increasingly more complex and dynamic. Moreover, because of widespread transmission expansion, it has been forced to operate closer to its stability limit. If localized in one or more items of equipment violate the stability limit, the system may respond by a cascade of outages and possibly even a system blackout. Therefore, the need arises to carry out contingency analysis on the system to identify system vulnerabilities and work towards corrective measures to guarantee reliable operation of the power system. [2]. Planning and operation of transmission systems are subject to N-1 criterion which requires that all single failures of network components do not violate safety limits. Therefore, traditional N-1 criterion is applied to the contingency analysis. This involves simulation of one contingency at a time and then assessing the system to determine whether any system violations have occurred.

1.1.1 Power System Stability

It is the ability to have the total system unviolated courtesy of having a majority of the system variables bound as a way for an electric power system within a definite starting operating state redeem the position of operating balance after a physical interruption. The disruption could be faults, load changes, generator outages, line outages, voltage collapse or rather a mix of either of these causes [2]. It can be broadly classified as shown in Figure 1.1

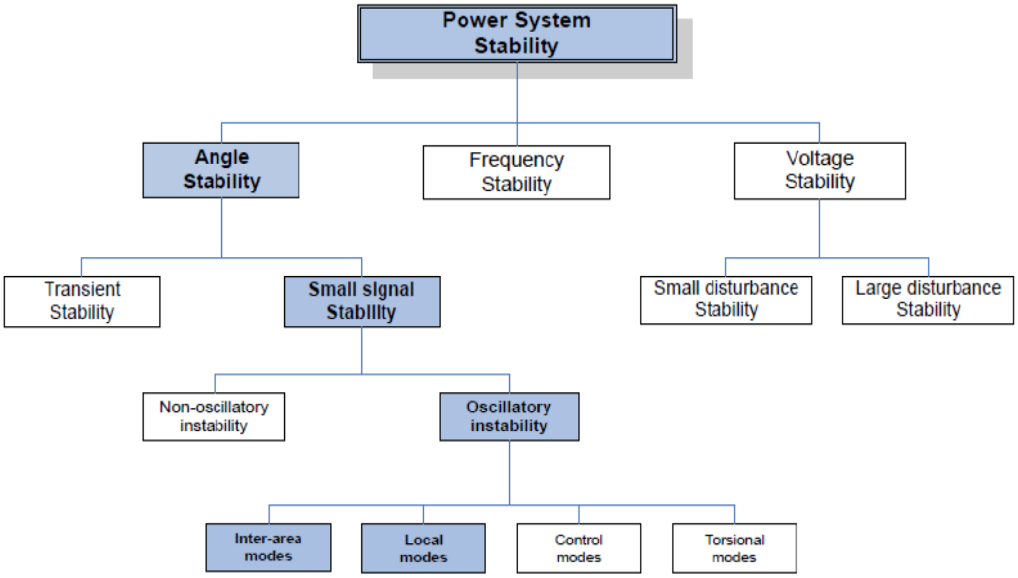


Figure 1.1 Power System Stability [1]

1.1.2 Power System Security

Refers to surveillance of power systems where real time parameters are observed over a period of time using telemetry systems or a SCADA .The investigation appraises the system operator by permitting corrective action in anticipation of the outage event. Security analysis comes up with regulation approaches which offer survival and ultimate maneuvering of emergency situations at the least cost [3].

Power system security is defined as the magnitude of probability to navigate contingencies without interference of customer service. T. Liaco accommodated the approach to analyze power security through the steady state model in 1978. This framework was the base on which power system security was established considering optimal power flow while acknowledging eventualities. According to Stott et al., steady state security assessment is a violation detection process under actual operating states and emergencies. Balu et al, 1992, states the security of a power system is determined through assessment in consideration to the given contingencies. The magnitude of survival through contingencies while ensuring no interruption to customer service is elaborated as power system security according to IEEE/CIGRE. Therefore, it is clear with consideration to prior research that contingency is a critical bit of power system security analysis [4].

1.1.3 Power System Contingency

In Power Systems, a contingency is the event where a component of the electric network breaks down. The element failure could be that of a substation, transformer, transmission line, or a generator. A Contingency Analysis is executed on simulations of the electric grid to establish the cause to a specific component malfunctioning. If a system is (N-1) Contingent or secure, it states that the grid can carry on with operations within normal limits if 1 element fails. Moreover, a contingency commences and winds up at a breaking device such as a circuit breaker [5].

1.1.4 Dynamic Security Assessment

Dynamic security assessment (DSA) is an examination of the resilience of a certain power system to overcome a given set of contingencies and to power through the transition to an agreeable steady state condition. There are several factors that are of fascination in dynamic analysis. Nevertheless, commonly DSA programs narrow down on two phenomena-voltage transients and system stability. Voltage transients are to be retained within agreeable limits as a protective approach for them. Therefore, it is needful to have them researched. Most DSA programs ideally examine voltage levels as they advance in a transient. System stability in power systems can be explained as the capacity to retain coexistent functioning of the AC generators in a system, also be cited as transient stability. The Primary emphasis for the current DSA programs is type of stability considering its associated constraint on operations. Proposed methods for DSA can be categorized into three areas i.e., simulation (numerical integration method, direct/Lyapunov methods and probabilistic), heuristic and database/pattern matching approaches [6] [7].

1.2 Problem Statement

Great strides have been made in the Kenyan energy sector to warrant reliability of power supply in the country. These include injection of additional power from geothermal sources to increase diversity of the energy mix, extension of the national grid to off-grid areas such as Garissa and Wajir and the construction of new transmission lines and substations to increase power transferred across the country.

Despite these efforts, the security of the Kenyan Power System has come into question with several blackouts affecting several regions of the country due to a failure of certain system components. For instance, as recently as 9th May 2020 there was a system blackout which was caused by a technical fault in a section of the main high voltage transmission line that evacuates power from Olkaria geothermal fields to Nairobi. This occurred when a power conductor came off the support insulators and crashed on the tower.

On 8th January 2017, the Nairobi, Coast and Mt. Kenya regions were plunged into darkness due to a technical fault at the Nairobi North Substation that cut off supply from the Olkaria geothermal fields to Nairobi. In another incident in June 2016, a technical fault at Gitaru Power Station caused the loss of the 180MW generation unit. This triggered a national blackout that lasted for several hours. Hence, the requirement to investigate the static security of the Kenyan power system.

1.3 Objectives

1.3.1 General Objective

To study the static security of the Kenyan power system through Contingency Analysis.

1.3.2 Specific Objectives

(i) To model the Kenyan Power System as had been projected to be by 2020 and run a load flow of the base case to ensure that no system violations exist prior to contingencies.

(ii) To perform (N-1) security investigation of the Kenyan Power System for the base case

(iii) To carry out (N-1) security survey of the Kenyan Power System for an operation scenario with minimal generation from thermal power plants

(iv) To execute (N-1) contingency survey of the Kenyan Power System for a scenario with low loading conditions (55% loading).

(v) To rank violations due to contingencies based on their severity for all scenarios mentioned.

(vi) To recommend possible solutions to mitigate the violations arising from these contingencies for all scenarios mentioned.

1.4 Research Questions

(i) What is the electricity demand in Kenya as of 2020?

(ii) How is Kenyan power system security surveyed and by which method?

(iii) What sources of energy are being added into the system to sustain the demand?

(iv) How is the analysis affected by the various energy sources added to the system?

(v) How is the analysis affected by different loading conditions?

(vi) What are the possible recommendations given to mitigate violations arising from the contingencies?

1.5 Justification

This project will help in identifying the vulnerabilities of the Kenyan power system through contingency analysis. Recommendations will be made to rectify these weaknesses derived on the acquired results. Additionally, the best location for the injection of new generation units to boost system reliability and supply will be suggested from the results.

Stability of the Kenyan Power System is a priority due to various factors such as growth in the industrial sector and introduction of renewable sources of energy. The above factors affect the economic stature of the Country and hence research towards this is required. The project will be focus on modelling and analysing the Contingency assessment of the Kenyan Power System while maintaining voltage stability.

1.6 Scope

This project study will be carried out on the transmission system network of the Kenya Power System. Different contingencies will be studied under the (N-1) criterion and their impact on the network security observed. The two sets of contingencies that will be considered are outages of generators and outages of lines. The grid will be modelled based on the peak loads, bus data and other parameters based on the available data.

Contingency Analysis entails the mirroring of each occurrence on the base case model of the Power system. The procedure of establishing incidences that lead to the infringement of operational restrictions is referred to as contingency selection. These indices are calculated through the conventional power flow for singular contingencies in an off-line mode. The system will be run using the DIgSILENT PowerFactory software to be able to simulate and detect contingency operational limits violations. The analysis will only consider losses of generators and transmission line above 132kV for the Kenyan Power System.

1.7 Report Organization

In Chapter 2, reviews on N-1 security analysis that were performed in other countries and their gaps were discussed. The power system operating states were also explained. This assists in knowing research gaps and challenges encountered in analysis, which includes software challenges, data challenges and accuracy levels.

In Chapter 3, Methods of performing contingency analysis were explained. This explains the use of DC and AC power flow systems taking into effect the advantages and disadvantages of each method in an analysis. DIgSILENT software was also discussed to discover its capability to run this system and examine its data. The Kenyan power system modelling was also explained to give an idea on the buses to be considered.

In Chapter 4, results of contingency analysis of different operating scenarios were conclusively discussed and recommendations on how to avert system violations were also discussed. This has been done after the system was modelled and contingency analysis carried out. The results were put in tabular form for ease of comprehension and understanding.

Chapter 5 entails all the conclusions derived from the previous chapters and in winding up they are elaborately explained. Recommendations for further works have also been put forward and discussed in detail.

CHAPTER TWO

LITERATURE REVIEW

2.1 Review of (N-1) Security in Other Countries

A Review of (N-1) Security analysis done on the Nigerian Power System using the Electrical Transient Analyser Programme (ETAP, when Nigerian Government needed to privatise the power sector did not exhibit any improvement on the same quest because Voltage instability stood out as the primary cause behind outages the on Kaduma Transmission Network. Thus an evaluation on power flow and contingency for the expanding 330kV Nigeria grid through simulation on the Power World Simulator was done and the outcome portrayed Damaturu and Gombe bus voltages to be having voltage variance [3].

The same study done on the Bangladesh Power System using the Newton Raphson approach in executing the contingency survey on Power System Application Framework (PSAF) indicated a 2.06% probability of load loss. Newton Raphson Algorithm was also used to perform an analysis on the Maryland Transmission Station and the outcome exhibited that a compensation was needed on the line. Contingency Study using MATLAB Simulink model was also proposed for a limited 220kV Karnataka Power Transmission Corporation Limited (KPTCL) system where a 15-bus system comprising 5 generators, 13 loads and 20 transmission lines was modelled and simulated using N-R technique and the results indicated Newton-Raphson method reduced the computation time for contingency analysis as compared to other typical methods [3].Analysis of the above-named systems were done in other software other than Power factory. Comparison of the results from various software helps to determine the accuracy levels in analysis. Some of the software used were unable to give data on loadability hence making the study difficult. DIgSILENT has a vast range of functions it can perform with a user-friendly experience in terms of design and analysis [11].

2.2 Power System Operating States

Contingency is an operational outage in one or more devices, such as transmission lines, generators, and transformers. Contingency Analysis entails the mirroring of specific occurrence on the base case model of the Power system. It encompasses investigation of the effects on line flows and bus voltages of the remaining system as well. It is an important tool used to anticipate which contingencies display system violations while ranking contingencies with reference to their level of extremity. Contingencies usually cause a power system to change operating states. Fink and Carlsen first suggested a classification of power system operating conditions [1]. Despite it being repeatedly modified, its essential form is as shown in Figure 2.1

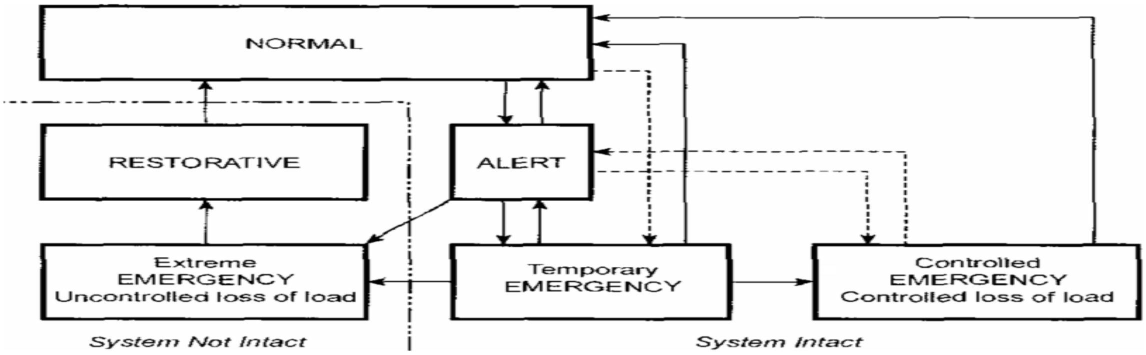


Figure 2.1 Power System Operation States [1]

In the normal state, no credible contingency can push the system to either temporary or permanent failure. In the *alert* state, the system is fully functional. However, further contingencies can result in the violation of inequality constraints in the system. This triggers the system to one of the three *emergency* states. In the *temporary emergency* state, the system operator can initiate actions to reduce intolerable line stresses or bus voltages reverting the system to an alert or even a normal state. Commonly, the system operator opts for load shedding due to its effectiveness. This usually causes the system to transfer to a *controlled emergency* state. A controlled emergency state can be attained from an alert state if a contingency can initiate supply interruption directly. This is without interference from the system operator, while system stability and integrity stand unaltered. Other contingencies in an alert state could compel the system into an *extreme emergency* condition which stands at having the stability and/or integrity of the system compromised. At this point, both equality and inequality constraints have been violated [1].

Planning and functioning of transmission systems are subject to (N-1) criterion, demanding all single failures of network elements not to cause a breach of safety limit. An analysis of a predefined set of credible contingencies while enforcing a threshold criterion of tolerable risk on system variables with reference to standard operating practices is how the Traditional (N-1) security assessment criterion is executed . Eventually having the system dispatched to pre-empt the happening of a worst-case scenario within the credible contingency sets. The (N-1) criterion is still commonly applied despite a highly unlikely outage as it does not concern itself with the probability of an outage and component loss is not agreeable [5].

The (N-1) criterion is a minimum system security measure that the System Operator should model the transmission network to address redundancy while averting potential power disruptions and/or system failure. The (N-1) criterion is satisfied if, after a single system element has failed, the following rules are observed:

a) No breach of the limiting values for network operation variables (i.e. operation voltage, frequency) which may compromise the dependability of the power system or result to an unacceptable strain on equipment, damage, destruction or an inadmissible reduction in the life of equipment. The Voltage Deviation scale should be satisfactory for transmission system from ± 5% in normal conditions to ± 10% for N-1 Criterion. The Frequency Deviation scale should be satisfactory for power system from ± 0.3 Hz in normal conditions to ± 0.6 Hz for N-1 Criterion [6].

b) No equipment/transmission line loading has exceeded 100% of its functional thermal limit capacity

c) Interruptions of supply are averted.

2.3 Modelling Contingency Analysis

In power systems, contingency analysis refers to the study of the outage of system components such as distribution/transmission lines, transformers and generators, and examination of the effects on line flows and bus voltages of the residual system. It is an effective tool used to project which contingencies make system violations and rank the contingencies with regards to their magnitude of extremity [5].

Contingency analysis is separated into three different stages, namely:

a) Contingency definition

b) Contingency selection

c) Contingency evaluation.

Contingency definition entails creating the set of all likely contingencies which may result in a power system. Contingency selection is the procedure of recognizing the most acute eventualities from the contingency list resulting to system infringement in reference to the power flow and bus voltage extent. As a result, this process eradicates the least critical contingencies and reduces the contingency list. Thus, having them ranked in reference to a scalar index called severity index or performance index (PI) [1]. The PI is a mensuration of system-wide outcome of an incident in the system. The final step in contingency analysis is contingency evaluation. This involves recommending the necessary remedial actions or control measures that need to be implemented to mitigate the effect(s) of contingency [5].

2.3.1 Modelling of system components for contingency analysis

In carrying out contingency analysis for a transmission system, the major components under consideration are:

(i) Generators

(ii) Transformers

(iii) Transmission lines

(iv) Loads

A single line diagram indicating the complete transmission system is executed with components mentioned above.

2.4 Research Gap

In Kenya, major power losses have been experienced from time to time. Kenyan systems have experienced contingencies by breakdown of generators and transmission lines. This emerges from fact that a bigger number of components are operating close to their loading limit hence any loss of a major equipment like generator or a transmission line in most times triggers a national black out. The failures of the power system exhibits a need to study the security of the system. Nevertheless, it is rather a demanding task for the power system engineers to sustain power system security. It is needful to be in the know in the likelihood of a contingency thus having the security assessment as a critical task. Contingency analysis technique is being widely used to anticipate the outcome of outages like failures of equipment, transmission line etc. It is also to execute the needed steps to maintain the power system secure and dependable. Contingency Analysis technique is the preferable direction to take in attaining system reliability and security criterion under contingency conditions. The famous (N-1) contingency criterion is broadly utilized in the power industry in developed countries but in Kenya, we are not there yet, this criterion is needed to ensure that the system has the ability to withstand single component outage. Contingency analysis (N-1) for the Kenyan Power System is required to be able to plan for these contingencies and therefore there is a need to perform a simulation considering outages of generators and transmission lines and propose recommendations to make the system more reliable as much as possible. Contingency analysis (N-1) gives a performance table containing all severe contingencies to which power system planners and controllers must pay special attention to in order to avert any system blackout in future.

2.5 Chapter Conclusion

The introduction of Renewable Energy Sources to the power system has led researchers to do contingency analysis on power systems. The intermittency of this energy sources has caused instabilities on the systems. Studies previously done have been on the IEEE 14 bus system on the Power world simulator with inclusion of geo-magnetically induced currents. This software is user friendly and has the capability to perform contingency analysis but large system analysis was never performed with this software due to its incapability [7].

From former researches, voltage stability was not done as the power world software was incapable of performing a modal analysis. Voltage stability was a major factor in the contingency analysis that was not considered. In Kenyan Power System contingency analysis, voltage limits are to be considered in a system and maintained between 0.95pu and 1.0pu but are not to exceed 1.05pu.

CHAPTER THREE

METHODOLOGY

3.1 Techniques used in Contingency Analysis

Contingency analysis is done using the following methods:

(i) Sensitivity factors -Direct Current (DC)Load Flow

(ii) Alternating Current (AC)load flow

3.2 DC Load Flow

3.2.1 Contingency analysis using DC Load Flow

Sensitivity factors is the simplest method that eliminates the difficulty of analysing thousands of possible outages required to present the outcome quickly. The factors denotes the approximate change in line flows for variations in the generation network arrangement which are acquired from DC load flow [8].

3.2.2 DC Load Flow Formulation

The performance of DC load flow using fast decoupled Newton Raphson method allows occurs by simply neglecting any QV equation which results in attainment of a linear and non-iterative power flow algorithm.To achieve these, assumption made is that |*Vi*| = 1 pu for every bus *i*.

Which gives: $$\begin{bmatrix} \Delta P_1 \\ \Delta P_2 \\ \cdots \end{bmatrix} = [B'] \begin{bmatrix} \Delta\delta_1 \\ \Delta\delta_2 \\ \cdots \end{bmatrix} \tag{3.1}$$

The elements of matrices B' are:

$$B_{ik}' = {}^{-1}/_{x_{ik}} \ (where\ xik\ is\ line\ impedance\ between\ buses\ i\ and\ k\ ) \tag{3.2}$$

$$B'_{ii} = \sum_{k=1}^{n} \frac{1}{x_{ik}} \tag{3.3}$$

The matrix **B'**elements are outlined in Eq. (3.2) and Eq. (3.3).The calculation of the real power flow (MW) is only attained by use of the DC power flow but gives no indication of the reactive power flow (Mvar) and apparent power (MVA) or the voltages .The power flow on each line using the sensitivity factors method can be described by the equations 3.4 and 3.5:

$$P_{ik} = \frac{1}{x_{ik}}(\ \delta_1 - \delta_k) \tag{3.4}$$

And

$$P_i = \sum_{k=nodes\ connected\ to\ i}^{n} P_{ki} \tag{3.5}$$

To make up for the losses inadequacy in the DC solution, the overall DC load is increased by the equal measure of AC losses. therefore, in the DC approach, the perceived transmission system losses could be apportioned to the bus loads. This requirement to consider the losses first,is usually not troublesome since the specified total control area "load" is actually the true load plus the losses. Computationally, DC power flow has three advantages over the standard Newton-Raphson power flow [9].

3.2.2.1 Advantages of DC load flow

(i) Solving DC load flow set of equations is easy and not time consuming since the real power balance equations is about half the size of the full problem.

(ii) The dc power flow is non-iterative, requiring just a single solution of Eq. (3.4) and Eq (3.5)

(iii) The **B'** matrix is state-independent provided the system topology doesnt change, one consideration is enough.

overally the result of the DC power flow is ten times faster than the regular power flow for the initial solution, and even faster for subsequent solutions since solving for **δ** with a modified **P** would only require a forward /backward substitution.

3.2.2.2 Disadvantage of DC load flow

The only disadvantage of this method is its inability to provide the MVAR flows and bus voltages information respectively.

DC load flow can be used for contingency analysis where the computational speedups available for using linear approximations are even more dramatic. Linear methods for contingency analysis have been used for many years [12],[13] in the line outage distribution factor (LODF) and Generation shift distribution factor approach.

Sensitivity factors used in contingency analysis include the following:

3.2.3 Line Outage Distribution Factor [12]

The effects of single and multiple line outages can be linearly approximated by calculating the state independent LODF.

$$LODF_{ij,st} = \frac{\Delta P_{ij}}{{P_{st}}^{0}} \tag{3.6}$$

where ΔPij is the change in MW flow on line *i-j* following the outage of line *s-t*, and ${P_{st}}^{0}$ is the original flow on line *s-t* before it was outaged. The LODF matrix contains the LODFs factor for all monitored lines. Similar values can also be calculated for line opening (closure) contingencies. Since the LODFs are state independent they can be calculated once and used many times for contingency analysis. Once the factored **B'** matrix is available, the computation requirements to calculate each LODF matrix are proportional to a fast forward/full backward substitution. [10].

Once we have the power angles from Equation (3.1), it is a simple matter to find the power flows over each edge, and indeed they are given by:

$$ {P_{ij}}^{C} = {P_{ij}}^{0} + LODF_{ij,st} \times {P_{st}}^{0} \qquad (3.7$$

In Eq. (3.7), superscripts 0 and c represent base case and contingency cases, respectively, subscript ij represents the set of monitored lines, and subscript st represents the set of lines on outage. $P_{ij}{}^{c}$ and $P_{ij}{}^{0}$ are post-contingency and pre-contingency power flows on monitored lines. $P_{st}{}^{0}$ is pre-contingency power flows for lines on outage. $LODF_{ij,st}$ represents an element of LODF matrix. This allows the contingencies to be linearly approximated many times faster than the approach of actually solving the power flow for the contingent system.

3.2.4 Generation Shift Distribution Factor [12]

The effects of single and multiple generator MW change or outages can be linearly approximated by calculating the state-independent GSDF. Using the DC load flow model, the Generation Shift Distribution Factor is expressed as:

$$A(m,i) = \frac{\partial P_m}{\partial P_{gi}} = \frac{\partial}{\partial P_{gi}}\left(\frac{\delta_j-\delta_k}{x_m}\right) = \frac{1}{x_m}\left(\frac{\partial\delta_j-\partial\delta_k}{\partial P_{gi}}\right) \tag{3.8}$$

With $m = 1, 2,\ldots, N_L$ is the number of lines. From equations (3.4) and (3.5), it is concluded that $\partial\delta_j/\partial p_{gi} = x_{ji}$ and $\partial\delta_k/\partial p_{gi} = x_{ki}$ thus,

$$sA(m,i) = \frac{x_{ji} - x_{ki}}{x_m} \tag{3.9}$$

where P_m is the real power flow on line m from sending bus j to receiving bus k; x_{ji} and x_{ki} are the elements j-i and k-i of reactance matrix X of the lines, respectively where X = [0 x_{12} x_{13} ... x_{1n}; x_{21} 0 x_{23} ... x_{2n}; ... ; x_{n1} x_{n2} ... 0]; x_m is the reactance of line m and p_{gi} is real power generated by the generator i.

The GSDF matrix contains the GSDFs factor for all monitored lines from equation (3.9) since all generation changes are compensated by the reference bus, the total generation is assumed unchanged.

$$\sum_{i=1}^{N_G} P_{gi} = \sum_{i=1}^{N_{LOAD}} P_i = constant \tag{3.10}$$

where N_G is the number of generators and N_{LOAD} is the number of loads.

The GSD factors of equation (3.8), the new line flows, after rescheduling generation,can be expressed as

$$P_m = {P_m}^0 + \sum_{i=1}^{N_G} A(m,i)\Delta P_{gi} \qquad (m = 1,2,\ldots,N_L) \tag{3.11}$$

Where ${P_m}^0$ is the base case line flow.

3.3 Contingency Analysis Using AC Load Flow

AC power flow solution methods are namely Gauss-Seidel, Fast Decoupled and Newton-Raphson. discussed further in [14] and [15] is preferred to CA using sensitivity factors because it gives information about MVAR flows and bus voltages in the system.

In systems involving underground cables where VAR flows predominate, analysis of only the MW will not be sufficient to indicate overloads therefore the sensitivity factors technique of contingency analysis is inadequate.

The Newton Raphson power flow is the most robust algorithm used in practice because it converges faster and has more accuracy than the other AC load flow methods.

3.4 Newton Raphson Load Flow Method

The Newton-Raphson method is the most preferred for load flow solutions because it has the merits and demerits explained in Sub Section 3.4.1 and Sub Section 3.4.2 respectively.

3.4.1 Advantages of Newton-Raphson load flow

(i) Potent convergence characteristics and low computation as compared to other alternative processes makes the NR approach to suit large networks [14][16]. This technique is very sensitive to good start conditions hence its application reduces the time for computation remarkably.

(ii) Determination of acceleration factors isnt a necessity for iteration and is not altered by the choice of slack bus .

(iii) Network modifications require less computational effort.

(iv) The NR method has great flexibility and generality, hence enables easy and efficient involvement of representational needs. These include on-load tap changing and phase-shifting devices, area interchanges, functional loads and remote voltage control.

(v) NR formulation is suitable for the system with large angles across transmission lines and with a control device which influences reactive and real power [16].

3.4.2 Disadvantages of the Newton-Raphson load flow

The only demerit with the NR method is that more functional methods are required at each evaluation[14]. However, with the advent of computer simulation programs, this is hardly perceived as a hurdle.Next, we discuss the N- R load flow solution.

3.4.3 Newton Raphson load flow solution

A bus in power systems refers to a node that connects one or more lines and can also contain multiple components like loads and generators as shown in Figure 3.1

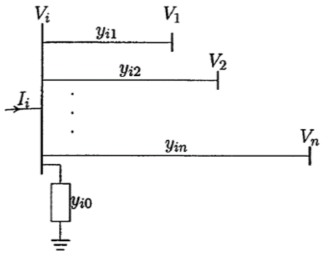


Figure 3.1 Showing a Typical Busbar of a Power System

The current entering the bus I is given as

$$I_i = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij} V_j \quad for\, j \neq i \tag{3.12}$$

Rewriting equation (3.12) in bus admittance matrix form, gives

$$I_i = \sum_{j=1}^{n} Y_{ij}V_j = \sum_{j=1}^{n} |Y_{ij}||V_j|\angle(\theta_{ij} + \delta_j) \tag{3.13}$$

The complex power at bus i is

$$P_i - jQ_i = V_i^{*}I_i = |V_i|\angle(-\delta_1)\sum_{j=1}^{n} |Y_{ij}||V_j|\angle(\theta_{ij} + \delta_j) \tag{3.14}$$

Splitting up real and imaginary part

$$P_i = \sum_{j=1}^{n} |Y_{ij}|\,|V_j||V_i|cos(\theta_{ij} - \delta_i + \delta_j) \tag{3.15}$$

$$Q_i = -\sum_{j=1}^{n} |Y_{ij}||V_j||V_i|sin(\theta_{ij} - \delta_i + \delta_j) \tag{3.16}$$

The equations for P_i and Q_i make up a set of nonlinear algebraic equations in terms of the independent variables, voltage magnitude in per unit, and phase angle in radians.

Expanding P_i and Q_i in Taylor's series about the initial estimate and neglecting all higher order terms results in the following set of linear equations.

$$\left[\begin{array}{c} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \\ \hline \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{array}\right] = \left[\begin{array}{ccc|ccc} \frac{\partial P_2}{\partial \delta_2}^{(k)} & \cdots & \frac{\partial P_2}{\partial \delta_n}^{(k)} & \frac{\partial P_2}{\partial |V_2|}^{(k)} & \cdots & \frac{\partial P_2}{\partial |V_n|}^{(k)} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_n}{\partial \delta_2}^{(k)} & \cdots & \frac{\partial P_n}{\partial \delta_n}^{(k)} & \frac{\partial P_n}{\partial |V_2|}^{(k)} & \cdots & \frac{\partial P_n}{\partial |V_n|}^{(k)} \\ \hline \frac{\partial Q_2}{\partial \delta_2}^{(k)} & \cdots & \frac{\partial Q_2}{\partial \delta_n}^{(k)} & \frac{\partial Q_2}{\partial |V_2|}^{(k)} & \cdots & \frac{\partial Q_2}{\partial |V_n|}^{(k)} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial Q_n}{\partial \delta_2}^{(k)} & \cdots & \frac{\partial Q_n}{\partial \delta_n}^{(k)} & \frac{\partial Q_n}{\partial |V_2|}^{(k)} & \cdots & \frac{\partial Q_n}{\partial |V_n|}^{(k)} \end{array}\right] \left[\begin{array}{c} \Delta \delta_2^{(k)} \\ \vdots \\ \Delta \delta_n^{(k)} \\ \hline \Delta |V_2^{(k)}| \\ \vdots \\ \Delta |V_n^{(k)}| \end{array}\right] \tag{3.17}$$

From, equation (3.17), bus 1 is assumed to be the slack bus.

The Jacobian matrix gives the linearized relationship between small changes in voltage angle $\Delta\delta_i{}^{(k)}$ and voltage magnitude $\Delta|V_i{}^{(k)}|$ with small changes in real and reactive power $\Delta P_i{}^{(k)}$ and $\Delta Q_i{}^{(k)}$.

Elements of the Jacobian matrix are the partial derivatives of $P_i{}^{(k)}$ and$Q_i{}^{(k)}$, evaluated at $\Delta\delta_i{}^{(k)}$ and $|V_i{}^{(k)}|$.

In short form, it can be written as

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\delta} & J_{PV} \\ J_{Q\delta} & J_{QV} \end{bmatrix} = \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \tag{3.18}$$

The diagonal and off diagonal elements of $J_{P\delta}$ are:

$$\frac{\partial P_i}{\partial \delta_i} = \sum_{j\neq 1}^{n} |V_i||V_j||Y_{ij}|sin(\theta_{ij} - \delta_i + \delta_j) \tag{3.19a}$$

$$\frac{\partial P_i}{\partial \delta_i} = -|V_i||V_j||Y_{ij}|sin(\theta_{ij} - \delta_i + \delta_j) \quad j \neq i \tag{3.19b}$$

The diagonal and the off-diagonal elements of J_{PV} are:

$$\frac{\partial P_i}{\partial |V_i|} = 2|V_i||Y_{ii}|\cos\theta_{ii} + \sum_{j\neq 1}^{n} |V_j||Y_{ij}|cos(\theta_{ij} - \delta_i + \delta_j) \tag{3.20}$$

$$\frac{\partial P_i}{\partial |V_j|} = |V_j||Y_{ij}|cos(\theta_{ij} - \delta_i + \delta_j) \; j \neq i \tag{3.21}$$

The diagonal and the off-diagonal elements of $J_{Q\delta}$ are:

$$\frac{\partial Q_i}{\partial \delta_i} = \sum_{j\neq 1}^{n} |V_i||V_j||Y_{ij}|cos(\theta_{ij} - \delta_i + \delta_j) \tag{3.22}$$

$$\frac{\partial Q_i}{\partial \delta_j} = -|V_i||V_j||Y_{ij}|cos(\theta_{ij} - \delta_i + \delta_j) \quad j \neq i \tag{3.23}$$

The diagonal and the off-diagonal elements of J_{QV} are:

$$\frac{\partial Q_i}{\partial |V_i|} = -2|V_i||Y_{ii}|\sin\theta_{ii} + \sum_{j\neq 1}^{n}|V_j||Y_{ij}|sin(\theta_{ij} - \delta_i + \delta_j) \tag{3.24}$$

$$\frac{\partial P_i}{\partial |V_j|} = |V_j||Y_{ij}|sin(\theta_{ij} - \delta_i + \delta_j)\ j \neq i \tag{3.25}$$

The terms $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$are the difference between the scheduled and calculated values, known as the power residuals, given by

$$\Delta P_i^{(k)} = P_i^{sch} - P_i^{(k)} \tag{3.26}$$

$$\Delta Q_i^{(k)} = Q_i^{sch} - Q_i^{(k)} \tag{3.27}$$

The new estimates for bus voltages are illustrated in equations (3.28) and (3.29) respectively

$$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta\delta_i^{(k)} \tag{3.28}$$

$$|V_i^{(k+1)}| = |V_i^{(k)}| + \Delta|V_i^{(k)}| \tag{3.29}$$

3.4.4 Contingency Ranking Approach

In practice, not all contingencies cause system violations. The practice of locatiing the contingencies that results in violation of operational limits is known as contingency selection [10], [11]. The contingencies are selected by either calculating severity indices known as performance indices(PI), sensitivity analysis or through computer simulations.

3.4.4.1 Performance indices

In [17], Sekhar and Mohanty studied power system contingency ranking using a performance index based on NR power flow. The calculation of performance index using the NR load flow method yields a criterion for measuring the severity of possible contingencies in a power system. Based on the values obtained, the contingencies with the highest PIs are ranked first. The analysis is then done starting from the contingency that is ranked one and until no severe contingencies are found.There are two types of performance indices [16], [17]which are mainly used for contingency analysis. They are active power performance index and voltage performance index.

a) **Active Power performance index (PIP)** is the index which helps in determining the extent of line overloads.It reflects the violation of active power flow and is given by the equation below:

$$PI_p = \sum_{i=1}^{N_L} (\frac{W}{2n})(\frac{P_i}{P_i^{max}})^{2n} \tag{3.30}$$

Where; P_i is the MW power flow of line and P_i^{max} is the MW capacity of line ,N_L is the number of lines of the system,W is the real non-negative weighting factor, and value is (= 1) and *n* is exponent of penalty function and value is (=1)

$$P_i^{max} = \frac{V_i \times V_j}{X} \tag{3.31}$$

Where,V_i is the voltage at bus ith obtained from the NR solution and V_j is the voltage at bus jth obtained from the NR solution while X is the reactance of the line connecting ith bus and jth bus.

b) Voltage performance index (PIV): This is the index which helps in determining bus voltages limit violation.

$$PI_V = \sum_{i=1}^{N_B} (\frac{W}{2n}) \left(\frac{|V_i| - |V_i{}^{sp}|}{\Delta V_i{}^{lim}}\right)^{2n} \tag{3.32}$$

Where, |Vi| is the voltage magnitude at ith bus and $|Vi^{sp}|$ is the specified (rated) voltage magnitude at ith bus. ΔV_i^{lim} is the deviation limit of the voltage while "*n*"is the exponent of penalty function and value is (=1). N_B is the number of buses in the system taken while W the real non-negative weighting factor and the value is (= 1)

3.4.4.2 High Computing Environment

The calculation speed of static contingency analysis is increased through successful application of Parallel computing .This has been made possible due to the ease to find Graphics Processing Units (GPU) in the market. With this method, accuracy is user defined and computation efficiency improves with its application to different power techniques. Thus, it offers more accurate results faster.

3.4.4.3 Sensitivity Analysis

The two main applications of this method in power systems is the power flow calculation and contingency ranking. In [1], a new λ/MVA sensitivity ranking algorithm of branch contingencies is proposed for voltage collapse analysis. The suggested method directly classifies saddle-node bifurcations to eliminate the problem. The new λ /MVA sensitivity ranking algorithm is efficient and accurate in estimating all single branch contingencies [1].

3.4.4.4 Remedial Action Scheme

These refer to the measures which the utilities need to take to get the system back to its normal functioning after an outage. Remedial Action Schemes (RAS) are also referred to as Special Protection Schemes (SPS) or System Integration Schemes (SIS). The RAS is designed to mitigate the effects of critical contingencies that provokes the actual system problems. Each critical contingency may require a separate attendance level and different remedial actions.

In the event of critical contingencies such as short- lived faults during stressed operating conditions, automatic single-phase or three-phase recloser may prevent the system from undergoing catastrophic failure. This happens in most cases. However, appropriate RAS action may still be required if reclosing is unsuccessful [18].

3.4.4.5 Types of Remedial Action

Corrective measures that are usually taken to mitigate the effects of contingency include:

a) Distributed Generation
b) Under load tap changing (ULTC) Transformer
c) Load shedding
d) Generation Re-dispatch
e) Islanding
f) Shunt capacitor switching

The effectiveness of the remedial actions has been demonstrated in [19] where the IEEE 6 – bus system undergoing contingency analysis through computer simulation was able to return to normal operating state after power generation of one of the generators was minimized and load shedding was done.

3.5 DIgSILENT Power Factory

PowerFactory is one of the available analysis software present in the market and can perform a contingency task with ease. Its applications covers generation, transmission and distribution hence this was the suitable tool for this project. It covers the full range of functionality from standard features to highly sophisticated and advanced applications including wind power, distributed generation, real time simulation and performance monitoring for system testing and supervision.

The contingency analysis module in PowerFactory offers two distinct contingency analysis method:

a) Single Time Phase Contingency Analysis
b) Multiple Time Phase Contingency Analysis

3.5.1 Single Time Phase Contingency Analysis

The analysis focuses on the non- probabilistic assessment of failure effects under given contingency within a single line period. It performs a pre-fault load flow calculation then it executes a corresponding post-contingency load flow which takes one or more main components out of service. The command calculates the initial consequences of the contingencies, but disregards the operational measures taken to mitigate voltage band problems or supply interruptions [6].

3.5.2 Multiple Time Phase Contingency Analysis

This analysis focuses on the non-probabilistic (deterministic) assessment of failure effects under given contingencies, performed over different line periods, each of which defines a time elapsed after the contingency occurred. It allows the definition of user defined post-fault actions that can lead to mitigation of voltage band problems or supply interruptions which are caused by faults in the networks under analysis [6].

3.6 IEEE Kenyan Equivalent Network

The introduction of Renewable energy sources to the power system has led researchers to do contingency analysis on power systems. The intermittency of these energy sources has caused instabilities on the systems. Studies previously done have been on the IEEE 14 bus system using the Power world simulator with the presence of geo- magnetically induced currents. This software is user friendly and has the capability to perform contingency analysis but large system analysis were never performed with this software due to its incapability [3].

The Kenyan Power System can be related to an IEEE 39 bus system as shown in Fig.3.2. Previous studies have been done on the voltage stability of the system to ensure the system is stable when the load flow is done using the Newton Raphson Method. The analysis was executed through simulations using MATLAB and MATPOWER. The design was evaluated with both AC and DC power flow, where the AC power flow is the accurate model of the power system in steady mode functioning, while the DC power flow is a linear approximation of the system in this mode of operation [12].

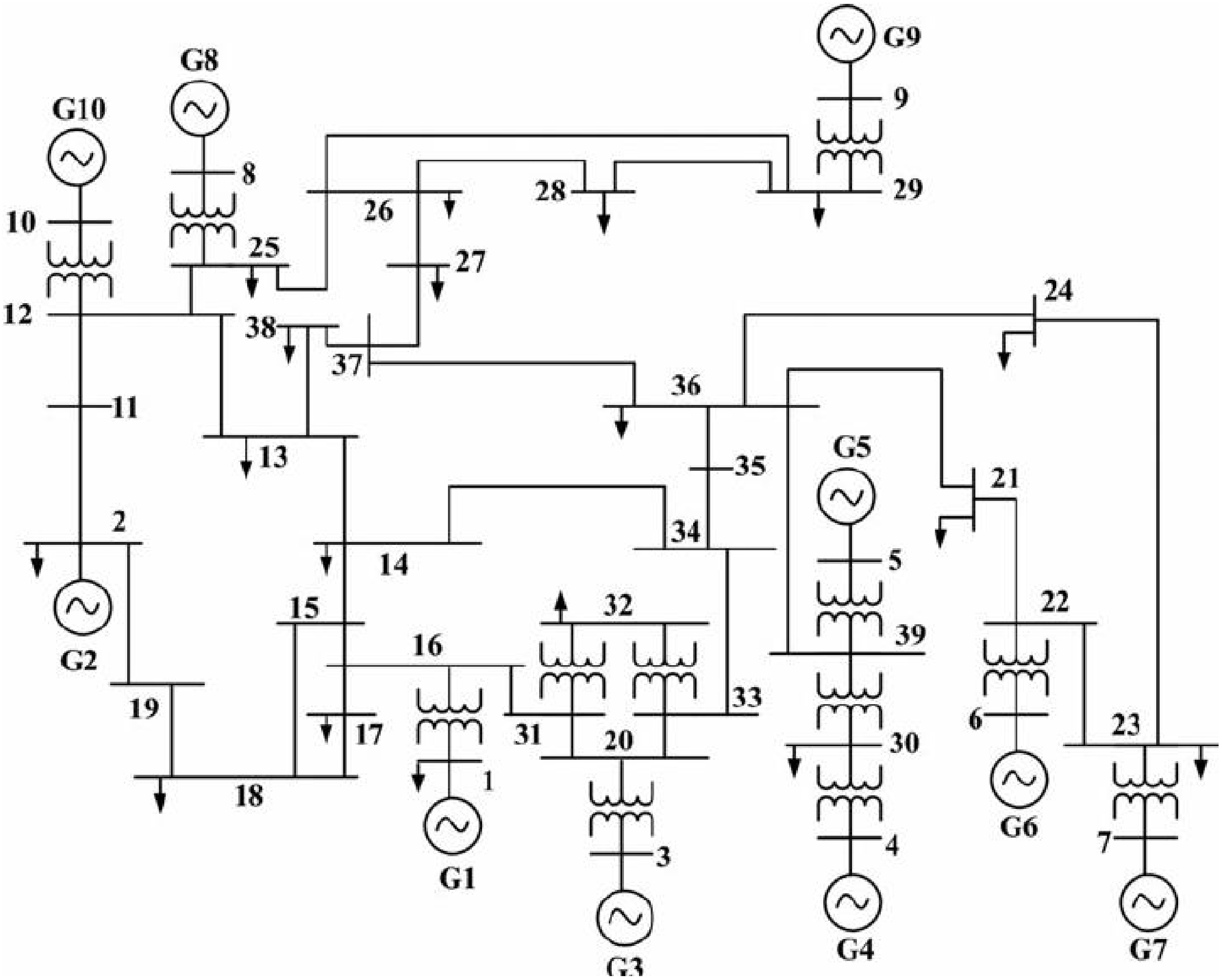


Figure 3.2 Single –Line Diagram of IEEE -39 Bus System

3.7 Kenyan Case Study

The Kenyan Power System will be modelled from the Kenyan transmission system data on DigSILENT Power Factory 15.1 software. Load, generation dispatch, transmission line data and bus data were used to come up with a model of the Kenyan Power System. At the transmission level, the voltage levels considered were 400kV, 220kV and 132kV. Only machines connected to those buses were used. The distribution network was not considered.

The Bujagali Generator will be set as the Slack/Reference bus. Wind power plants will be set as PQ buses. All other remaining generators will be set as PV buses. All generators and relevant data on them used to create the model of the Kenyan power system are shown in Appendix A1.All system loads will be set as PQ buses. All load buses and relevant data are as shown in Appendix A2.The lumped (pi) parameters will be used to model the transmission lines. The derating factor used for all lines was 1. The transmission lines, types and their specifications used to create the model of the Kenyan power system are shown in Appendix A3.

Reactors and capacitors connected to the system will also be modelled. Their service states, buses to which they are connected and their operational voltages are as listed in appendix A4.

In simulating the load flow for the base case, voltage dependency of loads will not be considered. However, voltage dependency of loads will be considered during simulations for the contingency analysis. The reactive power limits will be considered in the load flow simulations for the base case and in simulations for the contingency analysis.

3.8 Conceptual Framework

The project was done in phases as illustrated in the block diagram shown in Figure 3.3.

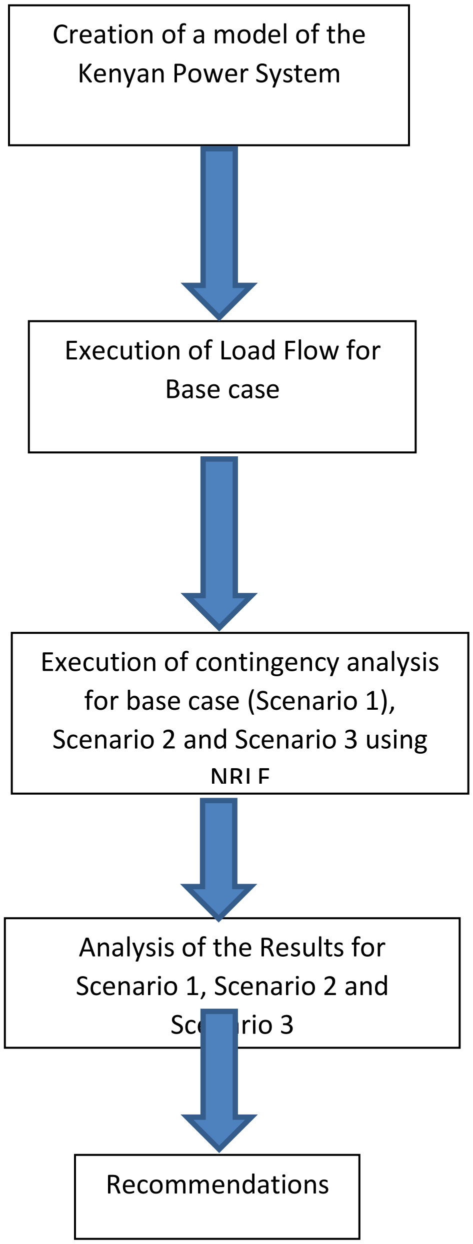


Fig. 3.3 Block Diagram of Project Phases

3.9 Chapter Conclusion

In the design process of the Kenyan Power system, factors to be considered from every component are crucial for better results. The Kenyan Power System has a set design rating for each component that will be put into consideration during analysis. The (N-1) criterion will be run on the system considering only buses and transmission lines above 132kV since they are more crucial than the other lines. The analysis is aimed at maintaining the voltage limits between 0.95p.u and 1.05p.u and ensure the loadability of every component is below 100%. The analysis will assist in knowing areas where generation should be added and areas that power is underutilised.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Description of the Base Case (Scenario 1)

The two types of contingencies considered during the simulation of the base case were Generator and Transmission line outages. In performing the load flow analysis in DIgSILENT, the calculation method selected is Newton Raphson algorithm AC load flow, balanced, positive sequence putting into consideration reactive power limits. Maximum loading of equipment is set at 100%. The lower limit of allowed voltage is set at 0.95p.u while the upper limit of allowed voltage is 1.05p.u. Bujagali generator located in the area of Tororo was set as the slack Bus and Kenyan grid was split into three isolated areas.

The Kenyan power system was analysed in three different scenarios described briefly as follows.

a) Scenario I- Base Case: this is where system was modelled as it is and load flow analysis is performed prior to any modifications before contingency analysis is done.
b) Scenario II-system was modelled to incorporate as Minimal Generation from the thermal plants as possible.
c) Scenario III-this is where the system was modelled at Low loading conditions (55% loading).

4.2 Base Case (Scenario 1) Analysis.

The Newton –Raphson algorithm load flow calculation was successful and managed to converge after six iterations. The voltage and loading violations of 0.69kV and 33 kV bus bar were 1.08p.u and 1.06p.u respectively and the 2-winding transformer was overloaded by 233.04%. The other bus voltages were within the set limits of 0.95p.u and 1.05pu and no other components were overloaded beyond 100% of their rating. Results for Simulation of Load Flow analysis for the scenario1 Of the Kenyan Power System execution is summarized as shown in the Table 4.1

Table 4.1 System Summary for the Kenya Power System Grid

Total	Generation	PQ Load	Line Charging	Losses
MW	1937.88	1873.30		64.58
MVAR	217.19	1078.30	-1893.33	-1391.98
Installed Capacity – 2815.50MW Spinning Reserve – 1041.46MW				

4.2.1 Results for Simulation of Generator Outages for Scenario 1

A contingency analysis of generator outages was done where 32 generator outages were simulated. There were 3 system violations found which affected the Kisumu- Kibos transmission line. They arose from outages of Sondu generator, Mumias Generator and Sangoro G generator. The maximum loading of the Kisumu – Kibos line was 108.0% which occurred when the Sondu generator was lost. The transmission line under normal operating condition is loaded to a maximum capacity of 87.1% and it can be seen that the line is operating close to its limit prior to a contingency occurring with a power of 85.3MW flowing through the 132kVbus which is majorly flowing from the Olkaria II power plant. The loss of these generators trigger increased power flow from nearby power plants to meet the demand which leads to overloading of the line.

Table 4.2 Outages Corresponding To Overloaded Components and their Violations.

Generator Lost	Overloaded Components	Loading Contingency Case (%)	Loading Base Case (%)
Sondu	Kisumu – Kibos Line	108.0	87.1
Mumias	Kisumu – Kibos Line	102.5	87.1
Sangoro G	Kisumu – Kibos Line	100.9	87.1

This results are observed when the system’s natural frequencies were not observed, which cause small signal instability. The system’s natural frequencies can cause instability as a result of unstable poles from plants, mainly renewable plants due to their intermittency. An Internal Model Principle is used in this control structure to supply closed loop transmission zeros which cancel the unstable poles of the disturbance and reference signals and is extended to the weakly non-linear systems subjected to step disturbances and reference signals.

The Kisumu –Kibos line is operating close to its operating capacity by 87.1% showing that future increase in loads will not be sustained considering it's a single circuit line. To curb this, doubling its loadability is advised through adding another parallel line. This is achievable since the Kisumu-Kibos is only 2km long. This will go a long way in ensuring the reliability and continuity of the power supply for the Western Region. There is an overloading on the transformer connecting the 33kV bus to the Loiyalangani bus; hence 2 parallel transformers were added to assist in the loadability of the line which improved from 233.1% to 78.5%.

4.2.2 Results of Simulation of Line Outages for scenario 1.

A contingency analysis on line outages was performed and 183-line outages were simulated. The results are indicated in the next sub-sections.

4.2.2.1 Outage of Tororo- Lessos Transmission Line.

The loss of the Tororo- Lessos Transmission Line affected the voltage at the Tororo bus to 0.031p.u. This is because the Bujagali generator is under excited hence draws reactive power from the Tororo bus. The Bujagali generator requires approximately 34.8MVAR in order for the bus voltages to be regulated to normal levels. A capacitor bank with a rating of 30MVAR is connected to the Tororo bus to regulate the voltages by supplying the required reactive power required to overcome the windage losses of the generator. The outage of the Tororo Lessos transmission line affected the following bus as shown in Table 4.3

Table 4.3 Buses Affected by the Outage of Tororo- Lessos Transmission Line.

Bus Affected by the Outage of Tororo –Lessos Line	Bus Voltage after a Contingency (p.u)	Bus Voltage for Base Case (p.u)
Tororo line	0.031	1.000

4.2.2.2 Outage of Eldoret- Lessos Transmission Line.

The loss of the Eldoret –Lessos transmission line caused the most severe under voltages with Eldoret North bus operating at the minimum voltage of 0.608 p.u. The Moi Barracks and Eldoret North Buses are all connected to the Eldoret 132 Bus which is supplied from the Lessos 132kV via the Eldoret- Lessos transmission line. The loss of this transmission line alters the system's functioning in that the Eldoret North and Moi Barracks buses are supplied from the Turkwell generator. In the base case scenario, the Eldoret 132kV bus is supplied from the Lessos 132kV bus with 27.4MVAR. With the loss of the Eldoret- Lessos line, the reactive power supply is lost. The reactive power received from Turkwell is not enough to meet the demand from Eldoret North and Moi Barracks buses resulting in under voltages in this buses. The outage of the Eldoret - Lessos transmission line affected three buses as shown in the Table 4.4

Table 4.4 Buses Affected by the Eldoret – Lessos Line Outage.

Buses Affected by the Eldoret – Lessos line Outage	Bus Voltage after the Contingency Case (p.u)	Bus Voltage For Base Case (p.u)
Eldoret North	0.608	0.961
Eldoret 132kV	0.612	0.963
Moi Barracks	0.655	0.968

To curb this effect, it is recommended that and automatic switchable 30MVAR capacitor to be installed at the Eldoret 132kV bus or the Eldoret North bus, to regulate the voltages of the adversely affected buses following the contingency. The capacitor addition to either of the buses improves the voltages at the affected buses which can be seen after running the contingency analysis simulation.

A more cost-effective short-term alternative with minimal supply interruption would be to take Eldoret North bus out of service following outage of the Eldoret- Lessos transmission line. This is because it reduces reactive power demand by 11.8MVAR and raises the bus voltages of Eldoret 132kV and Moi Barracks buses to 0.99p.u. The voltages may be improved further by taking the Moi Barracks load out of service to serve as a remedial action. The second recommendation is not advisable since load shedding would not be taking care of the problem on a long-term basis and may affect the customer services in the load shedded areas.

4.2.2.3 Outage of Loiyangalani- Suswa- Silali- Rumuruti 400 kV Transmission Lines

From the design we can see that outage of any of the transmission lines isolates the Maralal load, Silali power plant and the Lake Turkana Wind farm from the rest of the grid. The loss of this plants will affect the Nyahururu bus which supplies other loads in the grid. Table 4.5 shows the bus voltages range from 0.686 to 0.854 p.u. The effect of the under voltages is also caused by the reactors placed on the Suswa and Rumuruti 400kV buses. The reactors initial use was to step down the voltages to acceptable levels at the receiving end of the Suswa- Loiyangalani line, Rumuruti-Rumuruti line. Under normal operating conditions, high voltages from the Suswa and Loiyangalani buses arise from the Ferranti effect. Ferranti effect is the situation whereby at no load or at minimal loads, the receiving end voltage of a transmission line is higher than the sending end voltage resulting from high line capacitance .Ferranti effect is usually seen in long transmission line whose length increases the capacitance, in lines which are loaded below the surge impedance load and in underground lines. Under normal operating conditions, the reactive power injected into the

Rumuruti 400kV bus is 132.5MVAR of which 106.1MVARis absorbed by the 100MVAR reactor that is installed at the bus. Buses that experienced under- voltage following the outage of the above stated transmission lines are shown in Table 4.5.

Table 4.5 Effect of Outage of Loiyangalani- Suswa- Silali- Rumuruti 400 kV Transmission Lines

Buses affected by the Outage of Loiyangalani-Suswa-Silali-Rumuruti 400kV Line	Bus Voltages after Contingency Case (p.u)	Bus Voltages for Base Case (p.u)
Rumuruti	0.686	1.008
Nyahururu	0.687	0.994
Rumuruti 132	0.691	1.007
Nanyuki	0.722	0.993
Isiolo	0.724	0.995
Maua	0.744	0.981
Othaya	0.745	0.975
Kiganjo 132	0.752	0.982
Meru	0.753	0.986
Prop Othaya	0.802	0.981
Kutus_T1	0.832	0.983
Kutus 132	0.851	0.984
Kyeni	0.854	0.988

When the 400kV line outage takes place, the reactive power previously being injected by these lines ceases to exist. As a result, the reactors draw reactive power from surrounding buses.

Now,

$$\Delta V = (RP + XQ)/V \qquad (4.1)$$

Practically R<<X, Hence

$$\Delta V \approx XQ/V \qquad (4.2)$$

Where R is the line resistance, X is the line reactance, P is the real power, Q is the reactive power and V is the Voltage.

From equation 4.2, voltage magnitude of a bus is approximated to be directly proportional to the reactive power, hence, a decrease in reactive power lowers bus voltage. The reactors placed in the 400kV buses absorb reactive power from the adjacent lines and greatly reduce the bus voltages in transmission lines.

4.2.2.4 Outage of Gilgil – Naivasha 132kV Transmission Lines

The Gilgil – Naivasha transmission line consists of 2 parallel lines that inject 16.6MVAR that is absorbed by the loads in the Nakuru West bus and Lanet 132 bus. This makes Gilgil- Naivasha transmission line very crucial, since loss of either of the lines causes a deficit of supply of reactive power to these loads. Since when the reactive power reduces, the bus voltages in these buses also reduces.

Table 4.6 Effect of Outage of Gilgil – Naivasha Line

Buses Affected by the Outage off the Gilgil- Naivasha Line	Bus Voltages after the Contingency Case (p.u.)	Bus Voltage for Base Case (p.u.)
Gilgil Tee1	0.889	1.004
Gilgil Tee2	0.890	1.005
Lanet 132	0.893	0.994

There are two ways to solve the under voltages experienced. The most cost effective and quickest action to remedy the under voltages following the contingency is load shedding. That is by either disconnecting the Lanet 132 load or the Nakuru West load, which will minimize the reactive power demand by 24.6MVAR and 14.8MVAR respectively.

Table 4.7 Effect of Loss of Loads on the Bus Voltage.

<table>
<tr><th colspan="4">Scenario 1 : Lanet Load offline</th></tr>
<tr><td>Bus</td><td>Gilgil Tee1</td><td>Gilgil Tee 2</td><td>Lanet 132</td></tr>
<tr><td>Voltage (p.u.)</td><td>1.03</td><td>1.03</td><td>1.03</td></tr>
<tr><td colspan="4">Scenario 1 : Nakuru West Load offline</td></tr>
<tr><td>Bus</td><td>Gilgil Tee1</td><td>Gilgil Tee 2</td><td>Lanet 132</td></tr>
<tr><td>Voltage (p.u.)</td><td>1.02</td><td>1.02</td><td>1.01</td></tr>
<tr><td colspan="4">Scenario 1 : Lanet & Nakuru West Loads offline</td></tr>
<tr><td>Bus</td><td>Gilgil Tee1</td><td>Gilgil Tee 2</td><td>Lanet 132</td></tr>
<tr><td>Voltage (p.u.)</td><td>1.05</td><td>1.05</td><td>1.05</td></tr>
</table>

From Table 4.7, simultaneously taking both loads out of service or either of the loads will improve the system voltages of the affected buses and return them to stable values. The Lanet load also serves as a proper location for injection of additional generation or a shunt capacitor of 20MVAR to help in stabilizing the voltages at the affected buses. This will maintain bus voltages of Lanet 132, Gilgil Tee1, Gilgil Tee 2 and also Nakuru West buses to acceptable levels. The addition of a generator or a shunt capacitor maybe costly but is a long term solution to the contingency and will avoid customer complains due to load shedding. Load shedding may also reduce revenues from utility companies and also violates the N-1 criterion since it interrupts continuity of supply and service.

4.2.3 Discussion and Analysis of Results for Cases of Overloading for Scenario 1.

For results analysis, 183 line outages were simulated. The individual contingencies, overloaded components affected by this contingency, their impacts and recommendations on how to mitigate these effects have been discussed below.

4.2.3.1 Outage of Naivasha – Olkaria 1 Transmission Line.

The effect of the outage of Naivasha-Olkaria 1 transmission line is a major one because the Naivasha – Olkaria I transmission line has only one line and the Olkaria transformer is only one. The overloading would lead to tripping of the Olkaria II transformer and later on isolation of the Olkaria 1 – Olkaria 2 transmission line due to overheating of the line. This will inevitably lead to the 206.9MW from Olkaria 1 A.U being lost hence blackouts from very many regions in the system. Table 4.8 shows the overloaded components resulting from the loss of Naivasha-Olkaria 1 line.

Table 4.8 Overloaded Components Following the Outage of Naivasha – Olkaria 1 Transmission Line.

Overloaded Components	Loading Contingency Case (%)	Loading Base Case (%)
Olkaria II Transformer	230.2	59.5
Olkaria 1 – Olkaria 2 transmission line	125.9	32.5

To curb the loss of Naivasha –Olkaria 1 line, it is necessary to add another set of parallel lines to offer backup protection for the Naivasha – Olkaria 1 transmission line in case other lines fail. Addition of a parallel transformer to the Olkaria II transformer is also required to go hand in hand but the solution will not hold but will be a temporary solution.

Alternatively, a new generation should be injected at Naivasha 132kV bus to reduce dependency of Ruaraka, Lanet and Nakuru West loads on supply from Olkaria 1 A.U. A new generator injecting 70MW into the Naivasha 132kV bus at a voltage of 1 p.u. was added as the Olkaria A.U. was reduced to 130MW. This is done simultaneously with the addition of parallel transmission line for Olkaria 1 – Olkaria 2 transmission and Olkaria II transformer. Doing this averted the overload on the two parts and handled the contingency.

4.2.3.2 Outage of the Kisumu - Kibos Transmission Line

The Kisumu – Kibos transmission line serves as a crucial link between the loads in Western Kenya and the generation from the Olkaria geothermal fields, delivering 95.4MW from these fields to the loads in Western Kenya. An outage of this line triggers increased generation from other nearby generators which are the Sondu generator and the Sangoro generator. The power from Olkaria II generator and OR power that supply the Olkaria II bus is redirected and flows to the Lessos 132kV bus hence overloading the Lessos transformer. Table 4.9 shows an overloaded component following the loss of Kisumu –Kibos line.

Table 4.9 Overloaded Component Resulting from the Outage of the Kisumu - Kibos Transmission Line

Overloaded components as a result of outage of Kisumu-Kibos line.	Loading after the contingency case[%]	Loading - Base case
load in Lessos transformers	150.0	93.6

Under normal operating conditions, the Kisumu – Kibos transmission line transmits 95.7MW (93.6% loading) injected on the Kibos bus to Kisumu. This implies that the line operates close to its limits prior to the contingency. Thus a slight increase in loading could cause it to be overloaded. It was also noted that the outage of the Kisumu – Kibos transmission line causes an overload of the Lessos transformers.

Taking into consideration the costs, the most economical option to tackle the violations arising from the outage of the Kisumu – Kibos transmission line or overloading of the Kisumu – Kibos transmission following other contingencies is to strengthen this line. This can be done through increasing its loadabillity by stringing an additional parallel line. Doing this doubles its loadability and allows it to ride out increased power flow arising from other contingencies. Additionally, the extra line serves as a backup line in case the other one fails thus improving the reliability of supply of power to the Western region of Kenya. The Lessos transformers are also affected not only by the Kisumu – Kibos line, but also other interconnected lines. Increasing the number of Lessos transformers increased the loadability.

4.2.3.3 Outage of the Loiyangalani- Suswa Transmission Line

This contingency removes Lake Turkana Wind Power, Silali Generator and the Maralal load from the system resulting in a net loss of 448.2MW of generation. In practice, the sudden loss of 448.2MW of generation would likely throw the entire Kenyan power system and the Ugandan power system into instability because of their interconnection. Table 4.10 shows a list of Overloaded components from the outage of Loiyangalani –Suswa line.

Table 4.10 Overloaded components from the outage of Loiyangalani –Suswa transmission line

Overloaded Components	Loading after the Contingency Case[%]	Loading - Base Case
Olkaria II transformer	239.6	230.1
Olkaria 1 – Olkaria 2 transmission line	131.0	125.8
Olkaria 2 – Suswa 2	120.3	42.1
Olkaria 2 - Suswa	120.3	42.1
Tororo – Lessos transmission line	104.8	52.7

The Loiyangalani –Suswa transmission line being the longest and the interconnector to other lines and buses should be monitored, inspected and maintained regularly to lower the probability of these contingencies. The number of parallel lines in the Loiyangalani- Suswa line could be increased to improve the loadability of the line and ensure there is a backup in case one line fails.

A second less viable alternative following either of these contingencies is to carry out load shedding on several load buses to match the 448.2MW of generation lost. This solution is impractical and is therefore not recommended.

4.3 Scenario 2: Minimal Generation from Thermal Plants

In this scenario, the system was modelled to incorporate little generation from thermal power Plants as possible. The following modifications were made to the base case to achieve optimal generation with minimal output from thermal sources:

(i) Load was scaled down to 87%

(ii) All generators were in service except Kipevu 1, Kipevu 2, Kipevu 3, Rabai power and Thika power thermal plants.

(iii) The Ruaraka capacitor was taken out of service.

32 generator outages were simulated and Kwale SC generator and Olkaria IV generator failed to converge. There were no components affected by maximum voltage violations but there were minimum voltage and loading violations observed. Following a simulation of the load flow of this system for Scenario 2, the system summary is as shown in table 4.11.

Table4.11 Total System Summary for the Kenyan Power System in Scenario 2

Total Energy	Power Generated	PQ Load	Line Charging	Grid Losses
MW	1710.20	1629.78	-	80.42
MVAR	507.84	1078.30	-1647.77	-1060.27
Installed Capacity – 2490.52MW Spinning Reserve – 908.33MW				

4.3.1 Components affected by Generator contingencies

4.3.1.1 Outage of Silali Generator

Table 4.12 shows the buses that experienced under voltages following the outage of the Silali Generator for the scenario with minimal generation from thermal plants. The contingencies shown are as a result of the disconnected thermal plants. The power quality and voltage profiles are affected in various interconnected buses since the system is radial in nature. The Silali generator injects power to various loads in the system and hence its failure affects very many buses and voltage profiles. To solve this, a generator at a sub transmission level is required to be installed in order to improve the voltage profile at the load buses. Rabai 132kV bus is main bus that connects all the affected bus bars, hence a connection of two 70.1MW generator at the bus in parallel to assist in catering for the loads in the affected buses and also improve the voltage profile. Injection of this two generators on the Rabai 132kVbus improved the voltage levels to a range of between 0.90 to 0.95p.u and stabilized the system to be able to withstand fault levels. This move also removes the contingencies caused by losses of other generators.

Table 4.12 Buses experiencing under voltages following the outage of Silali Generator

Buses that experienced under voltages following the outage of the Silali generator	Bus Voltage after the contingency case (p.u.)	Bus voltage for base case (p.u.)
Prop Mbaraki	0.694	0.760
Kipevu 132	0.699	0.764
Kipevu 2 132	0.702	0.767
Jomvu	0.710	0.774
Likoni 132	0.722	0.786
Titanium 132	0.722	0.788
Likoni Tee	0.724	0.788
Galu	0.725	0.790
Rabai 132	0.725	0.788
Kokotoni	0.726	0.788
Mariakani 132	0.730	0.792

Samburu	0.738	0.799
Kilifi	0.745	0.810
Kwale SC	0.748	0.812
Maungu	0.755	0.812
Taveta	0.755	0.812
MSA CEM	0.757	0.821
Vipingo Ring	0.757	0.819
Mtwapa	0.758	0.818
Lamu	0.760	0.822
Voi	0.762	0.818
New Bamburi 132	0.769	0.827
Manyani	0.777	0.830
Garsen	0.777	0.838
220kV	0.783	0.839
Malindi	0.791	0.848
Rabai 220	0.793	0.847
Mtito Andei	0.799	0.848
Mariakani 220	0.812	0.864
Makindu	0.824	0.866
Kiboko	0.829	0.869
Sultan Hamud 132	0.848	0.885
S_Hamud Tee	0.851	0.887
S_Hamud New	0.852	0.887
Kajiado	0.857	0.892
Machakos 132	0.858	0.892
Namanga 132	0.857	0.893
Ulu	0.860	0.895
Konza 132	0.862	0.896
Wote	0.864	0.895
Isinya 400	0.881	0.918
Kitui 132	0.881	0.907
Githambo	0.884	0.911
Isinya 220	0.891	0.925
Gatundu	0.892	0.919
Loiyangalani	0.894	0.948
Thika Road	0.894	0.923
Tatu City 3	0.896	0.923
Athi River	0.896	0.927
Mangu	0.897	0.924
Thika 132Kv	0.897	0.924

Othaya	0.898	0.933
Embakasi -CC	0.898	0.928
Embakasi 220	0.899	0.928
Matasia BSP	0.899	0.929
Komarock	0.899	0.927
Nyahururu	0.900	0.944
Nairobi North 220	0.900	0.929

4.4 Scenario 3 (55% Loading)

In this scenario, it was intended to simulate low loading conditions (off – peak load) and assess the security of the system. It was also modelled to represent the system on light load. The following modifications were made to the base case to achieve this scenario:

(i) All capacitors were turned off

(ii) All loads were scaled to 55%

(iii) All generation apart from Lake Turkana plant was scaled to 55%

Following a simulation of the load flow of this system (Scenario 3), the system summary of the same is shown in table 4.13 where installed capacity remained at 2815.5MW just as the initial point when the load flow analysis was performed. This is because no generator was added. However, the spinning reserve values decreased from 1041.35MW to 854.30MW. Grid losses increased from a value of 64.68 to a value of 182.16. MVAR values changed from 218.99 to -128.48, this is because all capacitors were turned off before running simulation.

Table 4.13 Total System Summary for the Kenyan Power System

Total	Generation	PQ Load	Line Charging	Grid Losses
MW	2048.53	1866.37	-	182.16
MVAR	-128.48	1073.80	-2359.59	-1202.28
Installed Capacity – 2815.50MW Spinning Reserve – 854.30MW				

32 generator outages were simulated. Lake Turkana wind plant and Olkaria 1 A.U. did not converge. There were maximum voltage violations and loading violations after the simulation.

4.1.1 Contingencies due to Loading Violations

4.1.1.1 Outage of Sondu Generator

Due to reduced generation from the Sondu generator, loads connected to the Sondu 132 bus bar are affected leading to other generators stepping in to fill in for extra generation. 7.2 MW is received from the Kisumu 132kV bus to assist in supplying the loads connected to the Sondu 132Kv bus. Loss of Sondu generator will make generation from the Kisumu 132kV bus should increase to cater for the load. This affects the loadability of the Kisumu – Kibos transmission line. The same goes for the Lessos transformer, Olkaria 2- Suswa transmission line, Olkaria 2- Suswa 2 transmission line and the Silali 11/132kV transformer. Addition of parallel components in each case assist in loadability of the components and also security in cases of loss of one of the lines ensuring the customers are not left in a blackout or system operators are not forced to shed some loads. It is recommended that for the components affected, components in parallel should be added to improve the static security of the system. Table 4.14 shows a list of Overloaded components affected by the outage of Sondu Generator.

Table 4.14 Overloaded Components Affected by the Outage of Sondu Generator

Overloaded Components	Loading – Contingency Case[%]	Loading - Base Case
Kisumu- Kibos transmission line	145.0	131.1
Lessos transformer	128.5	122.1
Olkaria 2 – Suswa transmission line	107.6	106.0
Olkaria 2- Suswa 2 transmission line	107.6	106
Silali 11/132kV transformer	101.6	100.8

4.4.1.2 Outage of Silali Generator

The Silali generator supplies 74.9MW to the Loiyangalani- Suswa 400kV transmission line at a distance of 107km which is then transmitted to loads connected to Suswa 400 bus. Loads connected to adjacent bus bars will draw power from other generator close to the Suswa 400 bus bar. This load strains the transformers transmitting the power; since their ratings are not able to handle such loading. Redundancy in components assists in handling loading and also act as a backup in cases of loss of a component. Table 4.15 shows a list of overloaded components affected by the outage of Silali Generator.

Table 4.15 Overloaded Components Affected by the Outage of Silali Generator

Overloaded components affected by the outage of Silali Generator	Loading after the Contingency case[%]	Loading - Base case
2- winding transformer	105.5	99.2
Isinya 2 220/400 transformer	102.4	81.9
Rabai 220/132 transformer	102.3	93.2

4.4.2 Outages due to Voltage Violations

Voltage violations experienced in this scenario greatly affect areas where reactors and capacitors were located. Capacitor banks assist in regulating voltages in power systems and since they were disconnected, under voltages and over voltages are experienced in the system making it unstable. Over voltages are mainly in bus bars with very high voltages being transmitted over long distances; a condition called Ferranti effect.

4.5 Validation

In a long time Southern Africa encountered power shortage resulting from several factors which led to a decline in generation reserve capacity against an expanding growth in demand of power supply in the member countries as well as load increase in areas not adequately planned for. This led to the formation of organizations such as SADC (Southern African Development Community) and SAPP (Southern African Power Pool) whose collective goal of realizing development and economic growth in the region. This is an undesirable situation and has a negative impact on industries, social services, trade and overall economic development of the region. Power outages and poor quality of supply are often the result of insufficient generation capacity or poor functioning of the power system [20].

The study aimed at alleviating the problem by conducting a steady –state contingency study on the SADC power network model subject to the N-1 criterion. The study done presented results from a security analysis of the region's electric power supply system using a baseline level of performance carried out by performing a steady-state contingency analysis on a SADC power grid [20].

In carrying out the assessment of SADC power grid security status, a contingency analysis was performed on the design model based on the assumptions that, this was a steady-state simplified analysis. The CA carried out showed that, in the event of a major disturbance (or fault) in any one component of the grid will result in overloading several interconnections making the network not secure. In extreme contingencies, this will lead to violations of statutory voltage and thermal limits. Electricity demand in the SADC region continues to grow each year partly due to population growth. However, initiatives taken by governments in the region to aggressively invest in new power generation infrastructure will assist in alleviating the problem of electricity shortages, while, increasing power accessibility. The initiatives will improve the reliability of the SADC power network and reduce the power deficit in the region. Proposed solutions included increasing generation capacity of member countries, strengthening existing delivery systems, and providing more strategic interconnections to facilitate power exchange between the member states [20].

In Kenya, contingency analysis of the power system has not yet been done making this research the first. The analysis aims to detect reliability and vulnerability of the power systems. Analysis done in other countries has mainly been on losses of transmission lines. The aim was to maintain bus voltages at a range of between 0.95p.u and 1.05p.u. From the analysis in chapter 4, we have seen that the loss of a component affects either loading of the line or the bus voltages. Variations in these values i.e., between the base case values and the contingency values shows the extent the system becomes unstable. Due to the power outages often experienced, there was need to perform an (N-1) Contingency analysis to curb outages and load shedding.

4.6 Chapter Conclusion

From the above, we have seen that most components in the system are operating close to their limits hence making the system unstable. During normal functioning, most of the transformers and transmission lines are loaded between 80 – 90 percent, which limits room for expansion in terms of addition of loads. Loss of a line is likely to occur due to extreme temperatures caused by high currents that can lead to short circuiting of the line. Most generators have been overloaded following a contingency on the system making the system unreliable. There need to add more generation mainly renewable so as to curb the emissions to the ecosystem is a priority. This will also help in removing thermal plants from the system which emit gases that destroy the environment and global warming concern.

CHAPTER FIVE

5.1 Conclusions

Renewable energy mix sources addition to the power grid, has compelled researchers to do contingency analysis on power systems. The intermittency of these energy sources has caused rampant instabilities on the systems hence the need to develop a secure robust system that is reliable.

It was noted that the contingencies in the base case encompassed those in Scenario 2 and Scenario 3. Analysis done when the generators are loaded at 55% showed the greatest stability followed by the one with low participation of thermal generation plants.

In summary, the following are the proposed changes to the Kenyan Power System to improve its static security based on the (N-1) contingency analysis done. This is while considering both line outages and generator outages for all the scenarios and taking into consideration the costs, the most economical option to tackle the violations arising from the outage of the Kisumu – Kibos transmission line or overloading of the Kisumu – Kibos transmission following other contingencies is to strengthen this line. This can be done through increasing its loadabillity by stringing an additional parallel line. Doing this doubles its loadability and allows it to ride out increased power flow arising from other contingencies. Additionally, the extra line serves as a backup line in case the other one fails thus improving the security of supply of power to the Western region of Kenya. It is also good in case of future increase in loading .The Lessos transformers are also affected not only by the Kisumu – Kibos line, but also other interconnected lines. Increasing the number of Lessos transformers increased the loadability.

It is recommended that the Suswa –Loiyangalani 400kv lines be regularly monitored, inspected and serviced to minimize the probability of an outage which lead to catastrophic system failure and will plunge the entire country to darkness. The number of parallel lines in the Loiyangalani-Suswa line could be increased to increase the loadability of the line and ensure there is a backup in case one line fails. The Loiyangalani –Suswa transmission line being the longest and the interconnector to other lines and buses should be maintained regularly.

Addition of a redundant parallel line for the Naivasha- Olkaria line to assist in loadability of the line and also in case of a contingency. This is because the Naivasha – Olkaria I transmission line has only one line and the Olkaria transformer is only one. The overloading would lead to tripping of the Olkaria II transformer and later isolation of the Olkaria 1 – Olkaria 2 transmission line due to overheating of the line. This will inevitably lead to the 206.9MW from Olkaria 1 A.U. being lost hence blackouts from very many regions in the system. It is thus necessary to add another set of parallel lines to offer backup protection for the Naivasha – Olkaria 1 transmission line in case other lines fail. Addition of a parallel transformer to the Olkaria II transformer is also required to go hand in hand but the solution will not hold but will be a temporary solution.

Alternatively, a new generation should be injected at Naivasha 132 bus to reduce dependency of Ruaraka, Lanet and Nakuru West loads on supply from Olkaria 1 A.U. A new generator injecting 70MW into the Naivasha 132Kv bus at a voltage of 1 p.u should be added.

Addition of a generator at the Rabai 132kv bus to act as a sub transmission level generator to improve voltage levels and power quality for a situation where all thermal plants are not in operation. The generators added should be 70.1MW and in parallel with each other.

It was noted that addition of parallel transformers to the Lake Turkana plant is also required. This will assist in power carriage and reactive power injection. Addition of the parallel transformers assists in loading hence improving the static security of that line.

In general, the whole systems components mainly transmission lines and transformers need to be made redundant through addition of similar components in parallel to improve the static security of the system as a whole.

The projected Kenyan Power System was successfully modelled and a load flow of the base case scenario carried out to ensure static security of the system. (N-1) contingency analysis of the same system considering generator and line outages was done using the DIgSILENT PowerFactory 15.1 simulation software. Based on the results of the contingency analysis, several changes to the system proposed improved the static security of the system and their effectiveness was tested and proven through simulations. Hence, the analysis of the project was considered successful.

5.2 Recommendations for Further Work.

In this project, the static security assessment of the projected Kenyan power system for the three scenarios was achieved using the contingency analysis tool in DIgSILENT. From the results in chapter 4, further research is required to be done for the system considering the following:

a) Modelling of three- winding transformers on the system to consider the improvement of the system and test whether the loadability factor will be solved. Three winding transformers are new in the market and the difference between 2-winding and 3-winding is basically the number of winding sets wrapped on the same core leg of the magnetic circuit, in the case of a 2-winding transformer, there are two sets. A three winding transformer has three sets. Each winding set will produce voltage when an alternating magnetic flux is present in the core leg of the magnetic circuit. This type of transformers are commonly used in large renewable energy generation systems like wind and solar.

b) Assessing of the static security of the system using the CA tool during dry seasons when generation from the Hydro plants is low. In my research, the assumption was generation from hydro plants was constantly at maximum.

c) Analysis of the dynamic security of the system for all three scenarios to observe how the system behaves.

d) Analysis of the loadability improvement of the Kenyan Transmission System with the use of High Temperature Low Sag conductors.

e) To perform an (N-2) Contingency Analysis after the improvements to the system are done.

5.3 Contributions.

Static security assessment of the Kenyan power system contributes to pro-active style of power management in a country because the national grid operations requires to be carried out very urgently in order to be of any use to the operators. Having a system that helps the system operator to predict a loss of a component is very important because by being pro-active means the system installed detects a possible future system outage hence the need to prepare first hand for an eventuality. N-1 contingency Analysis will therefore make the system planners to be better prepared to react to system outage by using pre-planned recovery strategies.

Currently voltage stability affects the security state of the Kenyan power systems due to fluctuations of voltage and increasing in loading around the country. A contingency study was done before to evaluate the voltage stability of the Kenyan Power System using the N-1 criterion where the focus was on the Nairobi North to Dandora line. The results showed that removal of the line affected the power transferred downwards.

Safe, reliable and quality power transmission is the other major contribution brought by static security assessment. In this project, a complete contingency analysis of the Kenyan Power System has been modelled and a detailed contingency ranking structure presented through which troublesome and unsteady situations in the system can be identified, operating constraints and limits can be applied and corrective actions can be planned. Thus, the results of CA will help the components of our System to be operated more safely and effectively.

(N-1) security criterion simply means we ensure generators are operated at optimum capacity so that the spinning reserve can that takes up the loss is greater than the largest generator's capacity in the power system. Generator losses affect both transmission line and other generator's operating conditions, hence, the remaining generators should compensate the inadequacy of a transmission line or transformer outage.

Low maintenance costs and increased customer satisfaction are the other benefits brought about by a secure Power system and reliability. Lower reliability resulting from frequent power outage, affects energy supply continuity brings dissatisfaction from the customers and is detrimental to a business .The price to pay for low reliability or poor system qualities are enormous and can be largely avoided by improving the level of static security.

Power System Reliability has a high priority in power systems, especially in large interconnected modern power systems with a possibility of wide spread blackouts. The essence of CA is to ensure a system is designed according to reliability constraints i.e. power systems have enough generation systems to meet the loads and adequate transmission lines to deliver the power from the generators to the load. The power system should be designed to operate with no violation in their constraints when there is a component failure on the system, based on the N-1 contingency rule.

REFERENCES

[1] L. Wu, J. Gao, Y. Wang and R. G. Harley, "A survey of contingency analysis regarding steady state security of a power system" , 2017 North American Power Symposium (NAPS), 2017

[2] J. P. V. A. e. a. P. Kundur, “Definition and Classification of Power System Stability,” in IEEE/ CIGRE Joint Task Force on Stability Terms and Definitions, IEEE Trans Power System, vol. 19, no. 3, 2004, pp. PP. 1387-1401.

[3] A. K. Roy, “Contigency Analysis in Power System,” ResearchGate, July 2011.

[4] J. E. C. CIGRE TF 38-03-12 (R.J. Marceau, “Power System Security Assessment:

A Position Paper,” Vols. No. 175, Electra, pp. pp. 48-78, December 1997.

[5] K. Patra, Contigency Analysis in Power System using Load Flow Solution no. 0975-8887, International Journal of Computer Application, pp 1-4, 2015.

[6] DigSILENT GmbH, “Contingency Analysis,” in DigSilent PowerFactory, Gomaringen, Germany, Digsilent Powerfactory, 2014, pp. 653-686.

[7] K. L. T. V. V. Peter W. Sauer, “Dynamic Security Assessment,” 1 May 2007. [Online]. Available: www.researchgate.net/publication/267201754_Dynamic_Security_Assessment. [Accessed 25 July 2018].9

[8] Power Africa, “Development of Kenya's power sector 2015-2020,” Power Africa, Nairobi, May 2016.

[9] P. J. I. C. I. A.E. Airoboman, “Contingency Analysis on the Nigerian Power Systems Network,” Institute of Electrical and Electronic Engineering (IEEE), Nigeria, 2019.

[10] A. Roy, Contigency Analysis In Power System, Patiala: Thapar University, 2011.

[11] O. A. A. M. B. Stott, “Security Analaysis and Optimization,” Proc. IEEE VOL 75, no. 12, 1987, pp. pp. 1623-1644.

[12] Y. Salami, “Multiple Contigency Analysis of Power Systems,” St Johns Newfoundland and Labrador, Canada, October 2017.

[13] Robak, S., Machowski, J., & Gryszpanowicz, K. (2017). Contingency selection for power system stability analysis. 2017 18th International Scientific Conference on Electric Power Engineering (EPE), 1-5.

[14] K. K. Patra, “Contigency Analysis in Power System using Load Flow Solution,” International Journal of Computer Applications, no. 0975-8887, pp. 1-4, 2015.

[15] A. M. e. al, Power System Contigency Analysis to detect Network Weaknesses, Zaytoonah University International Engineering Conference on Design and Innovation in Infrastructure, 2012.

[16] C. C. e. al, “Analysis in Restructured Power Systems,” International Journal Research and Development, vol. volume 2, no. Issue 11, pp. 109-118, 2013.

[17] Souag, Slimane & Benhamida, Farid & Salhi, Yacine & Bendaoud, Abdelber & Gherbi, F.Z.. (2013). Sensitivity factor for power system security analysis using LabVIEW. Proceedings of 2013 International Renewable and Sustainable Energy Conference, IRSEC 2013. 385-390. 10.1109/IRSEC.2013.6529671.

[18] O. S. Alvarando F., “Transmission System Operation and Interconnection,” U.S. Department of Energy, National Transmission Grid Study, no. Issue Papers, May 2002.

[19] K. S. O. N. R. G. V. R. Antonio Rota, “Livestock and Renewable Energy,” International Fund for Agricultural Development, October 2012.

[20] R S. J. Mwale and I. E. Davidson, “Security analysis of electric power supply in SADC region,” Africon, vol. 10, no. 1109/AFRCON.2013.6757702, pp. 1-6, 2013.

APPENDICES

A1: Generation Dispatch

The Table A1 below shows the generating units, their types, maximum power they can generate, power dispatched for each of them and their corresponding voltages.

Table A1. Generation dispatch and voltages of various generators

POWER PLANT	TYPE	MAXIMUM POWER(MW)	POWER GENERATED(MW)	VOLTAGE(P.U
KINDARUMA	HYDRO	72.0	30.0	1.015
KAMBURU	HYDRO	94.4	75.0	1.00
MASINGA	HYDRO	40.0	32.0	1.00
KIAMBERE	HYDRO	164.0	100.0	1.00
GITARU	HYDRO	225.3	172.9	1.02
TURKWELL	HYDRO	106.0	90.0	1.00
SONDU MIRIU	HYDRO	60.0	30.0	1.00
SANGORO	HYDRO	21.3	20.0	1.00
OLKARIA I A.U	GEOTHERMAL	281.3	210.0	1.03
OLKARIA II	GEOTHERMAL	160.0	96.6	1.00
OLKARIA III(ORPOWER)	GEOTHERMAL	49.0	36.0	1.01
OLKARIA IV	GEOTHERMAL	400	140.0	1.00
SILALI	GEOTHERMAL	150	140	1.00
NGONG WIND	WIND	25.5	15	1.00
AEOLUS WIND	WIND	60.0	20.0	1.00
KIPETO WIND	WIND	52.0	20.0	1.00
PRUNUS WIND	WIND	52.0	20.0	1.00
LAKE TURKANA	WIND	300.0	125.0	1.00
RABAI POWER	THERMAL	97.5	48.9	1.04
KIPEVU 1	THERMAL	73.5	27.0	1.00
KIPEVU 2	THERMAL	80.7	48.0	1.04
KIPEVU 3	THERMAL	122.9	96.6	0.97
THIKA POWER	THERMAL	87.0	48.0	1.00
KWALE SC	BIOMASS	18.0	15.0	1.00
MUMIAS	BIOMASS	37.5	37.5	1.03

Table A2: Loads

Below is a table listing all the load buses and their corresponding P and Q values used to model the Kenya Power System?

Table A2. Load bus data for the Kenyan Power System

LOAD	P_L(MW)	Q_L(MVAR)		LOAD	P_L(MW)	Q_L(MVAR)
ATHI RIVER L.	-3	9		KONZA L.	6.1	4
AWENDO L.	4.7	3		KUTUS(1)	4.9	18.4
BAMB L.	36.6	22.4		KWALE L.	34.8	24.6
BOMET L.	9.1	5.9		KYENI L.	13.1	5.7
CHAVAKALI L.	22	16.2		LAMU L.	4.2	2.6
CHEMOSIT L.	19	14.2		LANET L.	7.3	4.5
ELDORET L.	18	11.8		LESSOS L.	0.5	0.2
ELDORET NORTH LOAD	159.3	69.3		LIKONI L.	9	6
EMBAKASI L.	25.2	17.2		MACHAKOS L.	16.4	11.2
GALU L.	3.6	2.3		MAKINDU L.	46.4	30.8
GARISSA L.	3.3	2.1		MAKUTANO L.	0.5	0.2
GARSEN L.	8.3	5.6		MALABA L.	0	0
GATUNDU L.	0.3	0.1		MALINDI L.	11	6.1
GILGIL	9.7	6.3		MANGU	0	0
GITARU	0	0.5		MANYANI L.	6.3	4.1
GITHAMBO L.	5.2	3.4		MARALAL 33 Load	0.5	0.2
General Load	5.1	3.1		MARIAKANI 132 L.	18	11.2
HOMA BAY L.	15.5	11.1		MARIAKANI 220 L.	10.2	6.6
ISIOLO L.	65.3	43.5		MASINGA L.	4.4	2.2
JOMVU L.	4	2.6		MATASIA BSP 6	0.5	0.2
JUJA RD L.	6.1	4		MAUA LOAD	15.6	10.2
KABARNET L.	0.8	0.3		MAUNGU L.	20.6	12
KAJIADO L.	3	1.8		MBARAKI L.	6.5	4
KAMBURU L.	0	0		MERU L.	15.8	9.2
KAPSABET L.	6.8	3.6		MOI BARACKS L.	1.7	1.1
KIAMBERE L.	16.4	10.4		MOMB CEM L.	136.2	85.2
KIBOKO L.	21.4	10.6		MTITO A. L.	8	2.8
KIGANJO L.	1.1	0.3		MTWAPA L.	22.4	14.8
KILIFI L.	109.8	84.2		MUHORONI L.	1	0.6
KINDARUMA	21.2	2		MUMIAS L.	12.2	-5.4
KIPEVU	32	-19.9		MUSAGA L.	2.5	1.6
KISII L.	8.4	5.4		MWINGI L.	24.4	23.8
KISUMU EAST L.	21.4	10.6		NAIROBI NORTH L.	5	3.3
KISUMU L.	6.8	4.4		NAIVASHA L.	13.4	8.8
KITALE L.	157.8	93.4		NAKURU WEST L.	30.3	12.7
KITUI L.	5.8	3.6		NAMANGA L.	10.2	4
KOKOTONI L.	17	11.4		NANYUKI L.	49.5	2.4
KOMA ROCK L.	6	2.9		NAROK L.	0.5	0.2
NGONG L.	7.8	5.2		SONDU L.	15.4	9.7
NYAHURURU L.	0.5	0.2		S_HAMUD L.	1.8	1.2
ORTUM L	1.8	0.9		S_HAMUD NEW L.	2.1	1.3
OTHAYA L.	3.8	2.4		TATU CITY L.	164.6	87.8
PROP BONDO L.	137	86.8		TAVETA L.	15.4	10.2
RABAI L.	6	2.9		THIKA ROAD BSP	7.8	5
RANGALA L.	0.5	0.2		TITANIUM	7.6	5
Ruaraka L.	0.5	0.3		ULU L.	31.2	21.2
SAMBURU L.	5.4	2.6		VIPINGO L.	4.6	3
WEBUYE L1+L2	5.2	3.2		VOI L.	27	17.6
WOTE L.	4.4	2.9				

Table A3: Transmission Lines

The Table A3 contains the transmission lines in the Kenya power system, their corresponding types and voltages.

TRANSMISSION LINES	LINE TYPE	LENGTH(KM)	VOLTAGE(KV)
Olk 3- Olk4	Canary 220	7	220
66 Wolf	66 Wolf	10	66
Arusha-Singida	400 3_Canary	320	400
Awendo-Kisii	Wolf 132kv	42	132
Aeolus-Olk	Lynx 132	45	132
Athi River-Isinya	Canary 220	46.3	220
Athi River-Isinya 2	Canary 220	46.3	220
Bamburi-Rabai	220 2_ Canary	22.8	220
Dandora -Kiambere	Canary 220	140	220
Dandora-Emba 2	Canary 220	14	220
Dandora-Embakasi	Canary 220	12.5	220
Dandora-Kamburu	Canary 220	104	220
Dandora-Kamburu 2	Canary 220	110	220
Eldoret- Eldoret North	Lynx 132	5	132
Eldoret-Lessos	Wolf 132kv	32.5	132
Emba Cc-Athi River	Canary 220	8.5	220
Emba-Emba Cc	Canary 220	6.75	220
Emba-Emba Cc2	Canary 220	6.75	220
Enba Cc-Athi River	Canary 220	8.5	220
Galu-Titanium	Wolf 132kv	14	132
Garsen-Malindi	220_300/50 Rmgl	106	220
Gilgil-Gilgil Load	Wolf 132kv	5	132
Gilgil-Naivasha 132	Wolf 132kv	44	132

Galu-Kwale	Wolf 132kv	31.5	132
Garissa-Mwingi	Lynx 132	180	132
Gitaru-Kamburu 1	Canary 132	7.7	132
H.Bay-Awendo	Lynx 132	43	132
Ishiara West-Meru	Canary 132	80	132
Isinya Mariakani	400 4_Lark.	401	400
Isinya-Mariakani	400 4_Lark	401	400
Isinya-Namanga	400 3_Canary	93	400
Ishiara West-Kyeni	Lynx 132	30	132
Isiolo-Nanyuki	Lynx 132	67	132
Jomvu-Kipevu 1	Lynx 132	16	132
Juja-Dandora 2	Canary 132	2	132
Juja-Dandora1	Canary 132	2	132
Juja-Konza	Lynx 132	85	132
Juja-Mangu	Lynx 132	20	132
Kiboko-Makindu	Lynx 132	12	132
Kiganjo -Prop Othaya	Canary 132	6	132
Kipevu 1-Kipevu 2	Lynx 132	2	132
Kisii-Sotik	Wolf 132kv	35	132
Kisumu 132-Kisumu East	Lynx 132	7	132
Kisumu132-Chavakali	Lynx 132	23	132
Kitale-Moi Baracks	Wolf 132kv	43	132
Kitui-Wote	Lynx 132	60	132
Kokotoni-Mariakani	Lynx 132	13	132
Kokotoni-Rabai	Lynx 132	5	132
Kajiado-Namanga	Lynx 132	80	132
Kambur-Gitaru	Canary 220	5	220
Kamburu-Gitaru 2	Canary 132	7.7	132
Kamburu-Ishiara West	Canary 132	44	132

Kamburu-Kiambere	Goat 220	35	220
Kindaruma-Kamburu	Lynx 132	18	132
Kindaruma-Mwingi	Lynx 132	40	132
Kisumu-Kibos	Lynx 132	2	132
Kmarok-Dandora	Canary 220	4	220
Komarok-Dandora	Canary 220	4	220
Konza-Kajiado	Lynx 132	45	132
Konza-Machakos	Lynx 132	20	132
Konza-Ulu	Lynx 132	5	132
Kutus T1-Kutus	Canary 132	18	132
Kutus Tee2-Kutus	Canary 132	18	132
Lamu-Garsen	220_300/50 Rmgl	96	220
Lanet132-Gilgil	Wolf 132kv	25	132
Lessos-Olkaria	Canary 220	220	132
Likoni Tee-Galu	Wolf 132kv	15	132
Likoni Tee-Likoni	Wolf 132kv	14	132
Lesos-Musaga	Wolf 132kv	67	132
Lessos-Kibos	Canary 220	76	220
Lessos-Kibos2	Canary 220	76	220
Lessos-Makutan	Wolf 132kv	50	132
Lessos-Musaga	Wolf 132kv	67	132
Lessos-Muhoroni	Wolf 132kv	56.7	132
Line	Lynx 132	33	132
Line (1)	Lynx 132	38.9	400
Loiyangalani-Suswa	400 3_Canary	170	400
Loiyangalani-Suswa_A	400 3_Canary	251	400
Loiyangalani-Suswa_B	400 3_Canary	260	132
Maaba Tee2-Musaga 132	Wolf 132kv	59	132
Makut-Nak. West 2	Wolf 132kv	56	132

Makutano-Nak. West	Wolf 132kv	56	132
Malaba Tee1-Malaba	Wolf 132kv.	6	132
Malaba Tee1-Musaga 132	Wolf 132kv	59	132
Malaba Tee2-Malaba	Wolf 132kv	6	132
Malindi-Mariakani	220_300/50 Rmgl	108	220
Mangu-Tatu 2	Lynx 132	25	132
Mangu-Thika 132	Lynx 132	0.2	132
Manyani-M. Andei	Lynx 132	55	132
Manyani-Voi	Lynx 132	36	132
Mariak-Rabai	Canary 220	24.1	220
Mariak-Rabai 2	Canary 220	24.1	220
Mariak-Rabai 3	220_300/50 Rmgl	30	132
Moi Baracks-Eldoret	Wolf 132kv	23.6	132
Msa Cement-Kilifi	Wolf 132kv	17.5	132
Mtito.A-Makindu	Lynx 132	68	132
Mtwapa-Vipingo	Wolf 132kv	15	132
Mwingi-Kitui	Lynx 132	60	132
Mangu-Gatundu	Lynx 132	20	132
Mangu-Githambo	Lynx 132	50	132
Mangu-Kindaruma	Lynx 132	80	132
Mangu-Tatu City	Lynx 132	25	132
Masinga-Kiamburu	Canary 132	16	132
Masinga-Kutus	Canary 132	52.3	132
Meru-Isiolo	Lynx 132	25	132
Meru-Maua	Lynx 132	36.8	132
Mumias-Rangala	Lynx 132	34	132
Musaga-Mumias	Lynx 132	27	132
Musga-Webuye	Lynx 132	18	132

Nairobi North-Thika Road	Canary 220	23.25	200
Namanga-Arusha	400 3_Canary	112	400
Nanyuki-Kiganjo 132	Canary 132	52	132
Nbi North-Suswa 2	Canary 220	45	220
New Bamburi-Mtwapa	Wolf 132kv	8	132
Ngong-Matasia Bsp	Canary 220	10	220
Ngong-Suswa 220	Canary 220	50	220
Naivasha-Olkaria 1	Canary 132	23.1	132
Naivasha-Ruarak	Wolf 132kv	72	132
Naivasha-Ruaraka	Wolf 132kv	72	132
Nak. W-Lanet	Wolf 132kv	14	132
Nak. W.-Lanet	Wolf 132kv	14	132
Nanyuki-Kiganjo	Canary 132	52	132
Nanyuki-Nyahururu	Lynx 132	73	132
Olkaria220-Lessos220	Canary 220	220	220
Othaya-Prop Othaya	Lynx 132	18	132
Olk 1-Olk 2	Canary 132	2.9	132
Olk 2-Suswa	Canary 220	23	220
Olk 2-Suswa 2	Canary 220	23	220
Olk 4-Suswa	Canary 220	25	220
Olk 4-Suswa 2	Canary 220	25	220
Olkaria-Narok	Lynx 132	56	132
Ortum-Kitale	Canary 220	91	220
Owen Falls-Tororo	Wolf 132kv	112	132
Prop Mbaraki (1)	Lynx 132	10	132
Prop Othaya- Kutus	Canary 132	30	132
Rabai-Jomvu	Lynx 132	12	132
Rabai-Kiambere	Goat 220	440	220

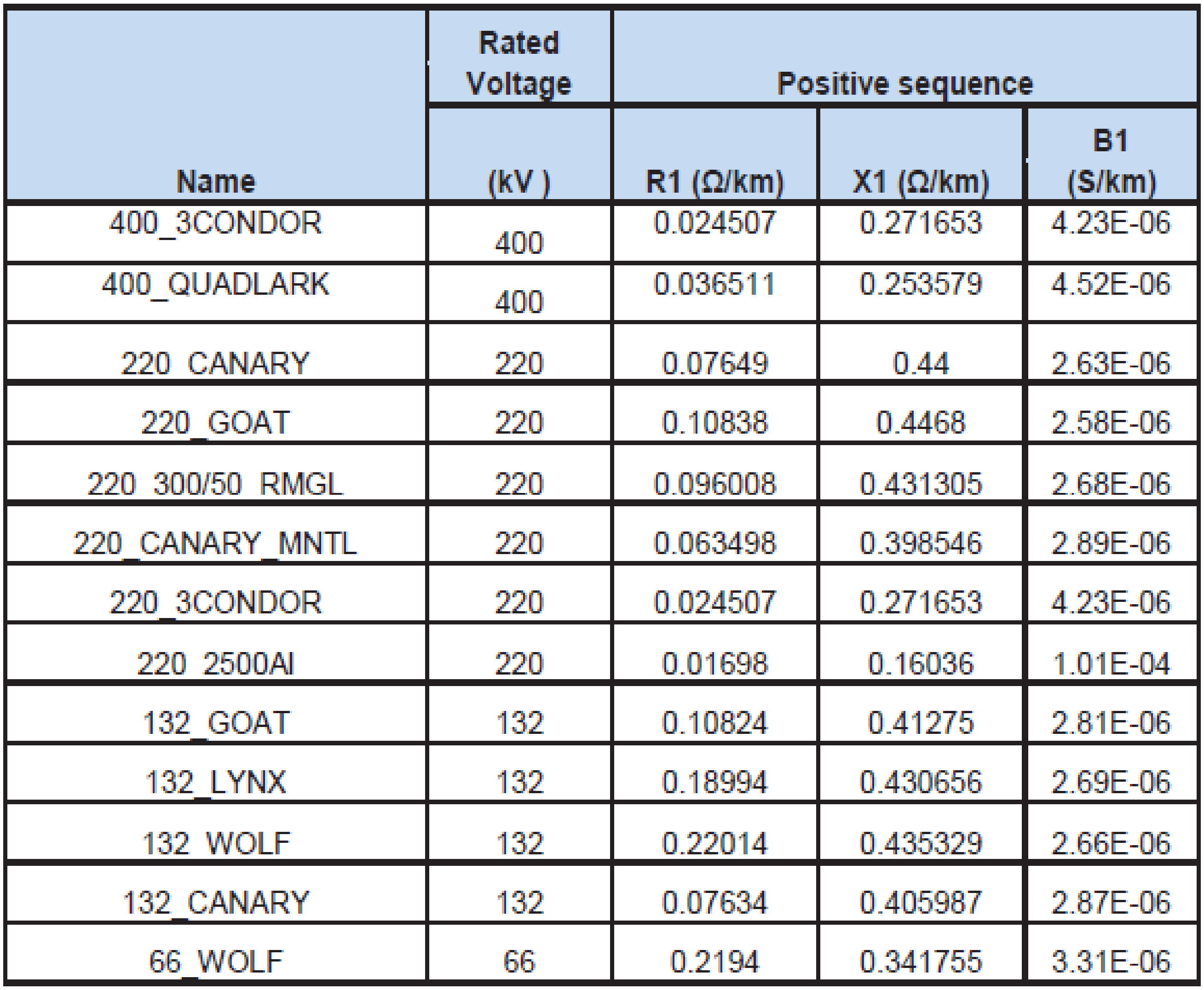
Rabai-Kipevu 1	Lynx 132	17	132
Rabai-Kipevu 2	Goat 132	18	132
Rabai-Kipevu 3	Goat 132	18	132
Rabai-Likoni Tee	Wolf 132kv	17	132
Rabai-Mtwapa	Wolf 132kv	46	132
Rabai-New Bamburi	Wolf 132kv	24.6	132
Rangala-Prop Bondo	Lynx 132	33	132
Rumuruti- Nyahururu	Lynx 132	35	132
Rumuruti-Isiolo	Canary 132	38.9	132
Rumuruti-Loiyangalani	400 3_Canary	10	400
Rangala-Kisumu	Lynx 132	57	132
Ruaraka-Juja	Wolf 132kv	6.5	132
Ruaraka-Juja2	Wolf 132kv	6.5	132
S. Hamud-S. Hamud Tee	Lynx 132	5	132
S.Hamud-Kiboko	Lynx 132	38	132
Samburu-Mariakani	Lynx 132	30	132
Samburu-Maungu	Lynx 132	60	132
Silali-Loiyangalani	400 3_Canary	30	400
Silali-Maralal	Lynx 132	50	132
Suswa-Isinya 3 400	400 3_Canary	97.7	400
Suswa-Isinya 400	400 3_Canary	97.7	400
Suswa-Nbi North 1	Canary 220	45	220
Taveta 132/33	Canary 132	104	132
Tee-S.H New	Lynx 132	5	220
Thika Rd -Dandora	Canary 220	23.25	132
Tororo-Malaba Tee1	Wolf 132kv	15	132
Tororo-Malaba Tee2	Wolf 132kv	15	220
Tororo-Lessos	Canary 220	140.5	220

Turk-Lessos	Goat 220.	228	132
Ulu-S.Hamud New	Lynx 132	35	132
Vipingo-Msa Cement	Wolf 132kv	12.5	132
Voi-Maungu	Lynx 132	30	132
Wote-Hamud	Lynx 132	45	132
Chemosit-Muhoroni	Wolf 132kv	31	132
Kisumu-Muhoroni	Wolf 132kv	49	132
Kisumu-Sondu	Wolf 132kv	50	132
Lessos-Kabarnet	Lynx 132	64.1	132
Lessos-Kapsabet	Lynx 132	7.11	132
Lessos-Makutano	Wolf 132kv	50	132
Owen-Tororo	Wolf 132kv	112	132
Sond-Sang	Wolf 132kv	5	132
Sondu- H.Bay	Lynx 132	55.3	132
Sotik-Bomet	Lynx 132	28.1	132
Sotik-Chemosit	Wolf 132kv	25	220
Sus-Ngong	Canary 220	50	220
Turk-Ort	Canary 220	50	

Transmission line data of the Kenyan Power System

The transmission line parameters for each type of overhead conductor are given in the Table A3.1.

Table A3.1 Transmission line type data



	Rated Voltage	Positive sequence		
Name	(kV)	R1 (Ω/km)	X1 (Ω/km)	B1 (S/km)
400_3CONDOR	400	0.024507	0.271653	4.23E-06
400_QUADLARK	400	0.036511	0.253579	4.52E-06
220 CANARY	220	0.07649	0.44	2.63E-06
220_GOAT	220	0.10838	0.4468	2.58E-06
220 300/50 RMGL	220	0.096008	0.431305	2.68E-06
220_CANARY_MNTL	220	0.063498	0.398546	2.89E-06
220_3CONDOR	220	0.024507	0.271653	4.23E-06
220 2500Al	220	0.01698	0.16036	1.01E-04
132_GOAT	132	0.10824	0.41275	2.81E-06
132_LYNX	132	0.18994	0.430656	2.69E-06
132 WOLF	132	0.22014	0.435329	2.66E-06
132_CANARY	132	0.07634	0.405987	2.87E-06
66_WOLF	66	0.2194	0.341755	3.31E-06

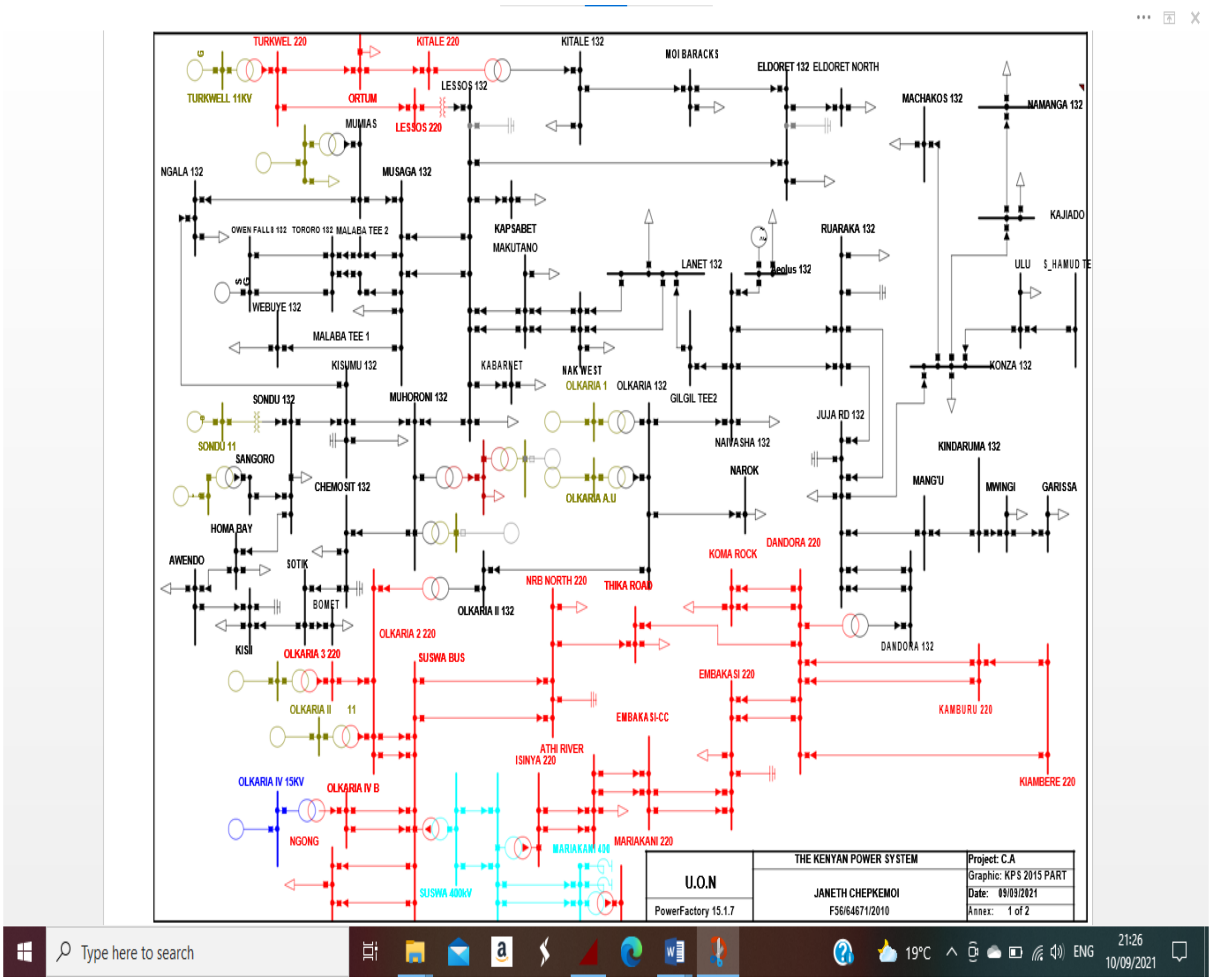
A4: Reactors and Capacitors

The following table lists the reactors and capacitors present in the Kenya power system, their ratings (Q_{max}), operating voltages, buses at which they are connected and service states.

Table A4. Reactors and Capacitors of the Kenyan Power System

component	terminal	service state	nominal voltage(kv)	q_{max} (mvar)
Capacitor	Chemosit 132	On	132	30
Capacitor	Embakasi 220	On	220	100
Capacitor	Juja Rd 132	On	132	190
Capacitor	Kisii	On	132	10
Capacitor	Kisumu 132	Off	132	45
Reactor	Lamu	Off	220	30
Reactor	Mariakani 400	On	400	100
Reactor	Mariakani 400	On	400	100
Capacitor	Nrb North 220	On	220	60
Capacitor	Nanyuki	Off	132	45
Reactor	Rabai 220	On	220	31.5
Capacitor	Ruaraka 132	On	132	50
Capacitor	Galu	On	132	20
Capacitor	Lessos 132	On	132	50
Reactor	Loiyangalani	On	400	175
Reactor	Loiyangalani	On	400	175
Reactor	Rumuruti	On	400	50
Reactor	Suswa 400	On	400	100
Reactor	Suswa 400	On	400	100
Capacitor	Ngong	On	220	70
Reactor	Isinya 400	On	400	175
Reactor	Isinya 400	On	400	175
Singida 400 R1.	Singida	Off	400	200
Singida 400 R2	Singida	Off	400	200

A5. Kenyan Power System 1

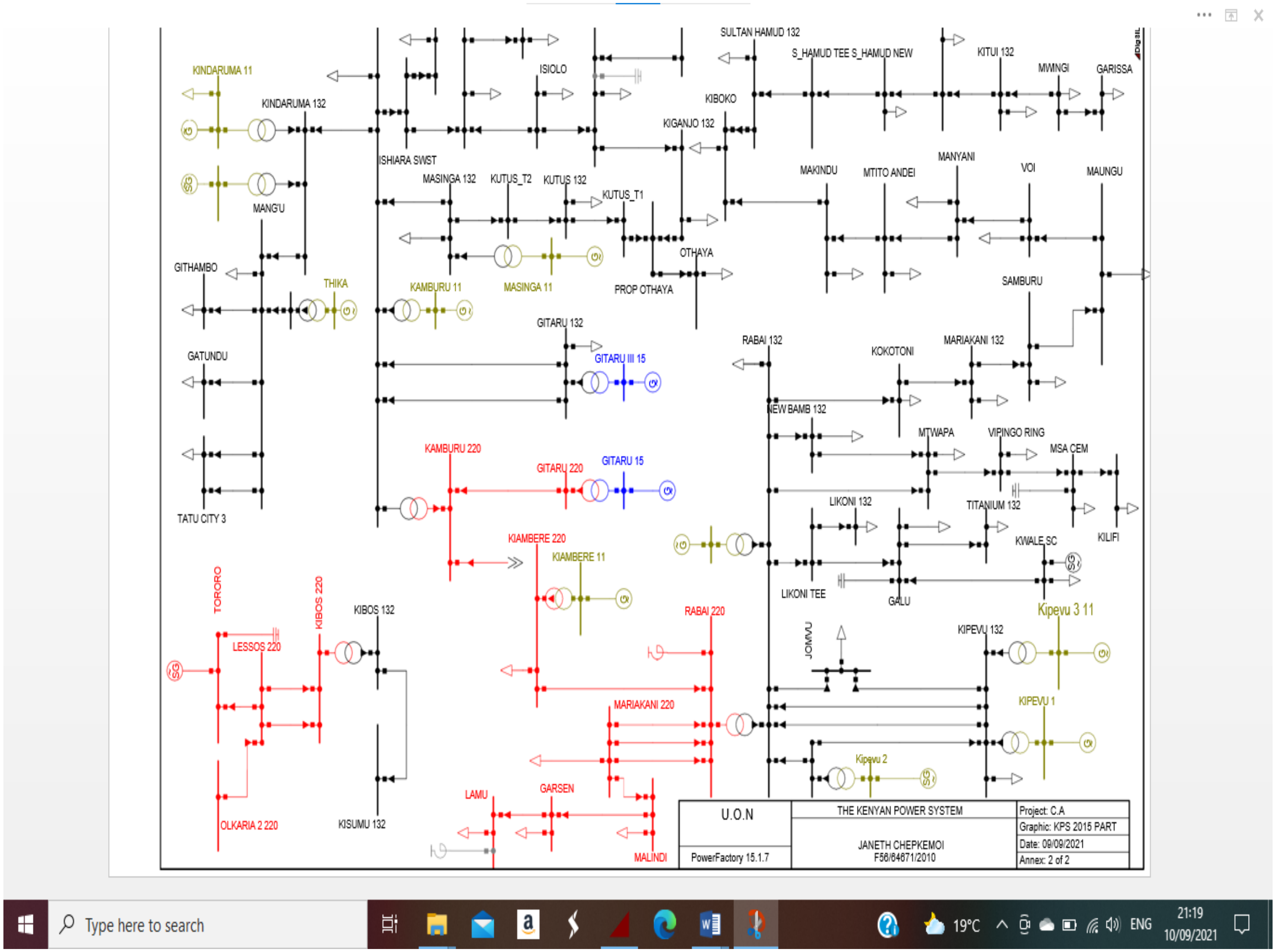


U.O.N
PowerFactory 15.1.7

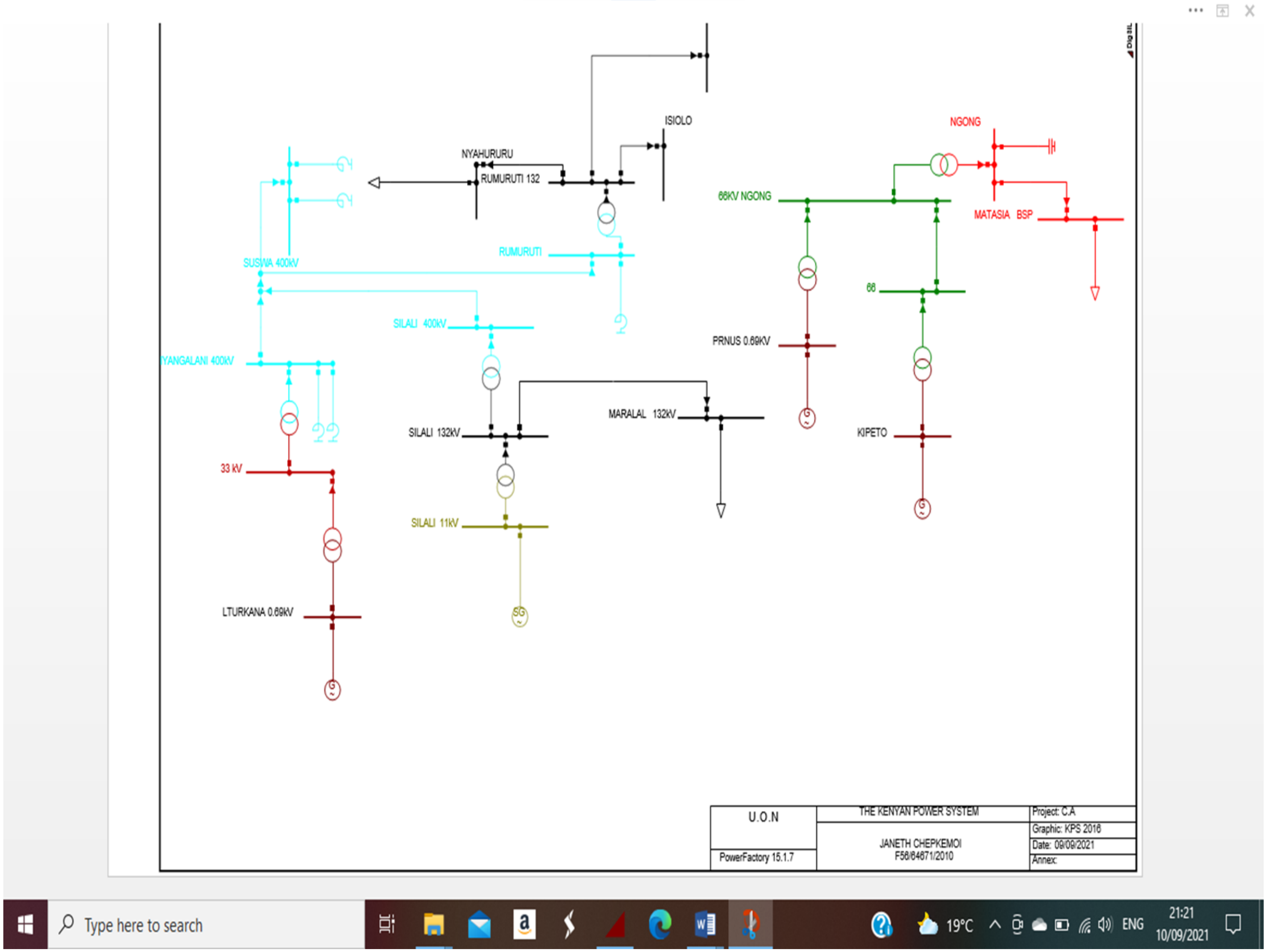
THE KENYAN POWER SYSTEM
JANETH CHEPKEMOI
F56/64671/2010

Project: C.A
Graphic: KPS 2015 PART
Date: 09/09/2021
Annex: 1 of 2

A6. Kenyan Power System 2

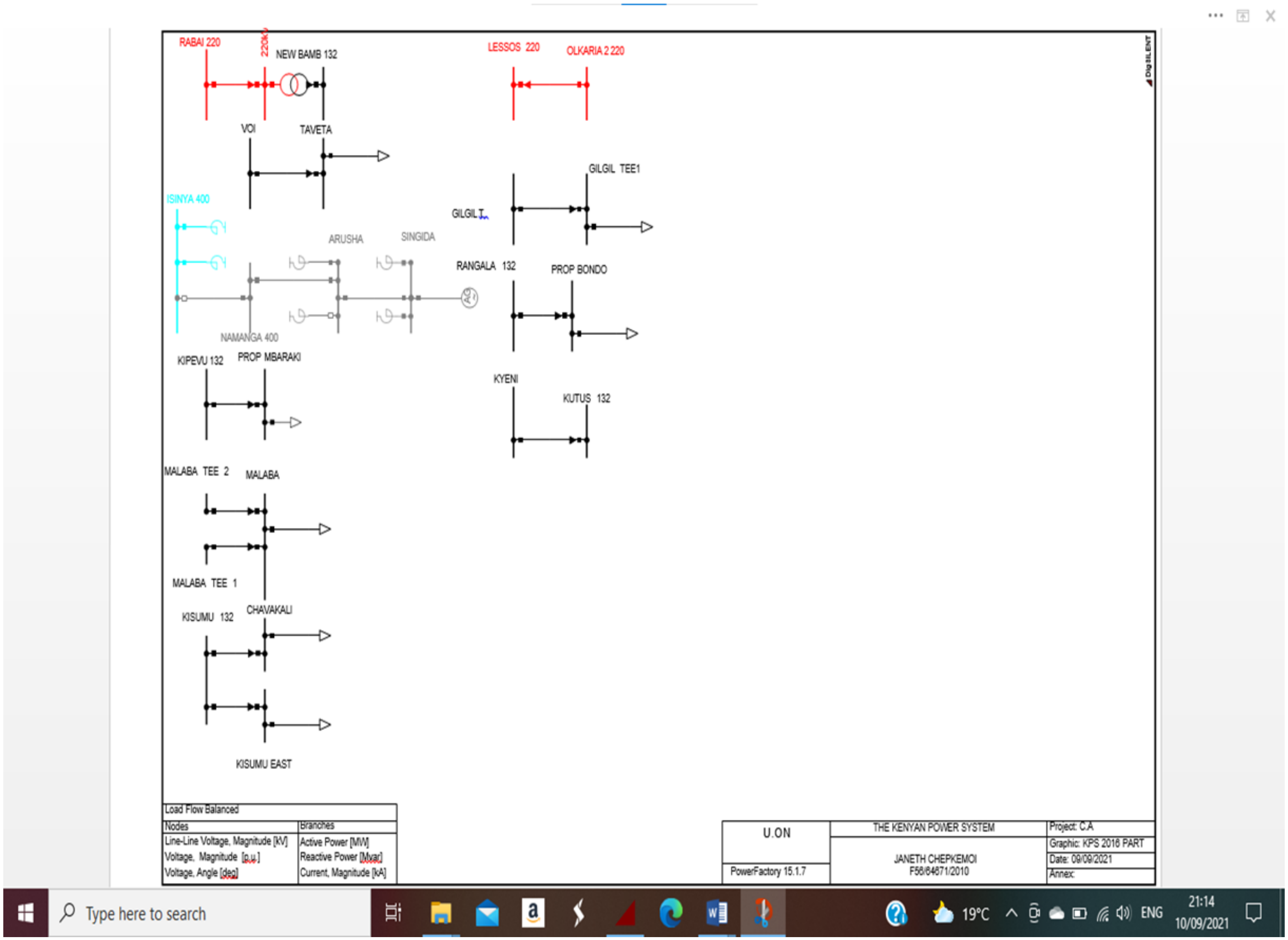


A7. Kenyan Power System 3



U.O.N
PowerFactory 15.1.7
THE KENYAN POWER SYSTEM
JANETH CHEPKEMOI
F56/64671/2010
Project: C.A
Graphic: KPS 2016
Date: 09/09/2021
Annex:

A8. Kenyan Power System 4



Load Flow Balanced

Nodes	Branches
Line-Line Voltage, Magnitude [kV]	Active Power [MW]
Voltage, Magnitude [p.u.]	Reactive Power [Mvar]
Voltage, Angle [deg]	Current, Magnitude [kA]

U.ON	THE KENYAN POWER SYSTEM	Project: C.A
	JANETH CHEPKEMOI F56/64671/2010	Graphic: KPS 2016 PART
PowerFactory 15.1.7		Date: 09/09/2021
		Annex: