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Title of the Project:

"Technical Assessment on Rwandan Power Grid Stability, Case Study: Northern Zone".

A Dissertation Submitted to the African Center of Excellence in Energy Studies for Sustainable Development (ACE-ESD)

In partial fulfillment of the requirement for the degree of
MASTER OF SCIENCE IN RENEWABLE ENERGY

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2024

Kigali-Rwanda

DECLARATION

I, the undersigned, declare that this Project thesis is my original work, and has not been presented for a degree in the University of Rwanda or any other universities. The thesis will have fully acknowledged all sources of the materials used in the work.

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Date of Submission**:** **21/10/2024**

This Thesis has been submitted for examination with my approval as a university advisor.

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Thesis Co-Advisor Signature

DEDICATION

This work is truly dedicated to my beloved Partner **Mrs. Bonne Marie HAGABIMANA**

ACKNOWLEDGMENT

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LIST OF ABREVIATIONS & ACRONYMS

REG: Rwanda Energy Group

EDCL: Energy Development Corporation Ltd

Kv: kiloVolt

Km: Kilometer

ARs: Autoreclosers

LBS: Load Break Switch

MW: Mega Watt

ACRs: Automatic Circuit Reclosers

MV: Medium Voltage

HV: High Voltage

LV: Low Voltage

SAIDI: System Average Interruption Duration Index

SAIFI: System Average Interruption Frequency Index

TSO: Transmission System Operator

SS: Substation

AC: Alternative Current

SIL: Surge Impedance Loading

AVC: Automatic Voltage Control

AGC: Automatic Generator Control

AI: Artificial Intelligence

NECC: National Electricity Control Center

ETAP: Electrical Transient Analyzer Program

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ABSTRACT

The objective of an Electric power system is to generate electrical energy and distribute that energy to the end user appliance at an acceptable voltage.

The Technical Assessment on Power System Stability in Rwandan Grid provides an in-depth analysis of the challenges and implications associated with the power stability of Rwanda's electrical grid. The availability of a stable and reliable electricity supply is crucial for a nation's economic development and quality of life. In Rwanda, the energy sector has been rapidly expanding, and the government has made substantial investments in infrastructure to meet the growing energy demands. However, the grid experiences power fluctuations that affect the reliability and efficiency of the electricity supply.

This technical assessment seeks to identify the root causes of stability issues in Rwanda's electrical grid, assess their impact on various stakeholders, and propose recommendations for mitigation. A northern network model was built in ETAP software as the study case. The collection of time series loading on different northern substations during 24 hours was conducted and the data collected were simulated using ETAP software to analyze the root cause of power instability in the network. The voltage stability analysis, Short circuit analysis, contingency analysis, optimal power flow, PV and QV curves, and surge loading event were analyzed in ETAP software.

As a result, it was discovered that the stability of the entire system is impacted when a substation fails or disconnects. Long transmission lines affect the voltage profile of the system in addition to faults, as they contribute to the significant voltage drop at some substations.

CHAP 1. INTRODUCTION

1.0. Background and Motivation

Energy plays an important role in people's daily activities despite the problem of frequent power cuts due to power supply instabilities and disturbances.

Rwanda has also been facing big challenges related to grid power fluctuation and power failure from different causes. This may be due to unstable power generation, fluctuating load, protection system, unstable control system, grid infrastructure aging, etc. The long persistent power fluctuation and failure may cause material losses from generation to the end-users and can be the source of huge economic losses in case of total blackout for instance.

From the architecture view, the Rwandan electrical grid has 23 substations and 10 main power plants which are located in different regions of the country. The transmission system is predominately 110 kV and 220 kV lines [1]. By the end of June 2022, the total length of the transmission network, including 220kV and 110kV lines, was recorded at 973.14 km across the country. Nowadays, in the whole country distribution lines of 28,985.8 kilometers have been constructed, to connect power producers and end users. From those constructed Distribution lines, Medium Voltage(MV) lines are equal to 10,520.1 km while low voltage(LV) distribution lines is 18,465.7km.

To further develop network dependability and power supply security in the nation's changing power request profile, a few substations are being upgraded.

1.1 Problem statement

The Rwandan power grid is the backbone of the nation's economic and social development, providing electricity to industries, businesses, and households. However, it faces persistent challenges related to power fluctuations and power outages, which adversely affect the reliability and efficiency of the electrical supply. These instabilities may occur in transmission and distribution lines as a result of different issues such as poor protection and control, poor maintenance, and lack of rehabilitation and upgrade of electrical lines. In case of long-term instabilities, network system operators have to intervene because a sustained failure may eventually result in a blackout.

To prevent the blackout from occurring, which also avoids related financial losses, the network needs to be kept stable through the usage of accurate protection and control systems, and make sure that the network is regularly maintained.

From this perspective, this technical assessment aims to comprehensively evaluate and understand the cause of the issues mentioned above. As long as the cause is identified, preventive measures can be taken.

Power stability refers to the consistent and reliable delivery of electrical power without fluctuations or interruptions. Issues related to power stability can have various causes and consequences, affecting both individuals and businesses. Some common issues include: Voltage fluctuation, Frequency variation, Power dips or sags, Power outages, Grid instability, Harmonics, Voltage imbalance, …

High-quality power grid is characterized by reliability, resilience, stable voltage and frequency control, efficient capacity and load balancing, environmental sustainability, cybersecurity measures, modernization efforts, and supportive regulatory frameworks. Continuous improvements in these aspects contribute to a more reliable, efficient, and sustainable power supply for consumers.

1.2 Objectives

1.2.1 Major Objectives

The major objective of this research is to conduct a technical assessment of the northern grid to evaluate the cause of power fluctuation and failure.

1.2.2 Specific objectives

This research aims at achieving the below specific objectives among others:

i. Assess the voltage profile at different substations during 24 hours
ii. Identify the minimum and maximum loading point of the substation
iii. Identify the surge load event in the network
iv. Analyze the transient stability of the reference generators
v. Analyze the contingency resistance of the network

1.3 Research questions

Several questions arise from the above-mentioned challenges that limit the efficient operation of the Rwandan grid. Among many questions arising, are:

i. What are the main causes of voltage sag or voltage swell in the northern network?
ii. What is the maximum loading capacity at the substation?
iii. How many surge loading events in 24 hours happened at the substation and their impact on the grid?
iv. How do the main generators respond to the transient fault in the network?
v. What are the effects of losing a feeder in the network?
vi. What is the appropriate corrective method to reduce power fluctuation in the northern grid?

This thesis attempts to find the answer to these questions.

1.4 Justification

This thesis is very important to the Rwandan Grid as it will give solution on power fluctuation issue that happen many times in Rwanda followed by long time restoration time that result to financial loss to the end users. After this work, recommendation will be given to minimize those fluctuations.

1.5 Scope of the study

This research will gather and analyze technical causes of power fluctuation in Northern zone, and then after analyzing those technical causes, the possible solution that minimize power fluctuation and time to restore power will be suggested for Rwandan Grid.

1.6 Significance of the study

Technical assessment on power on Rwandan Power grid is significant because it addresses critical aspects of energy reliability, economic development, environmental sustainability, and overall societal well-being. The findings and recommendations from such a study can drive positive changes in Rwanda's energy infrastructure and policy landscape. It will also help Rwanda company in charge of Grid power(REG) in managing and controlling of Power disturbances on Rwandan grid in order to have reliable power supply systems, thus avoiding losses caused by unplanned power outages.

1.7. Thesis Organization

This research has three chapters:

- Chapter One: Introduction
- Chapter Two: Literature review
- Chapter Three: Methodology
- Chapter Four: Simulation results and Discussion
- Chapter Five: Conclusion and Recommendation

CHAP 2. LITERATURE REVIEW

2.1. Electricity Access in Rwanda

The capacity of various power plants in Rwanda is currently estimated to be around 276.068 MW. Of these, 51% are thermal, followed by hydro (43.9%) and solar (4.2%). [1]. Several projects to construct new power plants are currently underway as part of the efforts to increase the current capacity. By 2024, the national grid will have more capacity. These include, among others, the 80MW Hakan peat to power plant, the 26MW Rusumo Falls hydropower plant, the 48.3MW Rusizi III, the 56MW Shema, and the 43.5MW Nyabarongo II. [1] . As seen in the graph below, these initiatives are anticipated to significantly alter the generation technology mix and decrease the use of costly sources (fuel):

As shown in the graph below, these projects are anticipated to change the generation technology mix and significantly reduce the use of expensive sources (fuel).

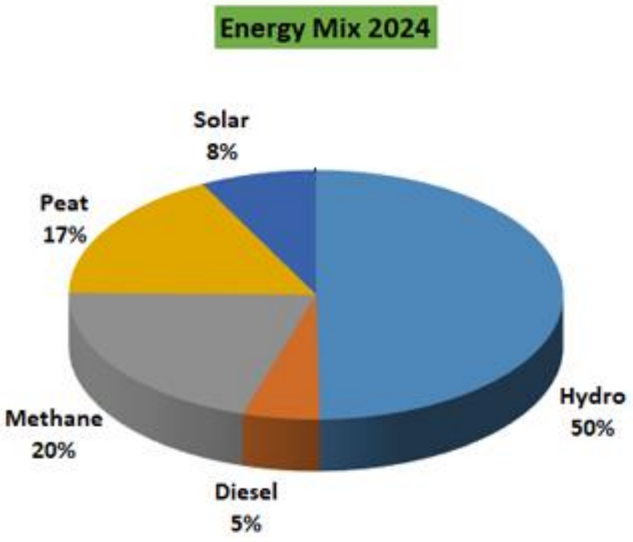

Figure 1: Energy mix 2024 (Source: REG website) **[1]**

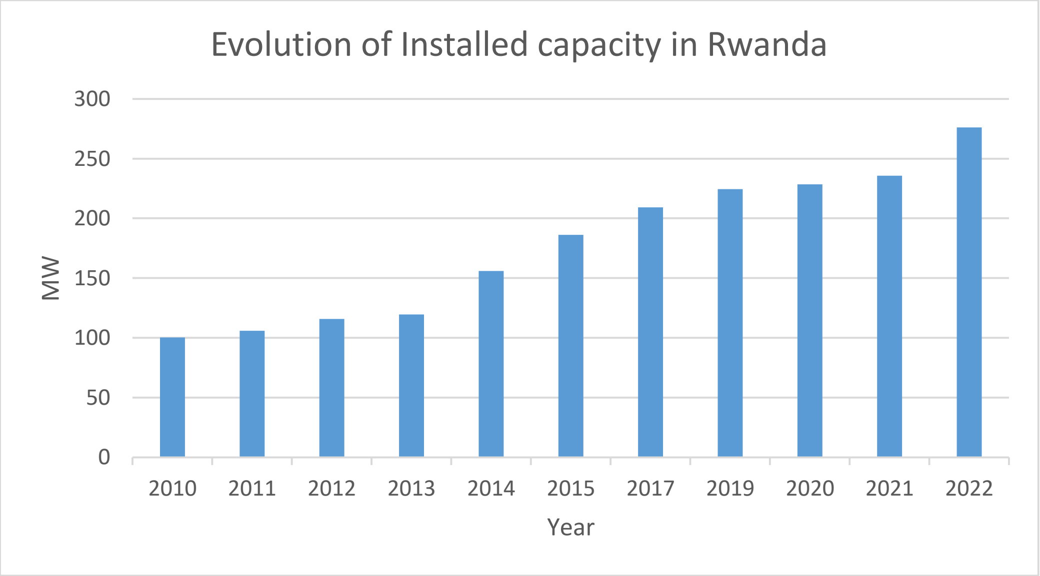

Figure 2: Evolution of installed capacity in Rwanda (Source: REG website) **[1]**

2.1.1 Hydro Power in Rwanda

Rwanda's hydropower industry has advanced greatly in the past ten years. 51.2% of the installed electricity capacity, or approximately 276.068 MW, comes from hydropower.

By including individual investors in the energy industry, this was accomplished; by Independent Power Producers (IPPs). A supportive legal and regulatory framework for private investors in the energy sector has equally contributed to success in this field. [2]

2.1.2 Grid-connected hydropower plants

37 hydropower plants are connected to the grid with 123.4 MW. Among them are shared and public regional power plants. Approximately 51.2% of the installed capacity is hydropower.

Private companies lease hydropower plants, which are owned and operated by the public, or privately owned (IPP). The national utility REG/EUCL is in charge of managing the publicly owned power plants. They include larger plants such as Ntaruka, Mukungwa, and Nyabarongo I.

Six (10 MW) plants are owned and operated by independent power producers. Through lease agreements with the Rwandan government, the remaining 8 power plants, totaling 13 MW, are privately run.

2.1.3 Off-grid micro hydropower plants

Right now, Rwanda has 11 isolated networks of micro hydropower plants with a combined capacity.These plants were initially evolved by the government and transferred to the control of the private sector in order to boost the private sector's contribution to energy generation. The government has recently leased out these sites to private investors to better operate, upgrade, and connect them to the grid. There are also pico hydropower plants in the scope of 1-10 kW which are either openly possessed and worked by the neighborhood networks or completely private. [2]

2.1.4 Solar Power

In Rwanda, solar energy has tremendous potential, with a potential of 4.5 kWh per m2 per day and approximately 5 peak sunlight hours. Currently, solar energy connected on-grid is 12.230 MW from 5 solar power plants such as the Jali power plant with 0.25MW, Rwamagana Gigawatt with 8.5 MW, Ndera Solar power plant with 0.15MW and the Nasho Solar plant generating 3.3 MW.

To take advantage of Rwanda's renewable energy resources and lower production costs, the Rwandan government plans to build more solar power plants. [3]

2.1.5 Methane Gaz

The Eastern African Rift Zone's Lake Kivu contains Methane Gas Resources. The lake has a lot of naturally occurring methane gas (CH_4) and carbon dioxide (CO_2), and the concentrations are highest at depths between 270 and 500 meters over an area of about 2,400 square kilometers.

The biological processes of the lake are sustained by the oxygenated top layer that extends down to a depth of 60 meters. Rwanda and the Democratic Republic of the Congo split the resources evenly.

In 2004, A small-scale gas extraction process was completed, and the extracted gas was used to power boilers at a Gisenyi brewery. Since then, to solve the nation's rising electrical energy shortfall, the Rwandan government has made the production of power from this special resource a top priority. [2]

2.1.6 Transmission network

Lines under light load or at no-load conditions generate reactive power due to the shunt capacitance. When the network is fully loaded, occasionally it absorbs reactive power. Likewise, underground cables supply reactive power under all load situations.

Let us suppose the transmission line is loaded by a current is I amperes and load voltage of V volts, by assuming the line has no loss within the system, the reactive power consumed by all transmission lines.

$$I^2\omega L \tag{1.1}$$

Where: ω is the angular frequency and L is the line inductance

Due to the shunt capacitance of the line, the reactive var supplied by the line are

$$V^2\omega C \tag{1.2}$$

Where C is the shunt capacitance of the line. In case the reactive vars absorbed by the line are equal to the reactive vars supplied, the equation will be:

$$I^2\omega L = V^2\omega C \tag{1.3}$$

$$\frac{V}{I} = \sqrt{\frac{L}{C}} = Z_n \tag{1.4}$$

Dimensionally the proportion V to I is impedance, and subsequently, Z_n is known as the common impedance of the line, and the stacking condition in which the consumed vars are equivalent to the vars delivered by the line is named the surge impedance loading(SIL) and where the length of the line is at voltage passing all through on it [15].

In case $I^2\omega L > V^2\omega C$, the voltage will sag and if $I^2\omega L < V^2\omega C$ (light load condition), the voltage will rise. Generally, the loading is more than the SIL; Thus, the condition $I^2\omega L > V^2\omega C$ exists and the net effect of the line will be sinking the vars. Under light load, the result of shunt capacitors is outweighing and the line serves as vars generator. [4]

2.1.7 Current Distribution Network Configuration

The countrywide distribution voltage is 30 kV, except for Kigali and Rwamagana, which operate at 15 kV; however, REG intends to phase it out and move to a single 30 kV distribution level.

By end June 2022, the distribution network is composed of 10,520km of medium voltage lines (30kV and 15kV), 18,465.7km of low voltage lines (0.4kV), a total of 6610 distribution transformers and a total of 1,376,998 customers connected to the grid. [1].

2.1.8 Challenges in the Distribution Network

The distribution network suffers from poor reliability and quality of supply, which requires a huge budget to improve the issues. Some of the key issues identified during this research are briefly described below:

- Overstretched LV network causing voltage drops in different parts of the country
- Weak sections of MV feeders are unable to facilitate load transfers.
- Power cuts and delayed fault identification due to old Underground network in Kigali and Secondary cities
- Single phase network unable to facilitate some economic activities in fast growing areas
- Un-mapped Distribution network limiting proper planning for network expansion & reinforcement
- Insufficient intelligent switching devices (automatic load breaker switches, auto reclosers)
- Old MV cabins and LV distribution boards/panel
- Long distance from the HV substation to the load centers [5]

2.1.9 Limitations of Power Disturbance in Rwanda Grid

The power disturbance in Rwanda demonstrated the relevance of the severe problems of loss of supply and MW loss followed by financial loss for the country and the stakeholders. The situation is further complicated by the necessity for the power system to survive under competition and uncertain conditions. Constantly occurring power failures today persist and the rate of failure is being increased due to different reasons. Some issues may be due to the un-proportional Sharpe increase in power demand for power generation. In addition, as mentioned above, the aging transmission and distribution network contribute too. From different data recorded by EDCL, the protection system contributes the most to power failure for the Rwandan electrical grid. Some statistical analyses before, present the issues of power failure on the Rwandan network.

The following figures show how was the situation of a power outage on different feeders connected to the Rwandan Grid.

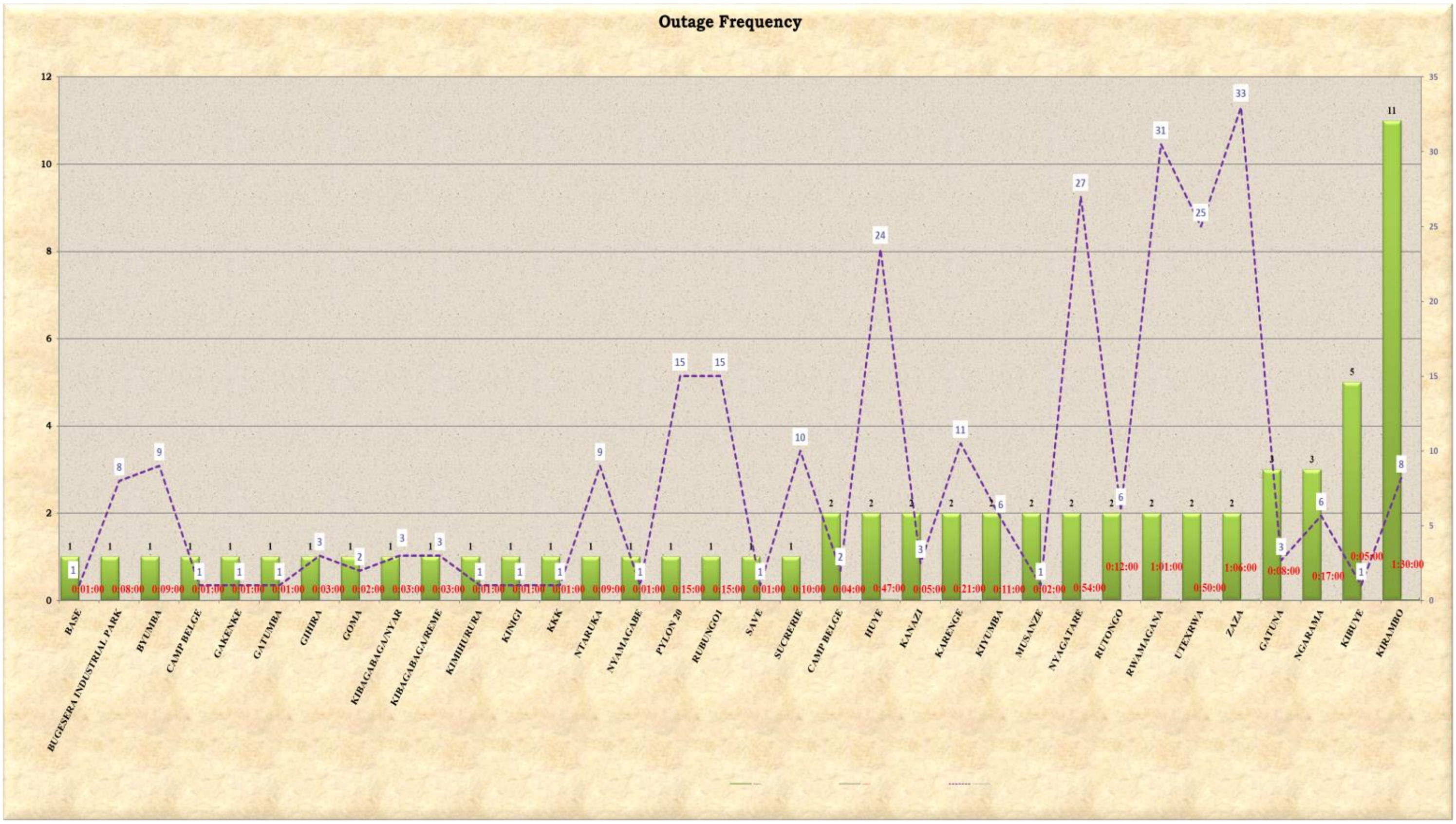

Figure 3: Outage frequency and duration per feeder

This figure shows all feeder in Rwandan grid and how they were out of service due to different causes, the number of outages(Frequency) and the time taken to restore power.

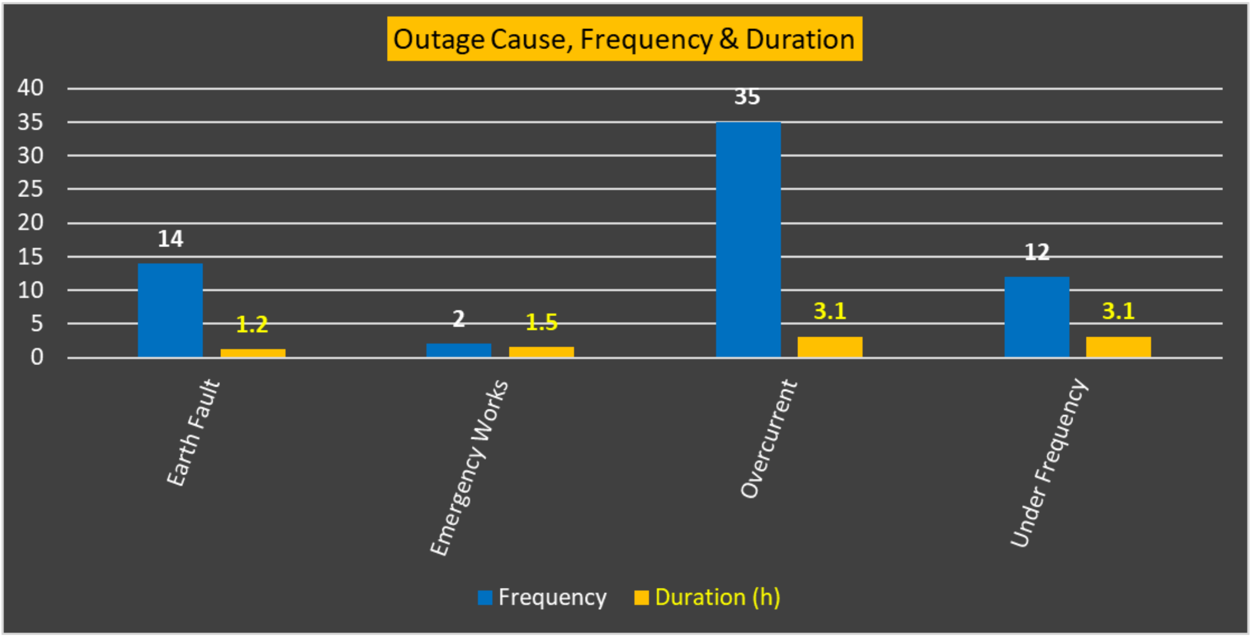

Figure 4: Outage cause, Frequency and duration

Those different feeder's outages have been caused by Earth fault, Overcurrent, Under Frequency, and Emergency works. It is seen in the figure that overcurrent is the main issue of power outage during this period as it has happened 35 times.

The outage associated with Energy not distributed aggregate on all distribution feeders is 13.3MWh

with a corresponding monetary loss of 2,471,413FRW.Additional 435.43MWh was recorded as energy not distributed caused by blackouts occurred two times on 23rd July 2023 at 12:29 for 1hr 5min and at 15:44 for 2hrs 4min with a total monetary loss of 80,989,050Frw. It took 3hr:09min for the system to be fully restored.

2.2 Network Performance Indices

2.2.1 System Average Interruption Duration Index (SAIDI)

The System Average Interruption Duration Index (SAIDI) is the most often used performance metric during a persistent interruption. This record estimates the complete term of an interference for the typical client during a given time span. Typically, SAIDI is calculated annually or monthly; Nevertheless, it is possible to calculate it daily or for any other time period.

Every interruption that occurs throughout the time period is multiplied by its length to determine the customer-minutes of interruption, which is used to compute SAIDI. The total customer-minutes are then calculated by adding the customer-minutes from each interruption. The customer-minutes are divided by the total number of customers to determine the SAIDI value. [6]

The formula is,

$$SAIDI = \Sigma (r_i * N_i) / N_T \qquad (1.5)$$

Where,

SAIDI = System Average Interruption Duration Index, minutes.

Σ = Summation function.

r_i = Restoration time, minutes.

N_i = Total number of customers interrupted.

N_T = Total number of customers served.

2.2.2 System Average Interruption Frequency Index (SAIFI)

The System Average Interruption Frequency Index (SAIFI) is the typical annual frequency of system outages experienced by a customer. The SAIFI is computed by dividing the total number of customers who were served by the total number of customers who were interrupted. SAIFI, which is a dimensionless number, is,

$$\text{SAIFI} = \Sigma(N_i) / N_T \qquad (1.6)$$

Where,

SAIFI = System Average Interruption Frequency Index.

Σ = Summation function.

N_i = Total number of customers interrupted.

N_T = Total number of customers served. [6]

The following parameters will be considered during this research: Power, Frequency, Voltage and Load variation.

In widely accepted international network reliability measurements, the duration and frequency of outages are continuously tracked by an automated computation system to obtain Network Performance Indices. These are the **System Average Interruption Duration Index (SAIDI)** and the **System Average Interruption Frequency Index (SAIFI).** [7]

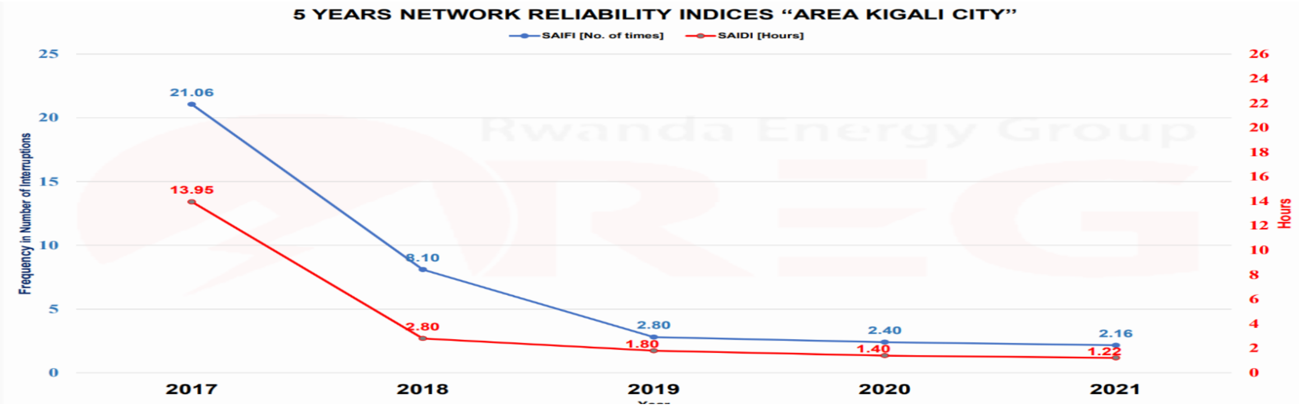

Figure 5: Reliability indices in Kigali city (REG website) **[7]**

2.3. Voltage stability

Voltage stability refers to the ability of an electrical power system to maintain steady voltage levels within acceptable limits under normal operating conditions and in the face of disturbances. In an electrical power system, voltage stability is crucial for ensuring the proper functioning of equipment, preventing damage to devices, and maintaining the reliability of the power supply [8]. The voltage instability problem can be classified into short-term and long-term.

The effects of a voltage fluctuation are the predominant ones and are similar to the effects of an under voltage. It causes lights to flicker or glow brighter. Since incandescent lights are made for a certain voltage level, this power issue may significantly shorten their lifespan. Poor quality or fluctuating power supply can often cause voltage fluctuations.

Due to the extensive power lines, rural areas may experience significant voltage fluctuations. When there is a lot of power use in the area, these power lines can lower the voltage. The voltage of a power distribution system typically fluctuates when arc furnaces, arc welding equipment, or even elevators are utilized. This present circumstance is like involving a shower in the second floor restroom of a house. At the point when somebody turns on the spigot in the pantry on the principal floor, the subsequent floor shower might run out of water [9].

Below there is a figure shows visualization of the periodic amplitude modulation of the voltage waveform envelope that is the root cause of flicker.

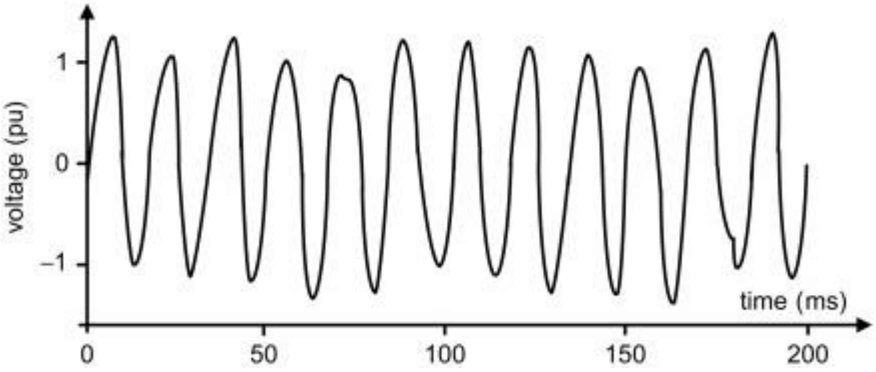

Figure 6: Periodic amplitude modulation of the voltage waveform envelope that causes flicker. **[9]**

2.3.1 The main causes of voltage stability issues

Voltage stability issues can arise due to various factors in an electrical power system. Some of the common causes include:

- **Load Variations**: Rapid and large changes in the load demand can affect voltage stability. Sudden increases or decreases in power demand can stress the system and cause voltage fluctuations.

- **Faults or Disturbances**: Short circuits, faults, or disturbances in the power grid can disrupt voltage stability. These events create sudden imbalances in the system and can lead to voltage sags or swells.
- **Generator and Transmission Line Outages**: Outages or failures of generators or transmission lines can result in voltage instability. Loss of a significant source of power or transmission capacity can strain the remaining components, causing voltage fluctuations.
- **Reactive Power Imbalance**: Reactive power is essential for maintaining voltage levels. When there's an imbalance between the reactive power demand and supply, it can lead to voltage instability. Inadequate reactive power support or mismatch between generation and consumption can affect voltage.
- **Voltage Control Issues**: Poor or inadequate voltage control mechanisms within the power system can contribute to voltage stability problems. Inefficient voltage regulation devices or controllers can lead to voltage fluctuations.
- **Weak Grids and Low System Inertia**: In systems with weak grids or low inertia, even minor disturbances can significantly impact voltage stability. Limited system strength makes it more susceptible to voltage fluctuations.
- **High Renewable Energy Integration**: Integration of renewable energy sources, such as wind and solar, can introduce intermittency and uncertainty into the power system, affecting voltage stability due to their variable nature. [8]

2.3.2 Management of voltage stability

The term "voltage stability" describes a power system's capacity to sustain constant voltage levels at different system locations both during regular operation and in the event of disruptions. Managing voltage stability is crucial in ensuring the reliability and proper functioning of electrical grids. Here are some key strategies and methods used in the management of voltage stability: [10]

Reactive Power Control: Reactive power is essential for maintaining voltage levels. Utilities and grid operators use devices such as capacitors, reactors, and voltage regulators to control reactive power flow and manage voltage levels within acceptable limits.

Load Shedding: In extreme cases where voltage instability occurs due to excessive demand or other factors, controlled load shedding can be implemented. This involves systematically disconnecting certain loads to prevent a complete blackout and restore stability.

Generator Control: Power generators play a crucial role in maintaining voltage stability. Generator controls, such as automatic voltage regulators (AVRs) and power system stabilizers (PSS), help manage voltage levels by adjusting generator output and providing stability during disturbances.

Optimal Power Flow (OPF): Using advanced optimization techniques, utilities can determine the best settings for generators, transformers, and other devices to maintain voltage stability while minimizing losses and costs.

Voltage Collapse Prediction and Prevention: Monitoring systems equipped with real-time data analysis and predictive algorithms can detect signs of voltage collapse or instability before they occur.

This enables operators to take preventive actions, such as reconfiguring the network or adjusting control settings, to avert potential problems.

Distributed Energy Resources (DERs): Integration of renewable energy sources and distributed generation requires careful consideration of their impact on voltage stability. Advanced control mechanisms for DERs, like smart inverters, can help regulate voltage levels in local areas and improve overall system stability. [11]

2.3.3 Impact of voltage stability issues

Voltage stability issues in an electrical power system can have significant impacts, affecting both the system's reliability and the quality of power supplied to consumers. Some of the key impacts of voltage stability issues include:

Equipment Damage: Voltage instability can cause voltage sags, swells, or fluctuations, which can damage sensitive electrical equipment. Rapid changes in voltage levels beyond the acceptable range can lead to premature failure or reduced lifespan of devices like computers, motors, and other electronic equipment.

Power Outages: Severe voltage instability can lead to cascading failures within the power system, resulting in blackouts or localized power outages. When voltage stability issues escalate, protective systems may trip, isolating parts of the grid to prevent further damage.

Reduced System Reliability: Voltage instability undermines the reliability of the power system. Unstable voltages can disrupt the normal operation of equipment and lead to unplanned downtime for industrial processes, data centers, or other critical facilities.

Economic Losses: Industries and businesses heavily reliant on stable power supply can experience financial losses due to production interruptions or damage to equipment. Unplanned downtime, repairs, and replacements of damaged machinery can incur substantial costs.

Diminished Quality of Power: Voltage instability affects the quality of power delivered to consumers. Fluctuating voltages can cause lights to flicker, affect the performance of appliances, and disrupt electronic devices, leading to inconvenience and dissatisfaction among consumers.

Safety Risks: Voltage instability may create safety hazards, especially in critical systems that rely on stable power, such as healthcare facilities, transportation networks, and emergency services. Unstable voltages can compromise the functionality of safety and life-support systems.

Challenges for Renewable Integration: Voltage instability can pose challenges for integrating renewable energy sources into the grid. Variability in generation from renewables, coupled with voltage stability issues, might hinder their efficient and reliable integration. [9]

2.4 Frequency stability

In practical, to accurately guarantee the generator–load power balancing is the challenging issues in power system. The frequency fluctuations may become severe whenever there is a power disturbance, which can be from input power or load change. Any grid system requires maintaining the frequency fluctuations within acceptable limits agreed with the standards to avoid the blackout of the system. It is critical to regulate frequency within predetermined limits to prevent unforeseen disruptions that might harm connected loads or possibly cause the system to fail. This is necessary to maintain expected operational conditions and deliver energy to all users (loads) connected.

Power systems typically operate at 50 Hz in many countries also in Europe and much of Asia and 60 Hz in North America. Technical compromises and historical circumstances motivate this choice. Typically, a system is considered to be under normal circumstances when it works within a frequency range of ±0.1 Hz. However, in a 50 Hz network, for instance, a system operating in the range of 47.5 to 51.5 Hz is referred to as an emergency condition or restoration condition. Due to such region, these values can be changed [12].

Different levels of frequency control are combined together to enhance the frequency stability issues. There are three layers of frequency control: **primary, secondary, and tertiary controls**. Every frequency control has unique characteristics and functions.

2.4.1 Primary Control

Because of its quick reaction time, the primary control, sometimes referred to as the frequency response control, is the quickest of the three levels and operates automatically. In the event of an imbalance between generation and load, the power system's frequency is altered.

For instance, with a heap increment, the created power doesn't quickly change, so the energy to make up for this heap increment shows up from the dynamic energy of the turning generators that begin diminishing the speed (this is known as the inertial reaction). Following this, each generator's speed controller, sometimes referred to as the "governor," works to restore the lowering speed and attempt to correct the imbalance by increasing the generation power. [13]

For the most part, in around 30 seconds, every age unit will have the option to produce the necessary extra power and afterward save it for no less than 15 minutes (this timing relies upon the prerequisites of the transmission framework administrator, or TSO).

Except for renewable energy sources (RES) that cannot be scheduled, all linked generating plants in the high-voltage power system are relied upon to provide this service (ie. wind, solar, biogas, hydraulic flow water), so, for this reason, each generation unit shall have a dedicated and proper “reserve” power to accomplish this regulation when active.

To restore the system to a stable state, the primary control is to eliminate the imbalance between generation and loads. All generators who are eligible to supply this service must do so; they are not paid for it.

The persistent development of RES suggests the decrease of thermoelectric plants in activity, with ensuing troubles to play out this recurrence guideline, for the reasons made sense of above. There are now various arrangements under examination and some of them currently set up in a few power frameworks (battery energy capacity frameworks are one of the most encouraging). One of the primary obstacles to the widespread use of Renewable Energy sources (RES) in power systems is this. [13]

2.4.2 Secondary Control

After the main regulation has achieved its goal, the frequency value differs from the nominal value, each generator's reserve margins have been exhausted, if not entirely, and the power exchange between the linked power systems deviates from the predetermined value. So, Restoring the power exchange between the power systems, the nominal value of the frequency, and the reserve of each previously utilized generator is essential. The secondary control serves this function.

More generation capacity must be started when the frequency value is lower than the nominal value, and some generation capacity must be halted or the load must be increased when the frequency value is greater than the nominal value. All of the generators that are a part of this regulation typically carry out the secondary control by sending a specific "set-point" to each generator.

An illustration of the initial two tiers of control following a frequency event in the system can be found in Figure. Depending on the system's amount of inertia (low generation power systems from spinning machines will have low inertia levels), the green and red-dashed lines display two distinct reactions.

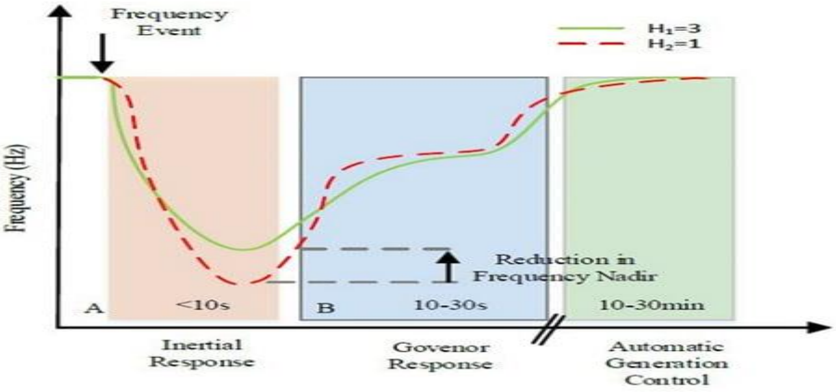

Figure 7:Frequency response after a frequency event. **[13]**

2.4.3 Tertiary Control

After secondary control is completed, the tertiary control's objective is to restore the reserve margin used for this control as well. (or replacement reserve) the last level of frequency control.

The TSO calls transmit individual producers—even those not participating in secondary control—the operational prescriptions pertaining to power variation for the generators that are now running. If necessary, they also request that the generators that are not running right now be started up.

This control level does not operate automatically; rather, it is carried out upon request from the grid operator. Its compensation is determined in the same manner as the secondary control. [12]

2.5. Angle Stability

In a power system, angle stability describes the system's capacity to continue operating synchronously in the face of disruptions. It is crucial for the reliable operation of an interconnected power grid. Angle stability ensures that the various generators in the system remain in sync with each other, maintaining the required phase relationship and frequency.

When an external disturbance, such as a fault or sudden change in the load, occurs in the power system, it can affect the rotor angles of the synchronous generators. If these angles deviate too much, it can lead to instability and even a cascading failure, causing widespread blackouts.

There are two primary types of angle stability:

Small-signal stability: This relates to the system's ability to maintain stability under small disturbances. It involves analyzing the response of the system to small fluctuations and ensuring that the oscillations die out over time.

Large-signal stability: This pertains to the system's ability to remain stable under large disturbances. It involves analyzing the system's response to severe events like faults and ensuring that the system recovers without losing synchronism.

Several factors contribute to angle stability, including:

Generator rotor inertia: Higher inertia helps stabilize the system as it resists rapid changes in speed and angle.

Power system controls: Effective control systems and devices, such as power system stabilizers (PSS), help dampen oscillations and maintain stability.

Transmission system characteristics: The impedance and reactance of transmission lines affect the system's ability to withstand disturbances.

Proper system design and planning: Adequate redundancy, correct settings, and appropriate protection schemes are essential for maintaining stability.

2.6. Harmonic Distortion

Common voltage and current differences caused by frequency shifts in the electrical distribution networks are known as harmonic distortions. In particular, there are variations in the voltages or currents that do not follow the typical sinusoidal fluctuations.

These non-sinusoidal components are integer multiples of the fundamental frequency of the power system, typically 50 or 60 Hz in most parts of the world. Harmonic distortion can have several undesirable effects on a power system, including:

- **Equipment Damage:** Harmonic distortion can cause overheating and premature failure of electrical equipment, such as transformers, motors, and capacitors. This is because harmonics introduce additional losses and stress on the equipment.
- **Voltage Distortion:** Harmonic distortion can result in distorted voltage waveforms. This can affect the proper functioning of sensitive electronic equipment and lead to erratic behavior or damage.
- **Increased Energy Losses:** Harmonics can increase energy losses in power distribution systems, leading to higher energy bills and reduced overall system efficiency.
- **Resonance:** The presence of harmonics can lead to system resonance, where the natural frequency of a power system coincides with a harmonic frequency. Resonance can result in excessively high currents and voltages, potentially causing equipment damage and system instability.
- **Reduced Power Quality:** Harmonic distortion can degrade power quality by introducing voltage flicker, waveform distortion, and frequency fluctuations. [14]

Common sources of harmonic distortion in power systems include:

1. **Non-linear loads:** Devices like variable speed drives, power electronic converters, and rectifiers introduce harmonics when they draw current from the power grid. These devices do not draw current in a sinusoidal manner.
2. **Arc furnaces and welding machines:** These heavy industrial loads are known for introducing significant harmonic currents due to their highly non-linear characteristics.
3. **Lighting systems:** Certain types of lighting, especially compact fluorescent lamps and LED drivers, can generate harmonics.
4. **Power factor correction capacitors:** These capacitors, if not properly controlled, can amplify harmonics in the system.

To mitigate harmonic distortion in a power system, several techniques can be employed:

i. **Harmonic Filters:** These are passive or active devices designed to reduce harmonic currents in the system.

ii. **Isolation Transformers:** Isolation transformers can help protect sensitive equipment from harmonic distortion.

iii. **Load Management:** Limiting the use of non-linear loads during periods of high system demand can help reduce harmonic issues.

iv. **Power Factor Correction:** Properly designed power factor correction systems can mitigate some harmonic problems.

v. **Harmonic Surveys and Monitoring:** Regular monitoring and analysis of the power system can help identify harmonic issues and allow for targeted corrective measures.

2.7 Case of Rwanda (frequency, voltage angle, and harmonics)

In Rwanda, like in many other countries, frequency fluctuations might occur due to several reasons:

Demand-Supply Imbalance: If electricity demand exceeds the available supply, the frequency might drop. Conversely, if there's excess generation compared to demand, the frequency might rise.

Grid Disturbances: Events like sudden changes in load, faults in the transmission lines or power plants, or the connection or disconnection of large loads or generators can cause frequency fluctuations.

Renewable Energy Integration: Introducing a significant amount of renewable energy sources (such as wind or solar) into the grid can cause frequency fluctuations because their output can vary based on weather conditions.

Frequency Regulation: The grid operator uses frequency regulation mechanisms to maintain a stable frequency. These mechanisms include adjusting the output of power plants, utilizing energy storage systems, or employing demand response measures to balance generation and load.

Rwanda, like other countries, has measures in place to manage and regulate frequency fluctuations to maintain a stable and reliable power supply. Grid operators and regulatory bodies continuously monitor the grid's frequency and take actions to mitigate fluctuations and ensure the stability of the electrical system.

Harmonics in an electrical grid refer to the distortion or fluctuations in the normal sine waveform of alternating current (AC) power. In Rwanda, as in any other electrical grid system, harmonics can be present due to various factors, and managing them is crucial to ensure the stability and efficiency of the power system.

Some factors contributing to harmonics in the Rwandan grid could include:

Nonlinear Loads: Equipment such as variable frequency drives (VFDs), power electronics, computers, and certain types of lighting generate harmonics when drawing non-sinusoidal currents from the grid.

Renewable Energy Sources: Integration of renewable energy sources like solar panels and wind turbines can introduce harmonics due to their intermittent nature and the use of power electronics in their control systems.

Faults and Imbalances: Electrical faults, unbalanced loads, and poor power factor correction mechanisms can contribute to harmonic distortion.

Grid Interference: Interactions between different parts of the grid, such as interactions between transmission lines and distribution systems, can cause harmonics.

Switching Operations: Rapid switching actions in power electronics and equipment can generate harmonics.

Managing harmonics is essential to prevent issues such as overheating in equipment, voltage fluctuations, and disruptions in power quality. Here are some measures that can be taken to mitigate harmonics:

Harmonic Filters: These are designed to reduce specific harmonics and improve power quality. They can be installed at strategic points in the grid to mitigate the effects of harmonic distortion.

Use of Power Factor Correction Equipment: Installing capacitors and other power factor correction devices can help improve power quality and reduce harmonics.

Proper Design and Installation: Ensuring proper design and installation of electrical systems, including grounding and shielding, can minimize harmonic distortions.

Voltage angle in an electrical grid refers to the phase difference in voltage waveform between different points in the power system. In Rwanda's electrical grid, just like in any other grid, voltage angles play a crucial role in maintaining the stability and reliability of the power supply.

The voltage angle represents the phase relationship between voltages at different points in the grid. In an alternating current (AC) system, the voltage waveform periodically oscillates between positive and negative values. The voltage angle measures the degree of rotation of this waveform concerning a reference point, usually defined as zero degrees.

Maintaining proper voltage angles is essential for ensuring the stability of the grid. In a synchronized AC power system, generators are connected in parallel and must operate at the same frequency and with consistent voltage magnitudes and angles to maintain stable and balanced power transfer.

Voltage angle control is crucial in managing power flows and avoiding issues such as voltage instability or even system-wide outages. When there are discrepancies or imbalances in voltage angles between different parts of the grid, it can lead to problems such as:

Voltage Instability: Differences in voltage angles between interconnected areas can cause reactive power flows, affecting voltage stability and potentially leading to voltage collapse.

Transient Stability Issues: During disturbances or faults, improper voltage angles can affect the ability of the system to maintain stable operation.

Loss of Synchronization: Large differences in voltage angles between different parts of the grid can lead to the loss of synchronization among generators, potentially causing cascading failures.

Managing voltage angles involves control mechanisms within the power system, including:

Automatic Voltage Control (AVC) Systems: These systems continuously monitor and adjust voltage and reactive power to maintain proper voltage angles and ensure stability.

Power System Stabilizers (PSS): These are used in synchronous generators to enhance stability by adjusting the generator's excitation system to control the voltage angle.

Load Shedding and Control Systems: These systems are designed to manage imbalances and alleviate stress in the grid by shedding load or controlling the flow of power during critical situations.

2.7.1 Methods of addressing stability

The capacity of an electrical grid to provide a steady and balanced supply of power in the face of variations in supply and demand is known as grid stability. Here are several methods used to address grid stability:

Energy Storage Systems: Supply and demand can be more evenly distributed by putting in place energy storage devices like flywheels, pumped hydro storage, or batteries, which store extra energy during periods of low demand and release it during times of peak need.

Demand Response Programs: By controlling demand variations, smart grid technology or incentive programs can assist stabilize the system by encouraging users to use less power during peak hours.

Distributed Energy Resources (DERs): By decreasing reliance on centralized power plants and diversifying energy sources, the integration of distributed energy resources such as microgrids, solar panels, and wind turbines into the grid can improve stability.

Grid Modernization and Automation: Upgrading grid infrastructure with advanced monitoring, control systems, and automation technologies allows for better real-time monitoring and control of the grid, enabling faster responses to fluctuations and disturbances.

Frequency Regulation: Maintaining the frequency of the grid within a specific range is crucial for stability. Automatic generation control (AGC) systems help adjust power generation to match demand, thereby stabilizing the grid frequency.

Grid Interconnections and Redundancy: Interconnecting multiple regional grids and creating redundancies within the system can improve stability by allowing for power transfer between regions and providing backup options in case of failures.

Predictive Analytics and AI: Implementing predictive analytics and artificial intelligence (AI) technologies can forecast demand patterns, identify potential grid issues beforehand, and optimize grid operations for better stability.

Grid Resilience Planning: Developing comprehensive plans for grid resilience involves assessing vulnerabilities, implementing measures to mitigate risks from natural disasters, cyber threats, or physical attacks, and ensuring a quick recovery in case of disruptions.

2.8. Complexity of the grid with renewable energy

Instability in the grids can result from variations in the supply and demand of energy for a specific location while producing power using solar energy. These variations arise from the fact that, for example, the amount of sunshine in an area where residences are equipped with solar panels fluctuates periodically. Therefore, there will always be periods when there is little power generation from renewable energy sources in homes, workplaces, or other end uses, even while the shift to sustainable energy is ongoing. In addition, waste may occur during periods of plentiful supply if grid operators fail to implement appropriate safeguards. [15]

The wind speed in these applications is what causes these variations. Using renewable energy sources has drawbacks of its own that require clear answers. These solutions can include alternatives for storing energy, managing variations, and requirements unique to a given renewable energy source; for instance, solar power solutions would differ, if not slightly, from solutions for hydropower, thermal energy sources, wind farms, and the rest.

In addition, the renewable energy-producing wind turbines are running at full capacity. However, fluctuations in power generation pose a danger to the stability of the systems.

When it comes to implementing renewable energy sources, conventional networks encounter the following three main obstacles:

1. Frequency and voltage anomalies

The frequency and voltage produced are somewhat unreliable due to the stochastic nature of the production of solar and wind energy. Solar power generation system fluctuations are supposed to be adjusted by power inverters. However, their inability to effectively carry this out has shown. Also, the time and the atmospheric conditions ceaselessly influence the creation of force. The grids' performance is seriously impacted by these conditions, pushing them to their limits.

2. Overloading of existing transmission lines

During peak hours, matching the power's inflow and outflow with increased loads presents a challenge for the existing transmission lines. When producers generate too much power without warning, a surge can occur, which would cause the entire system to fail. Thermal loads will build up on a transmission line if this capacity is exceeded, resulting in damage.

3. Demand and supply mismatch

As much as many homes, workplaces, and structures need the ability to run their tasks, it can't be at a time. At times, the production of renewable energy can reach very high levels. However, it can also be low in other circumstances. As a result, the generated power may not be sufficient or meet the demand when it is needed. [15]

How They Can Be Solved

Grids using renewable energy sources can overcome the challenges they face. As difficulties emerge, new innovations that can really handle these moves begin to introduce an answer. Dissemination Framework Administrators can recover network solidness by applying strategies and innovation to guarantee the compelling variation of sustainable power in the power area.

1. Use of energy storage technologies

Energy capacity is an incredible method for handling the matrix dependability issues with environmentally friendly power. Mobile batteries are included as well as immobile lithium-ion batteries. The utilization of 'moving' batteries includes energy capacity in electric vehicles utilizing V2G innovation. One of the technologies that plays a role in specially configured battery systems is virtual transmission. They alleviate congestion on transmission lines and aid in maintaining grid stability.

2. Implementation of Smart grids

Smart grids have many features working together intelligently. The most invaluable elements that influence network security incorporate the control and correspondence frameworks. Additionally, imbalances in power distribution can be detected and evaluated by the sensors. Along these lines, the hardware's wellbeing is firmly checked. Consequently, you can guarantee framework solidness with brilliant networks, and Hive Power gives the advances expected to this execution.

Grid and tally these increases with their corresponding costs. Additionally, operators can discover renewable energy and grid stability options in:

- Installing several reactive power compensation plants and building high voltage direct current (HVDC) transmission links from the generating centers to the load centers. The application of traditional load flow controllers, which, when compared to the rate at which renewable energy demand is increasing, proved to be too slow.
- Unified power flow controller's dynamic load flow management system, which appears to be the best option, can respond quickly. This arrangement ought to keep electrical cables inside the n - 1 basis adjusted by overseeing both series and equal pay, which would keep the power on and streaming at ideal. [16]

2.9. Related work from National and International Context

Mateusz Michalski, Grzegorz Wiczy´nski,2016 [17] They wrote on Determination of the parameters of voltage variation with voltage fluctuation indices.

The parameters that describe Several voltage variation measures are included in the quality of power in power grids. The voltage fluctuation indices are one of these measures, composed of magnitude, _*U*, and rate, *f*, of fluctuations. This research shows example of the use of this measure to reconstruct the voltage changes.

Measures of voltage variation are fundamental parameters that determine the quality of electricity in power grids. The estimation and assessment of voltage variety is a complex metrological issue. Power grid load changes are typically the cause of voltage variation.

The results of the analysis are time plots for rates of voltage changes in a selected ranges of the changes' absolute values. A magnitude rate characteristic is used to assess the obnoxiousness of voltage fluctuations. They have shown that voltage variation may cause fluctuation but they didn't propose a way to avoid this fluctuation caused by voltage variation.

Edward Reid,1996 [18] This paper frames the huge elements related with power quality by summing up the key contemplations, the pertinent norms, the regions where principles are being created, and helpful application rules. System disturbances, harmonic distortion, and grounding are the three main categories under which power quality is discussed. The researcher didn't discuss Angle stability in this research.

Gilbert S,2021 [19] did a study of assessment of the stability of Rwanda's power system from big data based on power generation. Rwanda's citizens have access to electricity at a rate of 53%, or 224 MW, making the country's supply of electricity inadequate. However, even among 53% of electrification, there are still some blackouts and erratic outages in cities during the night when many devices are connected on the system. This blackout and sudden shutdown could make the power system stability of Rwanda to be questionable and it can be so-called unstable. In his study, the current and proposed Rwanda power generation sector, transmission sector, and distribution sector have been discussed. In this study, the researcher didn't mention the better way to prevent power fluctuation

Tchawou Tchuisseu, E.B.; Gomila, D.; Colet, P. (2019). [20] They did their research on Reduction of power grid fluctuations by communication between smart devices.

This paper shows that the increase of the electric demand and the progressive integration of renewable energy sources threatens the stability of the power grid. Instead of increasing the spinning reserve in the supply, a number of strategies to control the demand side have been proposed as a solution to this problem.They have focused on dynamic demand control (DDC), a method in which smart devices can autonomously delay its scheduled operation if the electric frequency is outside a suitable range. The Researchers focused only on Dynamic demand control using smart devices and they didn't show clearly how the grid voltage must be stable to avoid fluctuation.

Power quality problem in Rwanda Grid network

To the greatest extent feasible, the electric power system need to be dependable, steady, and predictable. The frequency and the voltage within allowable bounds determine the system's stability.

Mutual agreements between the components that produce and consume ensure that their equipment is strictly controlled. Harmful loads that may require specific starting methods and equipment utilizing power electronics and switching devices cause voltage distortions and harmonics to enter the system.

A careful regulation of the power quality disturbance in voltage and frequency within allowable limits is necessary due to the Rwanda Grid Systems' increasing complexity in terms of new technologies and automation.

That reason why Rwanda grid has problems to manage the reactive power, where the voltage increased during peak hour and decreased in off peak. the main problems on Rwanda grid is Reactive Power, Overvoltage and under voltage, frequency those caused by the non-linear load

The reactive power in the power system in Rwanda grid increased in lightly loaded where power plant start for consuming that reactive power produced by transmission line where some transmission lines 2020Kv are closed.

The main power plants that consume the reactive power are Kivuwatt -7.5MVAR, Nyabarongo hydro -7Mvar, Mukungwa -4Mvar, Ntaruka -3Mvar and Jabana -3Mvar, those reactive power consumed in only one machine in power plant mentioned. whenever the power plant reaches on a maximum of reactive supposed to be consumed, the operators send their remaining reactive power to Mururu 2 for consumption by interconnected countries like Congo and Burundi in case those countries are not consuming that reactive power and reverse power which is located at Ntendezi substation opened and Rwanda grid voltage swells up because of excess of that reactive power. those reactive power consumed by machines in power plants affected machine windings. the average of reactive power was sent to Mururu 2 varie according to the load and voltage of the system in Rwanda Grid (**information from National Electricity Control Center of Rwanda Grid<** NECC>).

Distribution lines and Load

The variation of load depends on the day and hours, there a normal days and holidays where we have peak hours and off-peak, during peak hours the load increases, and off-peak, the load decreases. the voltage depends on the load variation and the reactive power consumed and generated however the reactive power increased in the system, the voltage also increased.

Rwanda Grid manages the load for the following methods

1. **Spinning reserve:** in normal it must be 10 percent of Demand, whenever the one largest generator trips on the grid system and also the frequency drop within different time, automatically we use this spinning reserve in order to balance demand and generation
2. **Standby Generators:** extract generating capacity which is not connected to grid system, this one is used when the load increased, it is not connected grid
3. **Load shedding:** we use this system in order to keep the frequency, Voltage within permissible limits, this system is occurred.

Relationship between voltage drop and reactive power in power system

The equipments in the power system are fabricated to operate adequately when level of voltage is within the range of their rated values. If the voltage level deviates, there will be deterioration of performance. In the short line, the total magnitude of the voltage drop in the single line is expressed by:

$$|\Delta V| = IZ = |V_S| - |V_R| \tag{2.1}$$

$$|\Delta V| = IZ = IR\,Cos\emptyset_r + IX\,Sin\emptyset_r = \frac{1}{V_R}[(V_R I\,Cos\emptyset_R)R + (V_R I\,Sin\emptyset_r)X] \tag{2.2}$$

$$= \frac{RP_r + XQ_r}{V_r} \tag{2.3}$$

$X \gg R$, in transmission line and the resistance R will not be considered,

And Then,

$$|\Delta V| = \frac{XQ_r}{V_r}\ , \qquad Q_r = \frac{V_r}{X}\,|\Delta V| \tag{2.4}$$

The relation in (2.9) shows that the reactive power Q_r is proportional to the magnitude of voltage drop in the line. Thus, reactive power control and voltage control are interrelated [21]

To ensure that the voltage magnitudes always remain at the predetermined levels, Maintaining the system's reactive power balance is essential. To put it another way, the amount of reactive power generated and consumed (absorbed) should be precisely equal. The bus voltage magnitudes are affected by any mismatch in the reactive power balance without significantly affecting the system frequency.

CHAP 3. METHODOLOGY

3.0. Introduction

In order to achieve the objectives and desired targets in this thesis, a combined methodology is used. It is including data collection and simulation of the model based on the collected data in order to highlight the effect of different parameters in power grid.

3.1. Data Collection

As our case study focus on the Northern Province, different data from substations, stations, and transmission lines are collected. Data used are collected from REG (Rwanda Energy Group) especially in Northern Zone. Used datas are from Substations (Campbelge and Gifurwe) and from Hydropowers (Mukungwa and Ntaruka). All those Substations and Hydropower plants are linked by Transmission and Distribution lines.Active Power P,Reactive Power Q,Power Factor, Frequency f,Voltage and currents are collected from those substations and Hydropower plants in 24 hrs.

Power Plants, Substations, Transmission and Distribution Lines

Power Plants

No	name	Generating Capacity	
		MW	MVAR
1	Ntaruka	9	124
2	Mukungwa	12	6

Transmission Lines

No	Name	Line Length(Km)
1	Ntaruka-Mukungwa	27
2	Mukungwa-Gifurwe	18.5
3	Gifurwe-Rulindo	25

Distribution Lines

No	Feeder Name	Load		Length(Km)
		MW	MVAR	
1	Cyanika	9.4	6.2	35
2	Ruhengeri from Ntaruka	1.9	2	30
3	Janja	0.5	0.4	90
4	Ruhengeri from Mukungwa	2.1	0.4	6
5	Rwaza	2.5	0.3	9

6	Kirambo	2	0.5	60
7	Gakenke	0.9	0.3	28
8	Ntaruka from Gifurwe	4.5	2.1	10
9	Musanze	2.5	0.6	35
10	Kinigi	1.8	0.3	20
11	Prime Cement	2.5	0.9	7

Table 1:Power Plants, Substations, Transmission and Distribution Lines

Load on Janja and Rwaza feeder from Mukungwa on 18th November 2023

JANJA		RWAZA	
HOURS	**Load(MW)**	**HOURS**	**Load(MW)**
0:00	0.2325	0	2.4458
1:00	0.3453	1	2.6785
2:00	0.2356	2	2.6477
3:00	0.2745	3	2.6456
4:00	0.2356	4	2.5454
5:00	0.3585	5	2.3451
6:00	0.3784	6	2.5984
7:00	0.3152	7	2.5454
8:00	0.2586	8	1.9785
9:00	0.3458	9	1.5451
10:00	0.3145	10	2.5456
11:00	0.2365	11	1.3452
12:00	0.2456	12	2.5456
13:00	0.3365	13	2.1451
14:00	0.2456	14	2.1456
15:00	0.3785	15	2.3458
16:00	0.3655	16	2.2451
17:00	0.3485	17	2.2356
18:00	0.3658	18	2.2485
19:00	0.5254	19	2.1456
20:00	0.6485	20	1.3665
21:00	0.5585	21	1.3485
22:00	0.3352	22	2.4485
23:00	0.3456	23	2.5456

Table 2: Hourly Load status at Janja and Rwaza feeder on 18th November 2023

Load Status recorded on 23rd November 2023 at Ntaruka,Gakenke,Kirambo and Musanze Feeders

NTARUKA		KIRAMBO		GAKENKE		MUSANZE	
HOURS	**Load(MW)**	**HOURS**	**Load(MW)**	**HOURS**	**Load(MW)**	**HOURS**	**Load(MW)**
0:00	2.89116	0:00	1.31822	0:00	0.233023	0:00	2.08508
1:00	2.73387	1:00	1.16356	1:00	0.224957	1:00	2.57418
2:00	2.62174	2:00	1.19078	2:00	0.216514	2:00	2.64123
3:00	2.48489	3:00	1.19246	3:00	0.215727	3:00	2.58925
4:00	2.42576	4:00	1.13494	4:00	0.215005	4:00	1.94223
5:00	2.57407	5:00	1.06366	5:00	0.217882	5:00	1.41064
6:00	2.90372	6:00	1.01671	6:00	0.231978	6:00	0.826887
7:00	3.10469	7:00	1.07066	7:00	0.231058	7:00	0.70377
8:00	3.30699	8:00	1.19155	8:00	0.250721	8:00	0.698623
9:00	3.26486	9:00	1.13316	9:00	0.259512	9:00	0.388371
10:00	3.48214	10:00	1.17051	10:00	0.318871	10:00	0.311824
11:00	3.42694	11:00	1.17279	11:00	0.343607	11:00	0.127722
12:00	3.19651	12:00	1.21792	12:00	0.326771	12:00	0.00943192
13:00	3.12694	13:00	1.51995	13:00	0.309034	13:00	0.22758
14:00	3.17756	14:00	1.30385	14:00	0.269841	14:00	1.60731
15:00	3.32531	15:00	1.36757	15:00	0.251985	15:00	1.40245
16:00	3.17192	16:00	1.01012	16:00	0.222454	16:00	1.33035
17:00	3.40768	17:00	1.24473	17:00	0.231897	17:00	1.60124
18:00	3.45164	18:00	1.04673	18:00	0.274392	18:00	2.05521
19:00	4.51123	19:00	0.807955	19:00	0.337571	19:00	1.45075
20:00	4.50553	20:00	0.879085	20:00	0.324974	20:00	1.32054
21:00	4.23659	21:00	0.880316	21:00	0.300325	21:00	0.540681
22:00	3.84025	22:00	0.935214	22:00	0.254784	22:00	2.14656
23:00	3.16721	23:00	0.991256	23:00	0.212782	23:00	2.4123

Table 3:24 hrs load status on Ntaruka,Kirambo,Gakenke and Musanze feeders

Load status at Kinigi and Prime cement on 9th August 2023

KINIGI		PRIME CEMENT	
HOURS	Load(MW)	HOURS	Load(MW)
0:00	1.08547	0:00	2.35673
1:00	0.99267	1:00	2.22625
2:00	0.97935	2:00	2.18168
3:00	0.95037	3:00	2.3563
4:00	0.92376	4:00	2.14103
5:00	0.95629	5:00	2.27796
6:00	1.09818	6:00	2.36969
7:00	1.13866	7:00	2.22619
8:00	1.22371	8:00	2.19491
9:00	1.26343	9:00	2.33836
10:00	1.29459	10:00	2.41019
11:00	1.29518	11:00	2.3274
12:00	1.28606	12:00	1.77336
13:00	1.08412	13:00	1.3516
14:00	1.05717	14:00	2.14363
15:00	1.06241	15:00	2.3113
16:00	1.08814	16:00	2.35939
17:00	1.13936	17:00	2.38075
18:00	1.19865	18:00	2.36774
19:00	1.54769	19:00	2.54241
20:00	1.65664	20:00	2.34025
21:00	1.53622	21:00	2.06231
22:00	1.36412	22:00	2.30426
23:00	1.12914	23:00	2.54051

Table 4:Kinigi and Prime cement on 9th August 2023

Simulation software (ETAP in our case)

ETAP (Electrical Transient Analyzer Program) is a widely used software tool for electrical power systems analysis and design. It's primarily designed for modeling, simulating, and analyzing electrical power systems, including power generation, transmission, distribution, and industrial systems. Its functionalities and the general architecture based on its known features:

User Interface (UI): ETAP has a graphical user interface that allows users to interact with the software easily.

It typically includes menus, toolbars, project explorer, and various windows for displaying system data, diagrams, reports, and simulation results.

Database and Project Management: ETAP organizes projects and system models using a database-like structure.

Users can create, manage, and store different projects containing electrical system models, simulation scenarios, and analysis results.

Modules and Functionalities: ETAP consists of various modules for different analyses and functionalities:

Load Flow Analysis: Determines the steady-state operating conditions of the power system.

Short Circuit Analysis: Calculates fault currents and helps in selecting protective devices.

Transient Stability Analysis: Evaluates the system's ability to maintain synchronism after a disturbance.

Harmonic Analysis: Evaluates harmonic distortion and its effects on the system.

Optimal Power Flow (OPF): Optimizes the power flow within the system to meet certain criteria.

Relay Coordination: Helps in coordinating protective devices to ensure proper system protection.

Solver and Algorithms: ETAP uses numerical algorithms and solvers to perform various calculations, simulations, and analyses based on the selected modules.

These solvers employ mathematical models and algorithms specific to each analysis type (e.g., Newton-Raphson method for load flow analysis, numerical integration for transient stability analysis).

Modeling Components: Users can model various system components like generators, transformers, transmission lines, circuit breakers, relays, motors, loads, etc., using data input specific to each component type.Each component is represented by mathematical equations and models that simulate its behavior within the power system.

Reporting and Visualization: ETAP generates reports and visual representations (diagrams, charts, graphs) of simulation results, allowing users to analyze and interpret the findings.

Integration and Data Exchange: ETAP may support importing and exporting data to and from other software or formats, enabling interoperability with other engineering tools.

Based on the data collected and the northern network architecture, the model in ETAP have been built. It can be shown below:

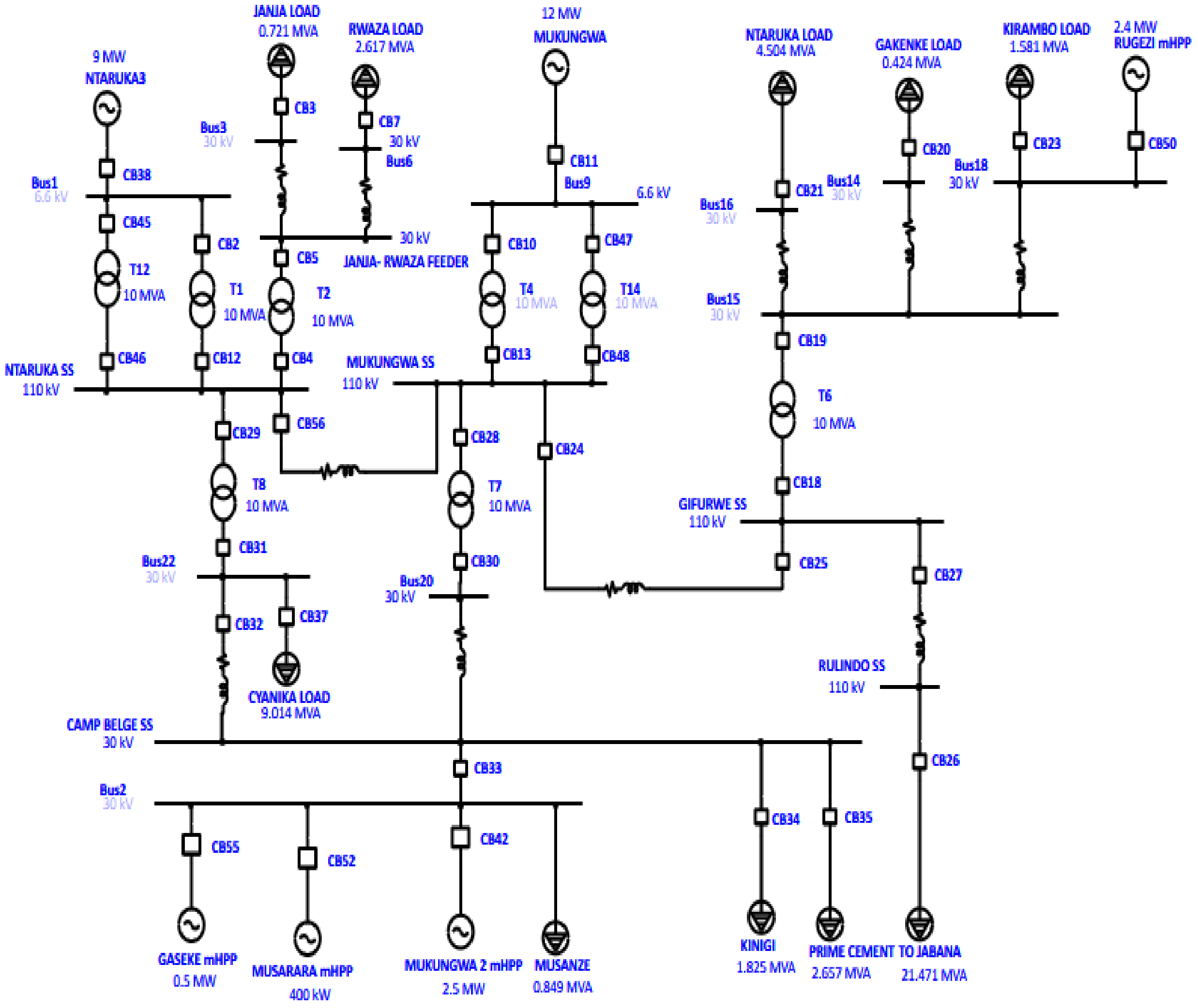

Figure 8: All connection of transmission and distribution lines in Northern Zone

CHAP 4: SIMULATION RESULTS AND DISCUSSION

4.1 System behavior under disconnection and connection of different Feeders

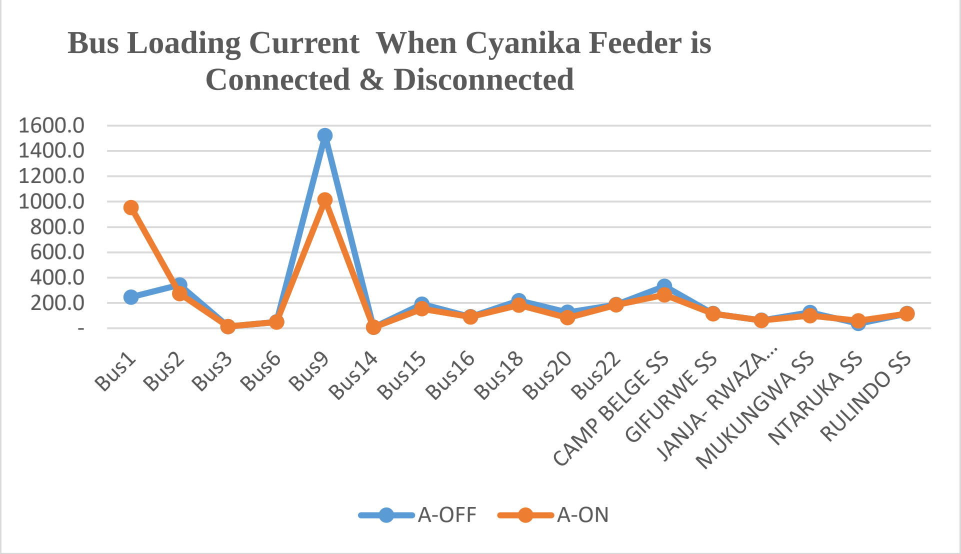

Figure 9: Loading current when Cyanika feeder is connected&Disconnected

When Cyanika feeder is disconnected from the grid due to any disturbance, the current on Bus 9 increases sharply as can be observed in figure above and below. This may result in overcurrent problems. As results, the overcurrent protection system will be activated, and Mukungwa side will be disconnected. If this continues, the effect may propagate through whole system and result in outage of the system.

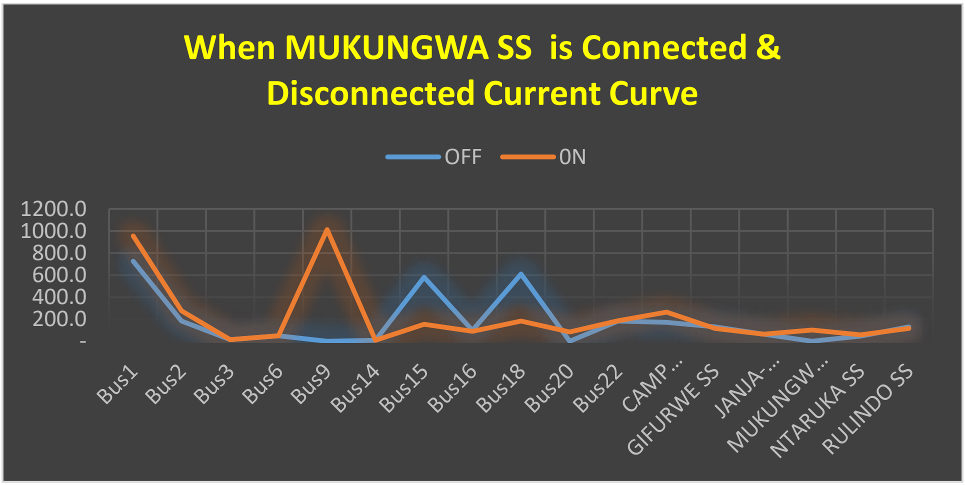

Figure 10:Current curve when Mukungwa ss is connected and Disconnected

When Mukungwa Substation is disconnected, the sudden change of Current at Bus 9 can cause the Relay and Circuit breaker to trip leading to power outage. Not only can result into blackout, but also the losses in other buses increase. The increases in losses can be observed in figure below.

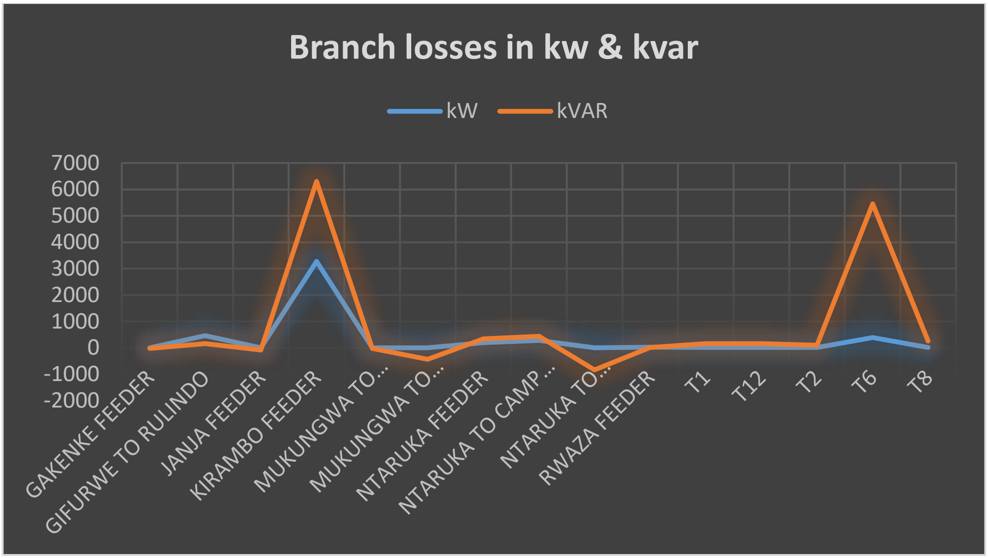

Figure 11: Branch losses in kW and kVAR when Mukungwa ss is connected and Disconnected

When Mukungwa ss is disconnected, also the buses voltage changes respectively as shown in figure below. Voltage decreases on the following feeders: Gifurwe to Rulindo, Gakenke Mukungwa to Gifurwe, Ntaruka and on T6. This voltage decreases to 80% of 110Kv Causing feeders to trip.

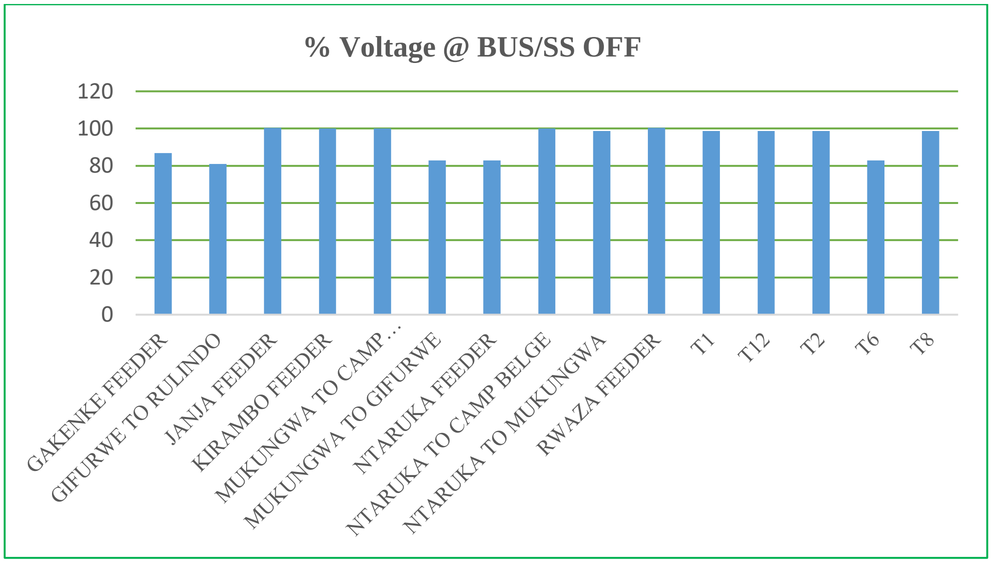

Figure 12: Percentage voltage at Bus/Substation off

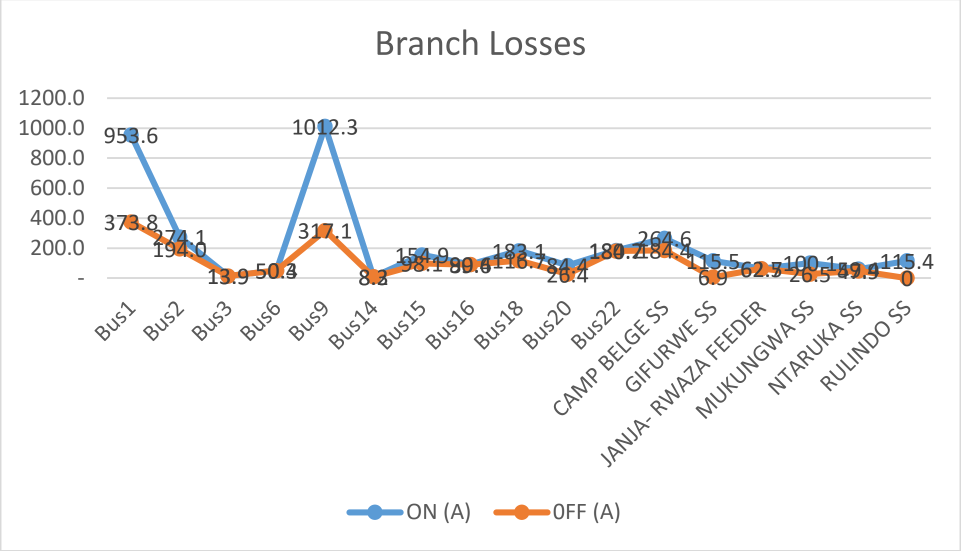

Figure 13: Branch losses when Rulindo transmission line is disconnected

The issues of losing generator at bus 1 and 9 (Ntaruka and Mukungwa) may occurs in the system when the load at Rulindo substation change suddenly. This may be caused by the sudden increase of current at the specified buses 1 and 9. From Figure above, it can be noted that current change from 1012.3A to 317.1A at bus 1.

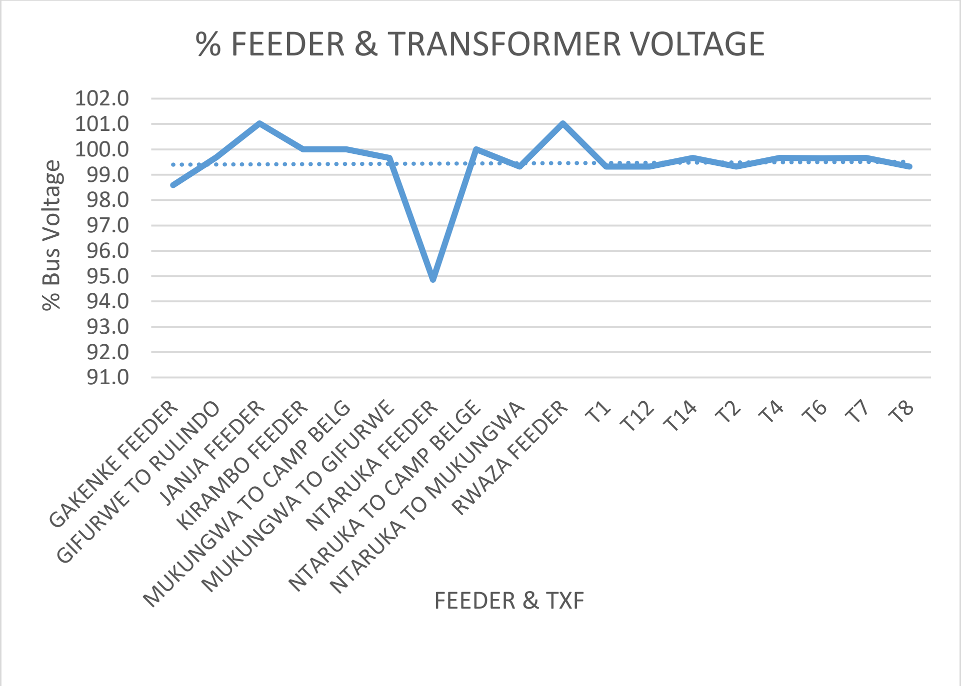

Figure 14: Voltage behavior at different feeders when load at Rulindo SS is disconnected

When Rulindo ss is disconnected, there is a change of voltage on different feeders where Ntaruka feeder voltage decreases to 94.5% and Rwaza feeder and Janja feeder increase to 101%, all of those behaviors cause fluctuation in network.

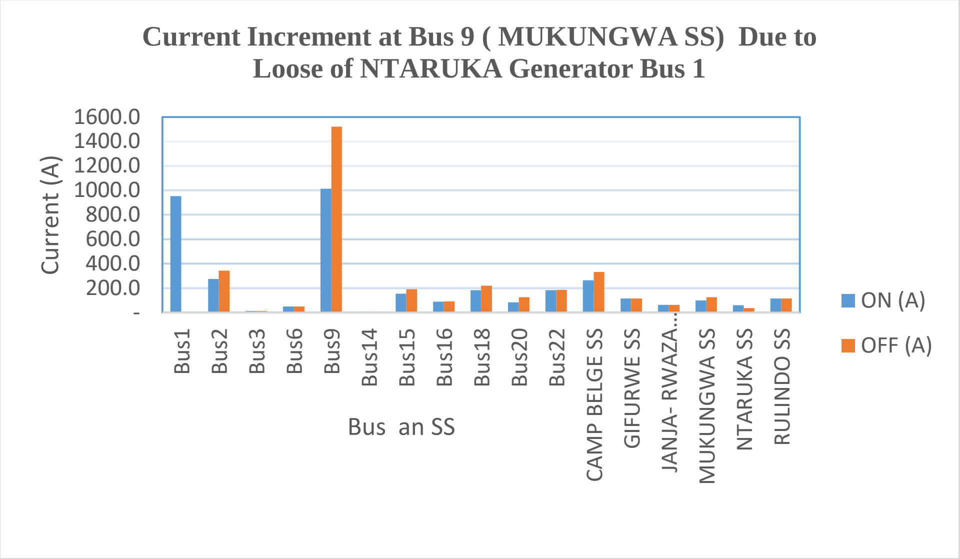

Figure 15: Bus loading current when Ntaruka Generator bus 1 is disconnected

When Generator at bus 1 lost, Ntaruka will be disconnected, there will be an increase of current at Bus 9, which is Mukungwa SS. This issue can be observed in Figure 15.

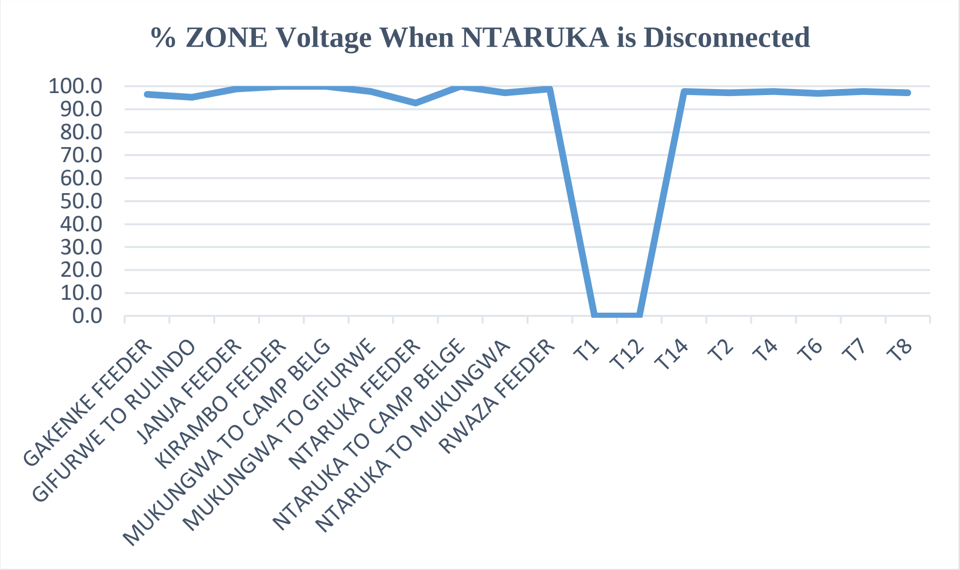

Figure 16: Voltage profile when Ntaruka is disconnected

From Figure 16, it can be seen that voltage at T1 and T2 decrease to zero due to the loss of Ntaruka SS. The rest of feeder connected in this region will be affected as voltage will decrease due to the reference substation losses.

4.2 Behavior of Ntaruka and Mukungwa when a phase to phase fault occur at Gifurwe ss

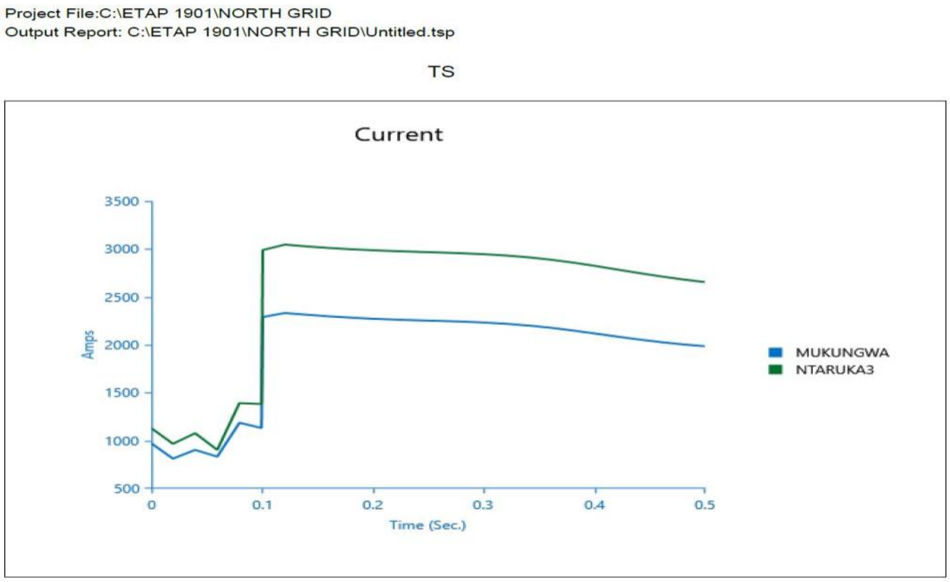
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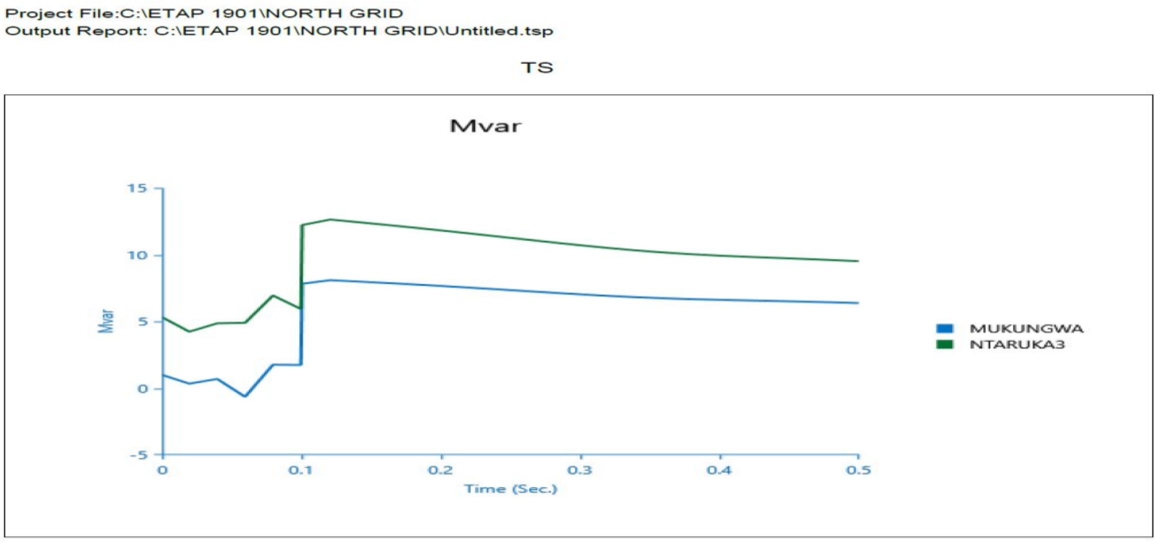
Figure 17: Current increament at Mukungwa and Ntaruka during a fault Gifurwe SS

If the fault happens at Gifurwe Substation, in 0.1 time second, the current will increase and causes overcurrent in network. When the fault at 0.5 times second is cleared, the system may regain its stable operation. However, the longer the fault will persist, the system may collapse as can be observed in Figure (a). Respectively, the reactive power also increase as the current increase as can be observed in Figure (b) below also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(b)

Figure 18: Reactive Power increases at the time when the fault occurred to Gifurwe Substation

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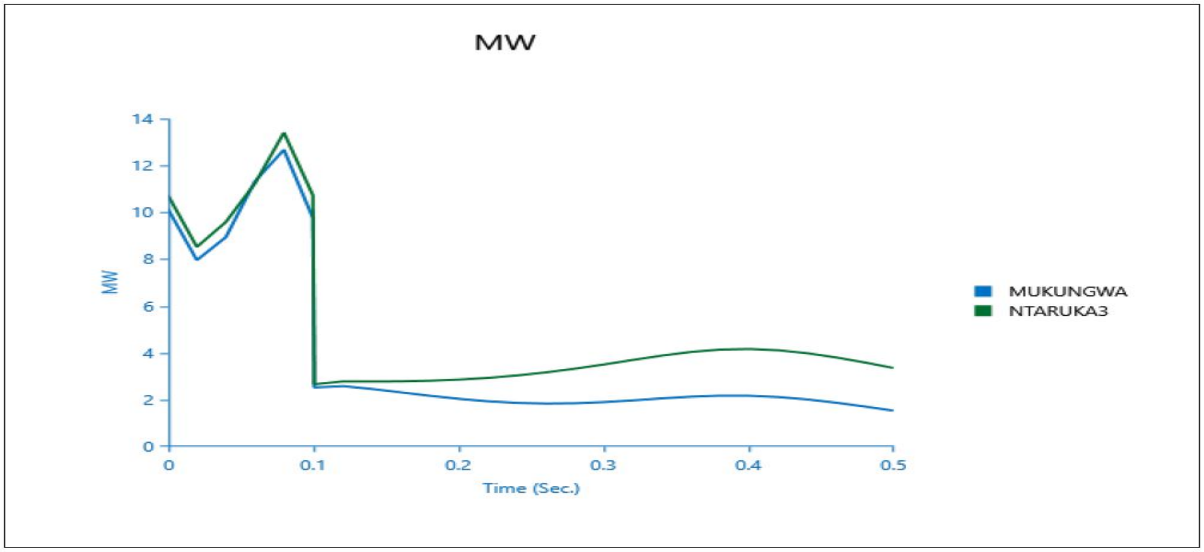

(a)

Figure 19: Active Power decreases at the time when the fault occurred to Gifurwe Substation

Due to the phase to phase fault at Gifurwe substation, Power will decrease to Mukungwa and Ntaruka and this loss of Mukungwa and Ntaruka production power, the whole system will trip. As the power from Ntaruka, and Mukungwa are decreased due to fault at Gifugwe, the generators speed increase and Power Angle also will increase for both Mukungwa and Ntaruka as can be observed in figures below (Figure 20 and Figure 21).

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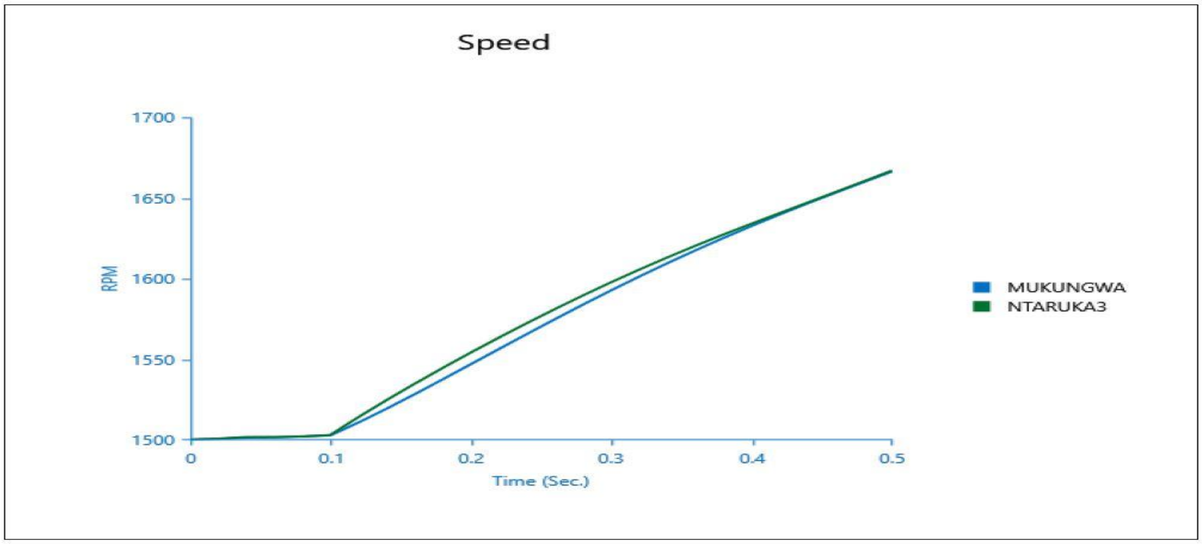

Figure 20: The generator speed increase due to the loss of synchronism.

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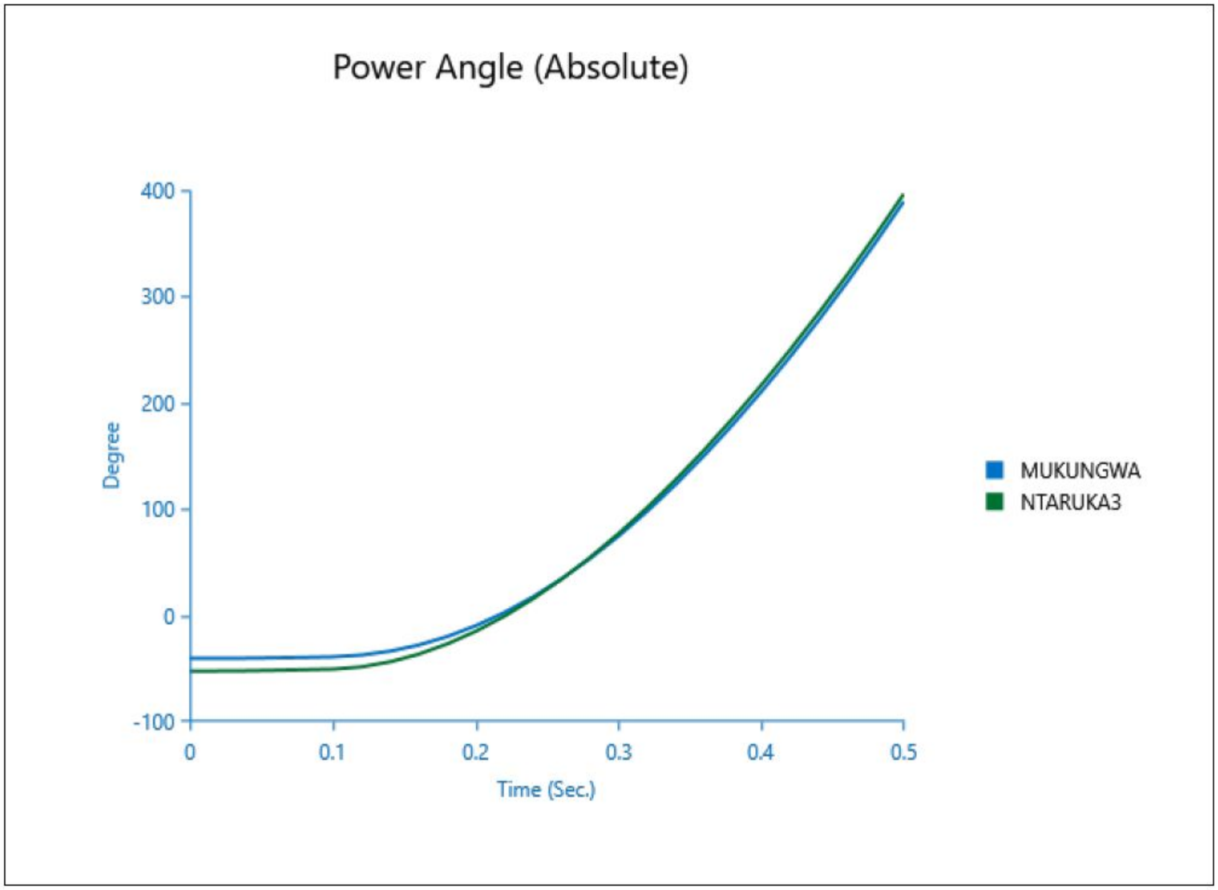

Figure 21: Power angle increases at Mukungwa and Ntaruka

4.3 Effect of LLG (phase to phase) fault occurred at Gifurwe ss

During the phase to phase fault happened at Gifurwe Substation, the Voltage, Active Power, Reactive Power will decrease at all buses and and the system frequency will increase. This over frequency will result to total shutdown of the network as shown on figure (22), (23), (24) and (25) below:

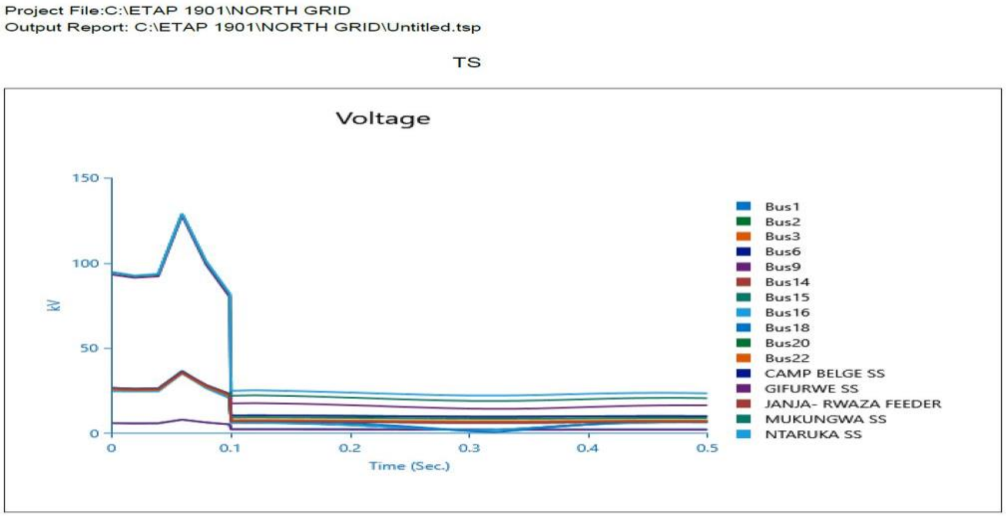

Figure 22: Voltage situation during phase to phase fault at Gifurwe Substation

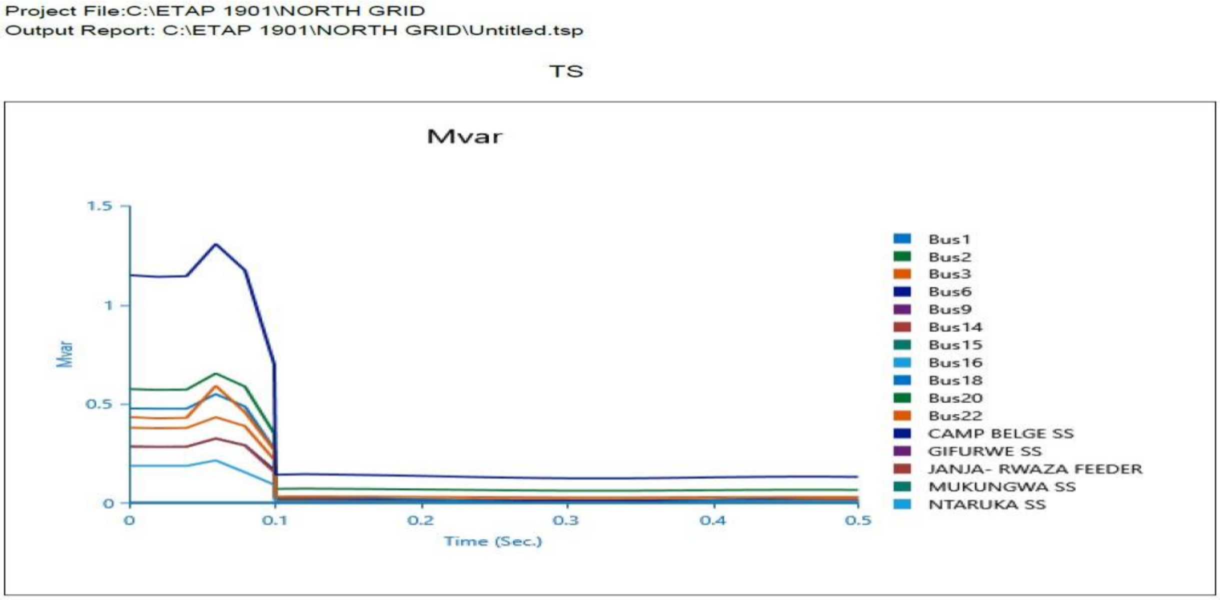

Figure 23: Decrease of Reactive Power

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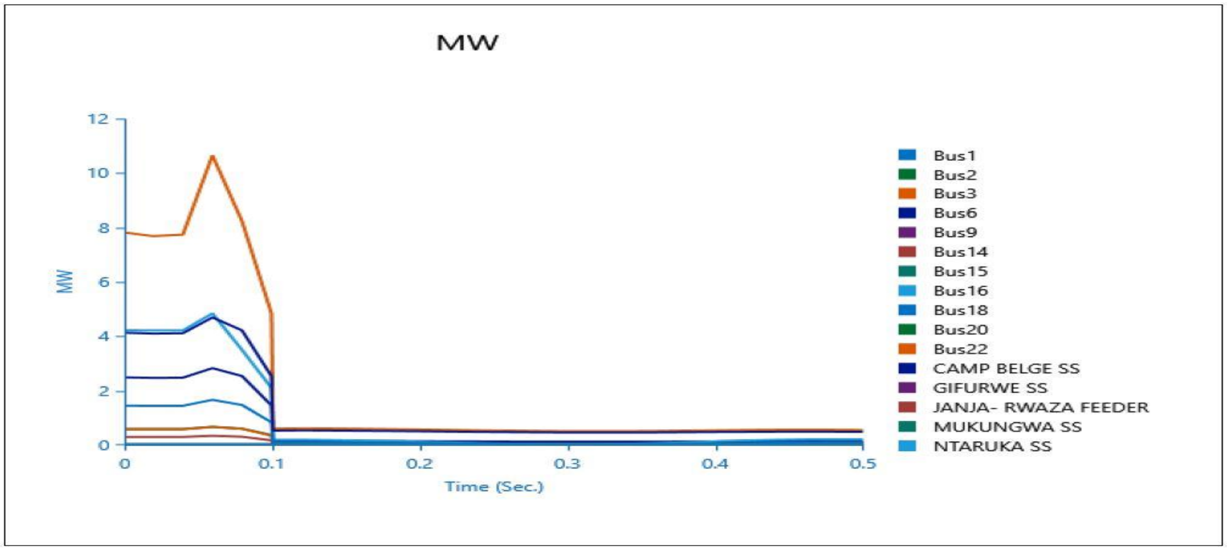

Figure 24: Decrease of Active Power

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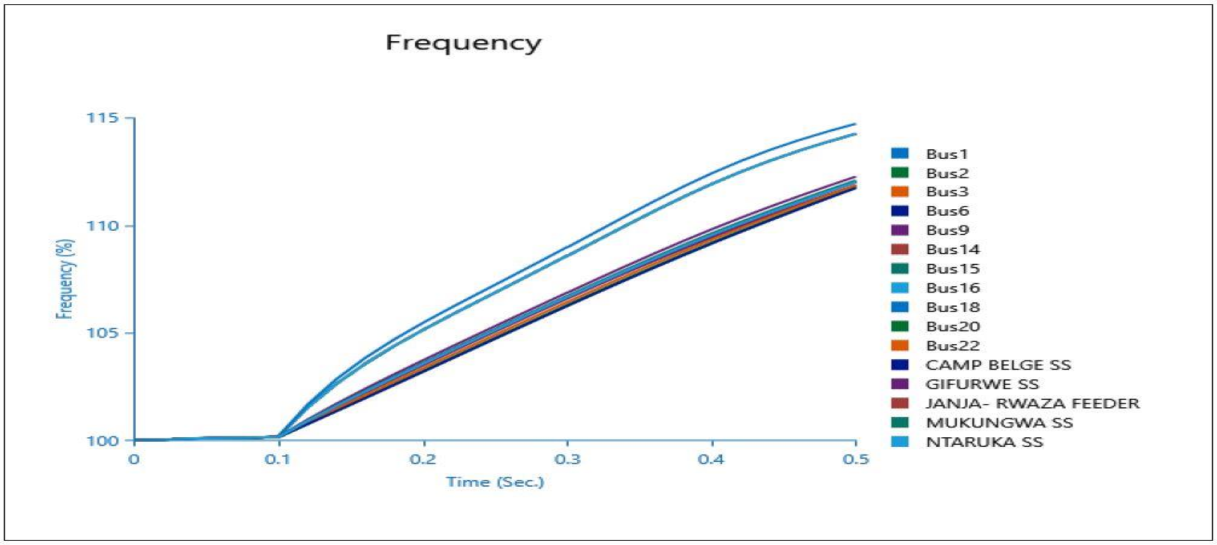

Figure 25: Increase of frequency

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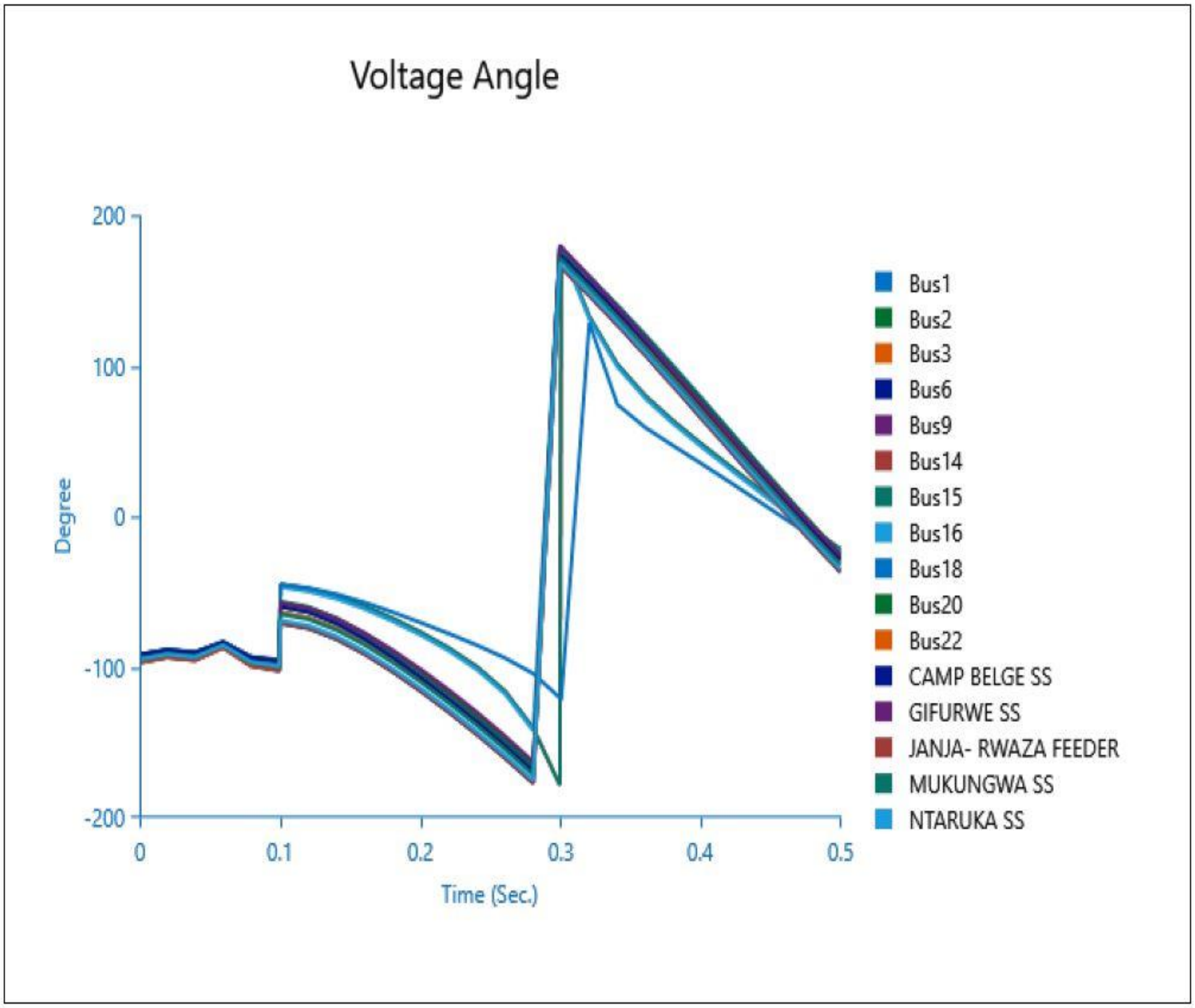

Figure 26: Voltage Angle fluctuation during a fault at Gifurwe Substation

Figure 26 shows how the Voltage angle fluctuates at all buses and substation. It can be observed that the abnormal change of voltage angle is induced by the fault at Gifurwe substation and result in power failure.

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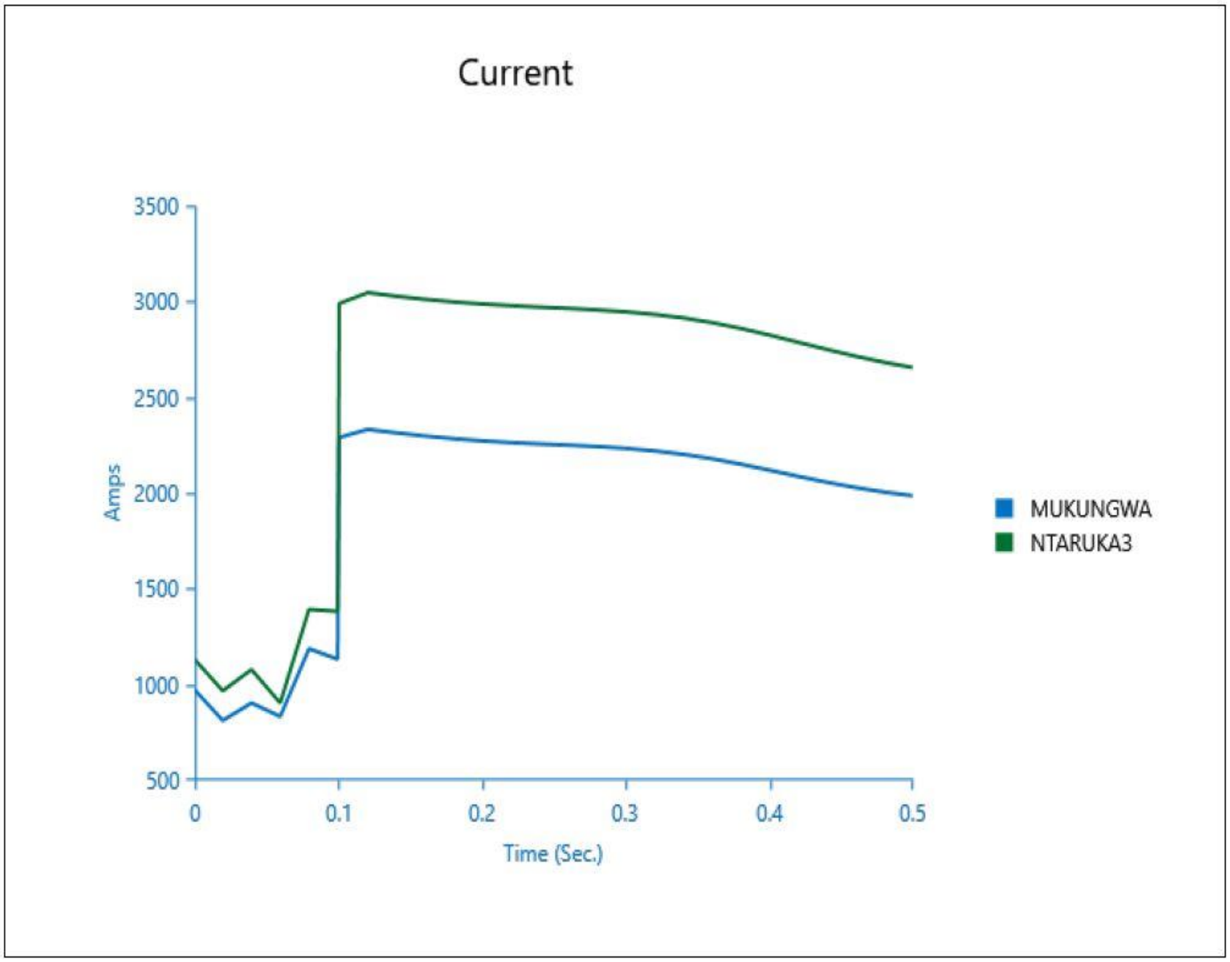

Figure 27: The Current increases during a phase to phase fault at Gifurwe Substation

From Figure 27, there will be increment of current at Mukungwa and Ntaruka which will cause overcurrent, at the corresponding buses due to Gifurwe ss fault. Due to the mentioned system behavior, the overcurrent protection system is activated for the protection purpose. Correspondingly, during that period, Reactive Power increase as the Load decreases as shown in Figures 28 and 29.

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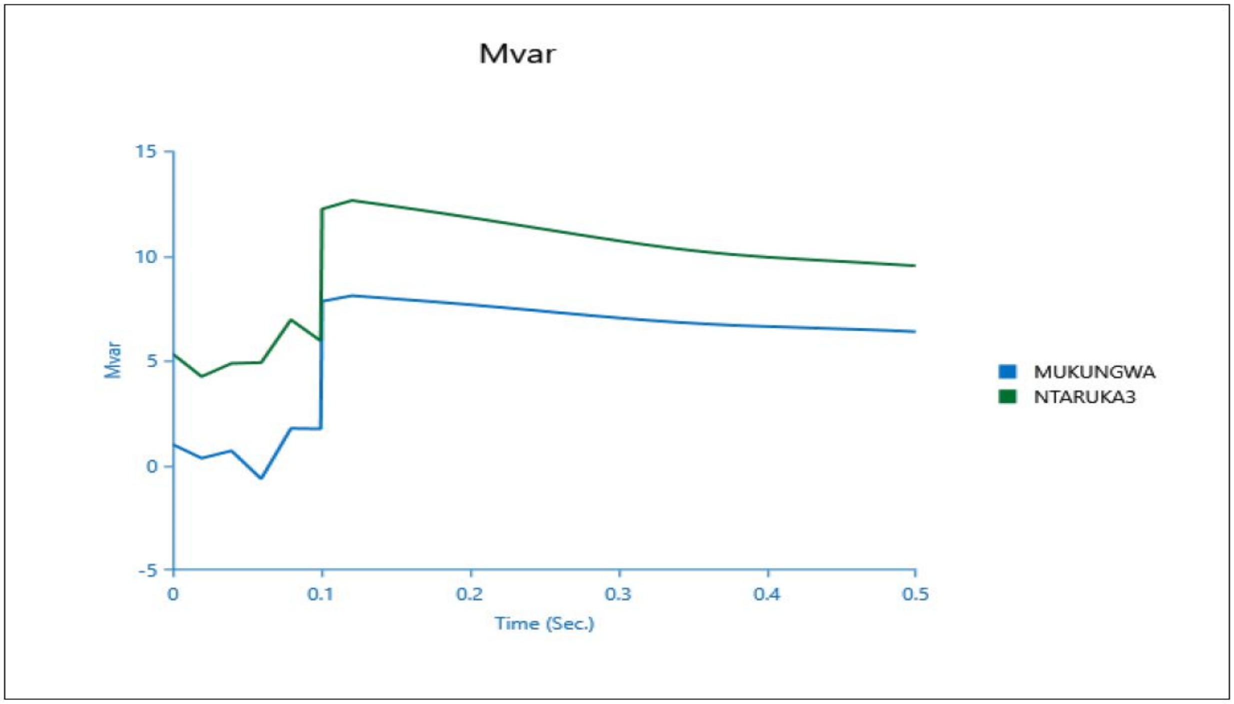

Figure 28: Increase of Reactive Power at Mukungwa and Ntaruka

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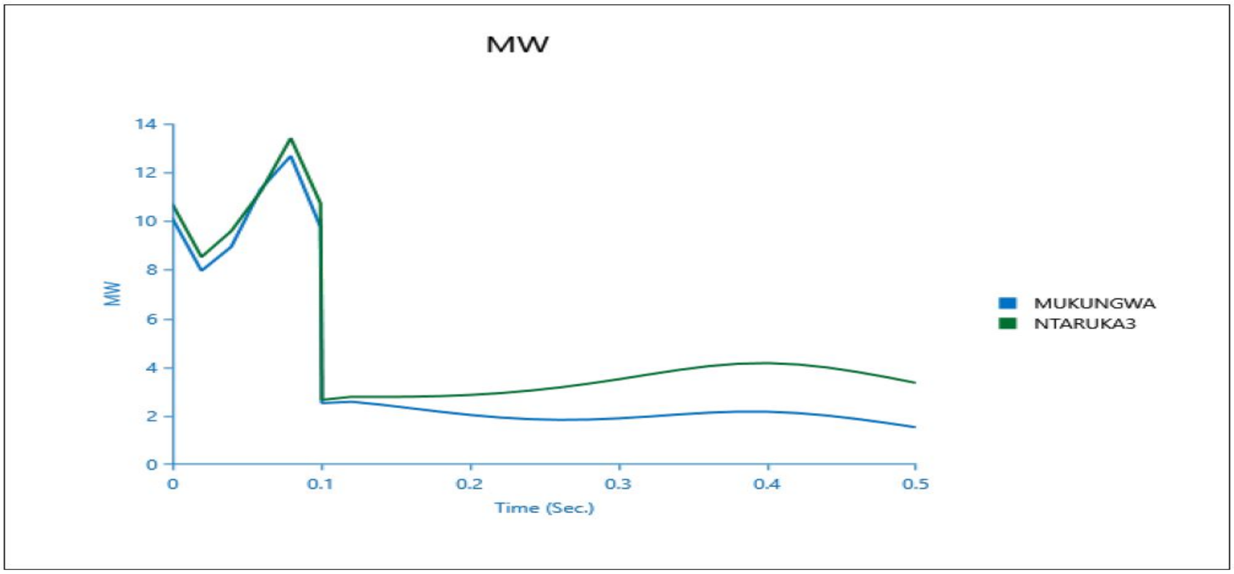

Figure 29: Decrease of Active Power at Mukungwa and Ntaruka

4.4 Effect of transient fault (LG fault) occurred at Rulindo ss

During the fault happened at Rulindo Substation, the system voltage, Active Power, Reactive Power, Voltage Angle will fluctuate and the frequency will increase at all buses and substation. This over frequency will result to power outage as can be observed in figures 30, 31,32,33 and 34. As can be noted, during that fault the the power output of the reference power plants Mukungwa and Ntaruka; fluctuates and cause instability of the system, which will at the end result in the system collapse.

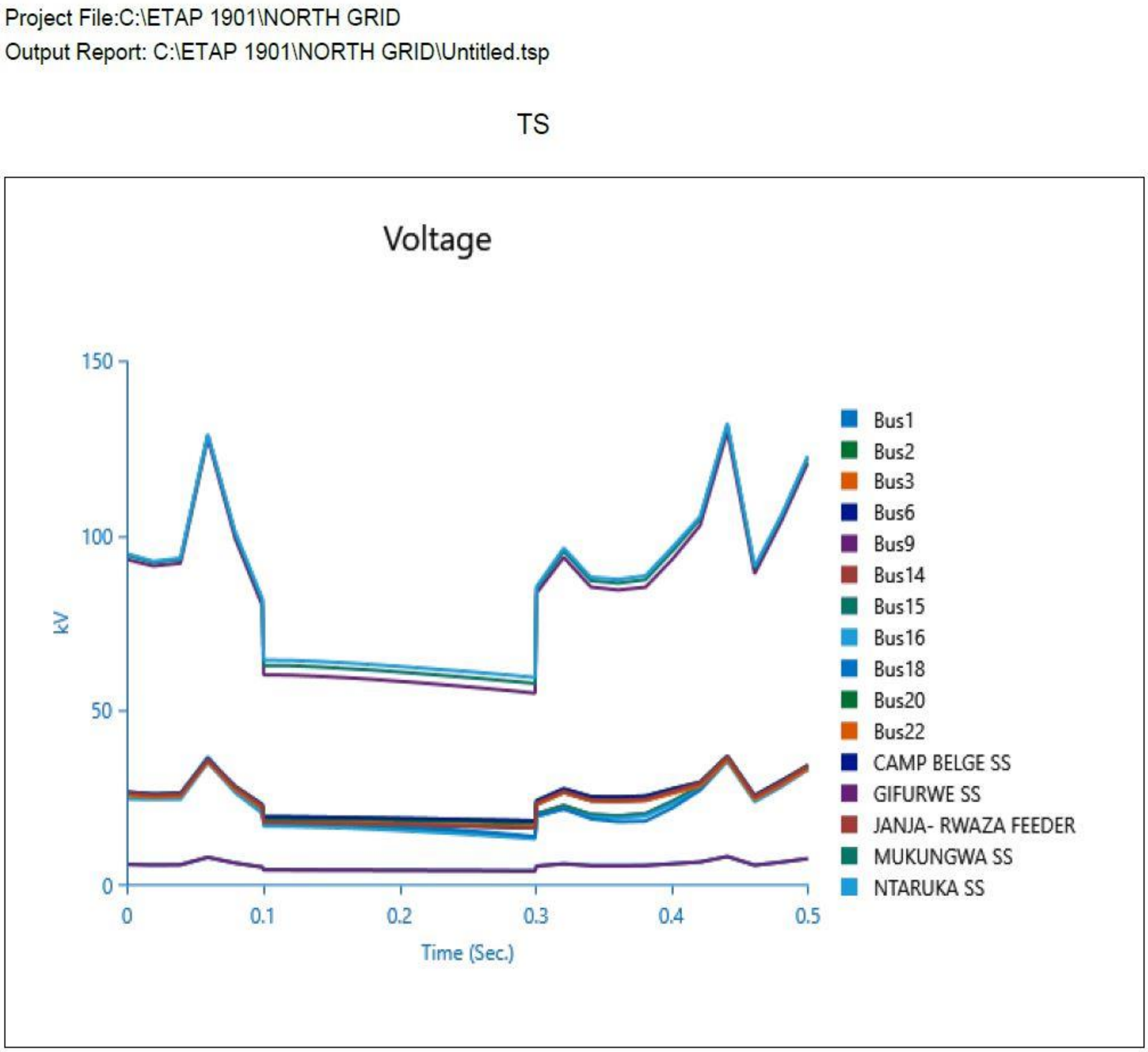

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Figure 30: Voltage fluctuation at all buses and Substations

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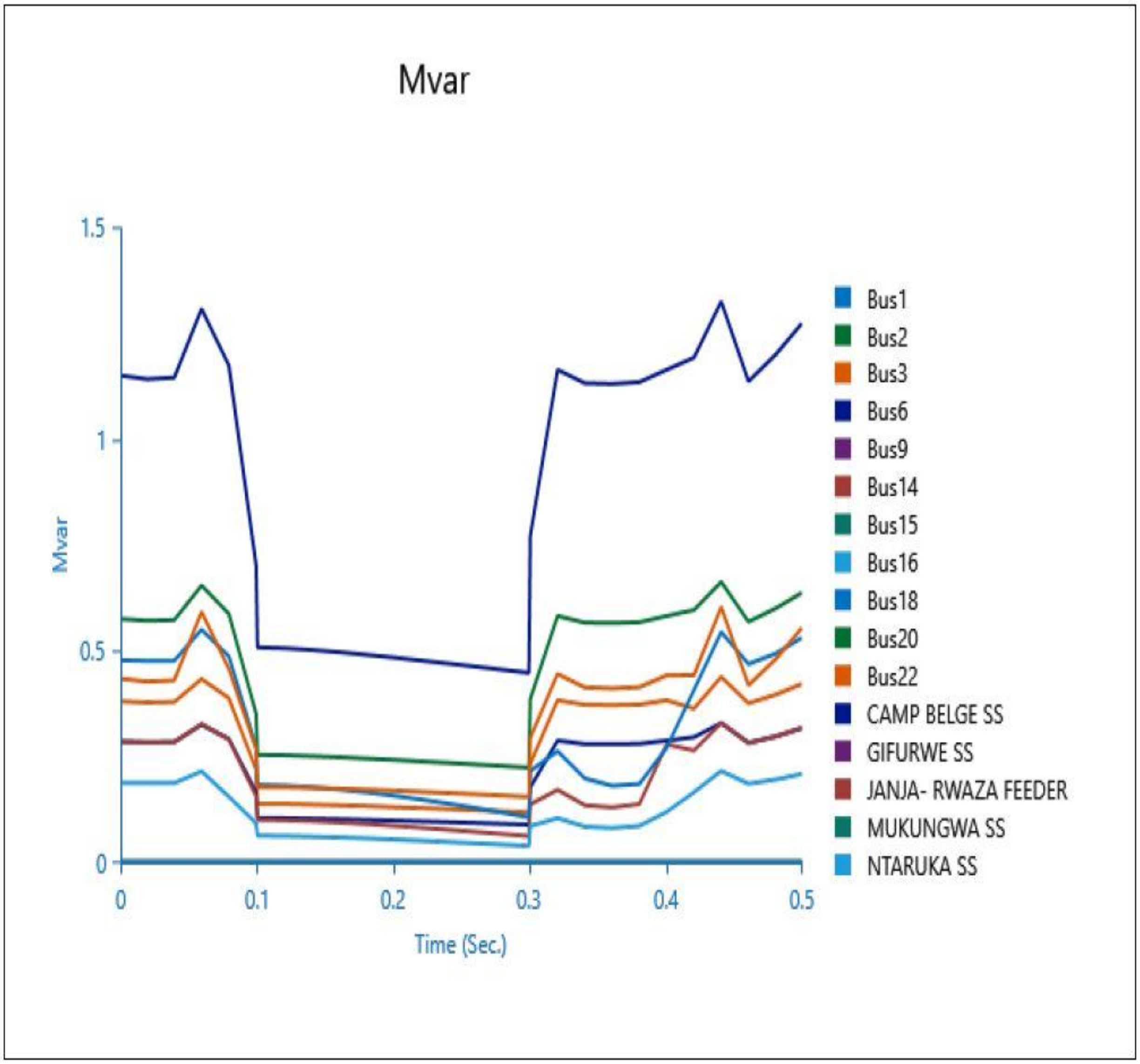

Figure 31: Reactive Power fluctuation

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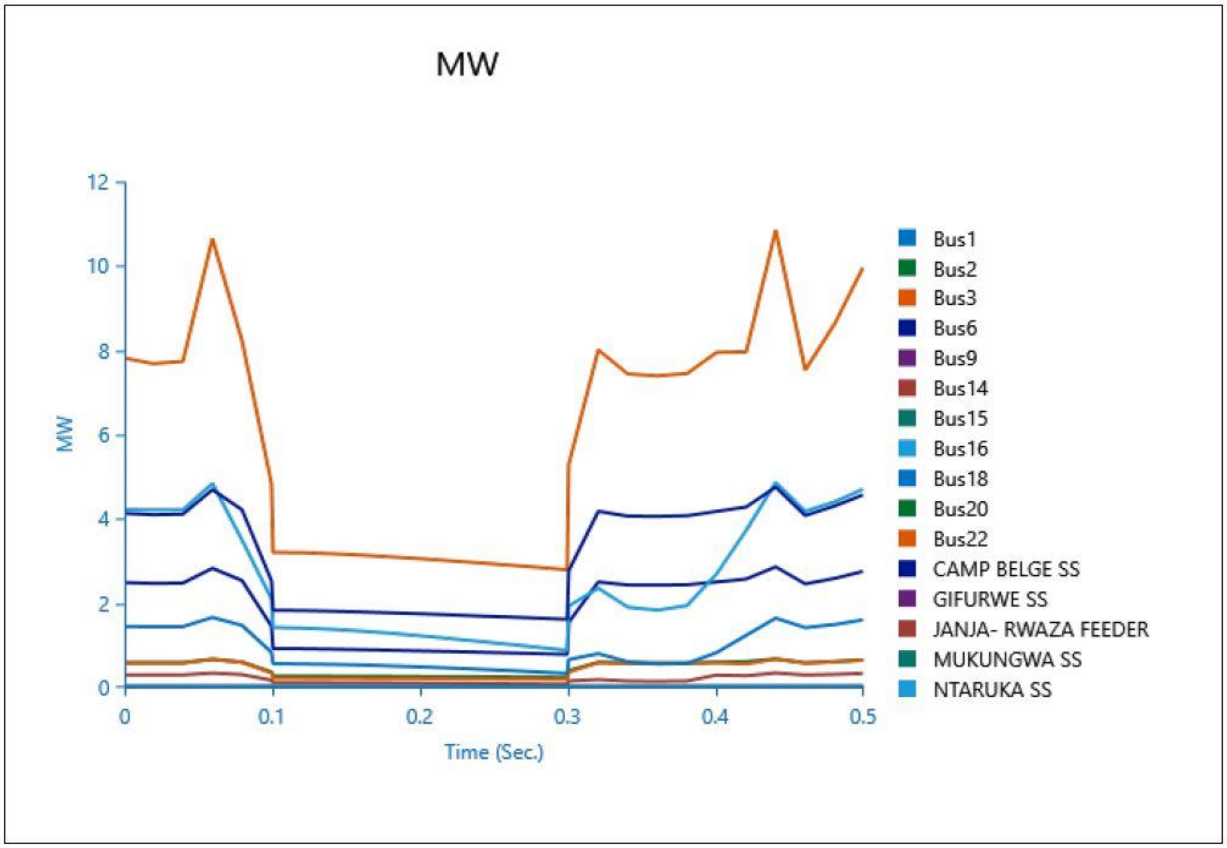

Figure 32: Active Power fluctuation

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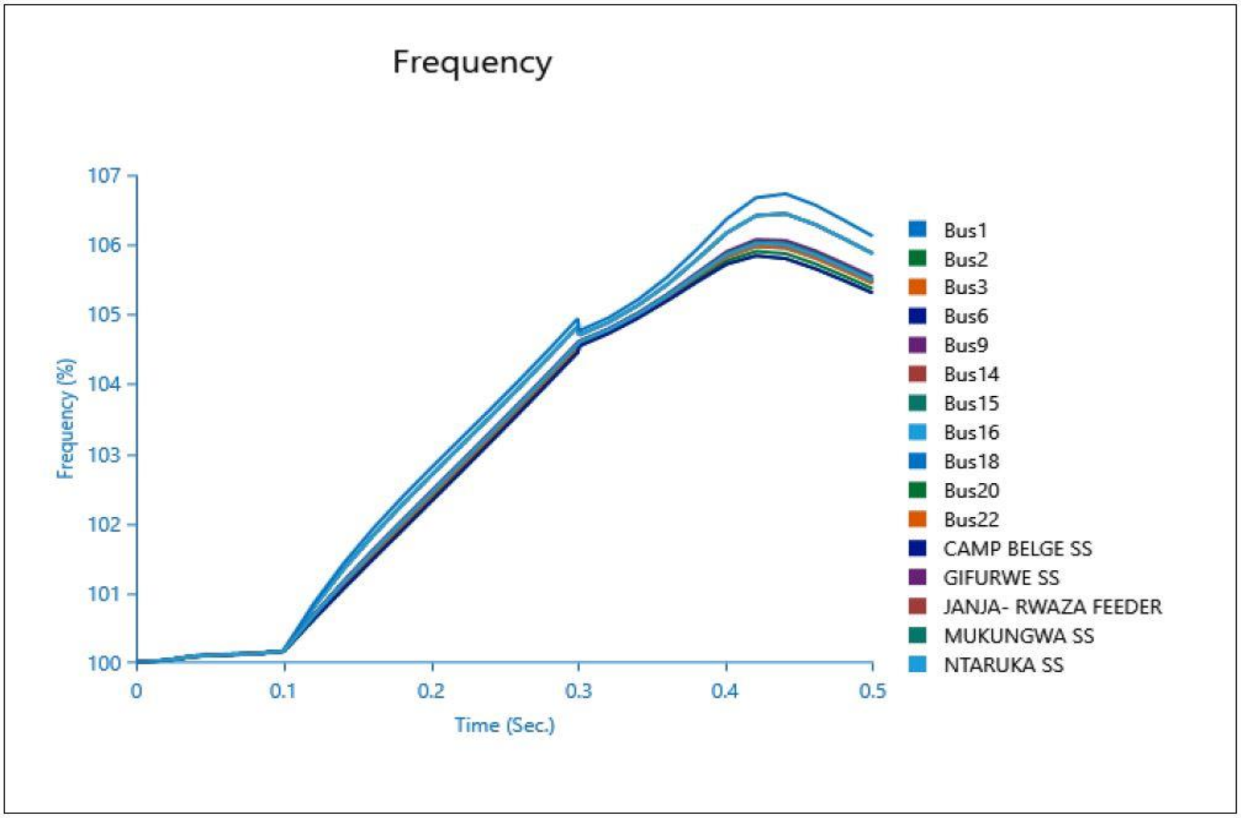

Figure 33: Increment of frequency

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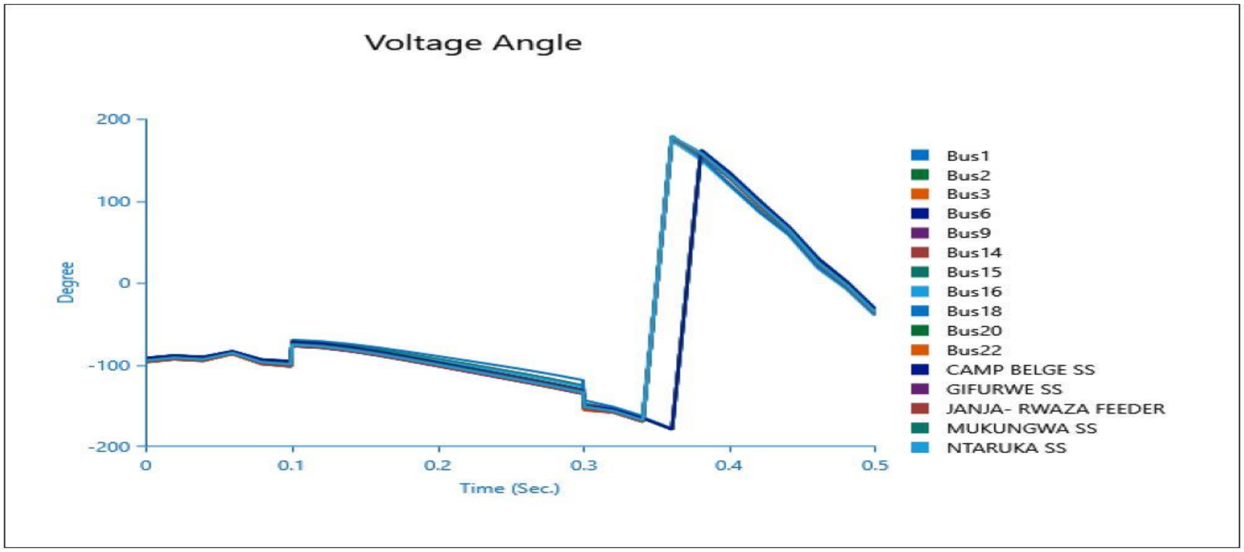

Figure 34: Voltage Angle fluctuation

4.5 Rotor Angle Stability when a 3-phase fault occurred at Rulindo ss

During the three phase fault at Rulindo Substation, there will be decrease of Active power which will cause increment of current, reactive power, power angle and speed of generators at Ntaruka power plant as shown seen below in Figures 35,36,37,38 and 39.

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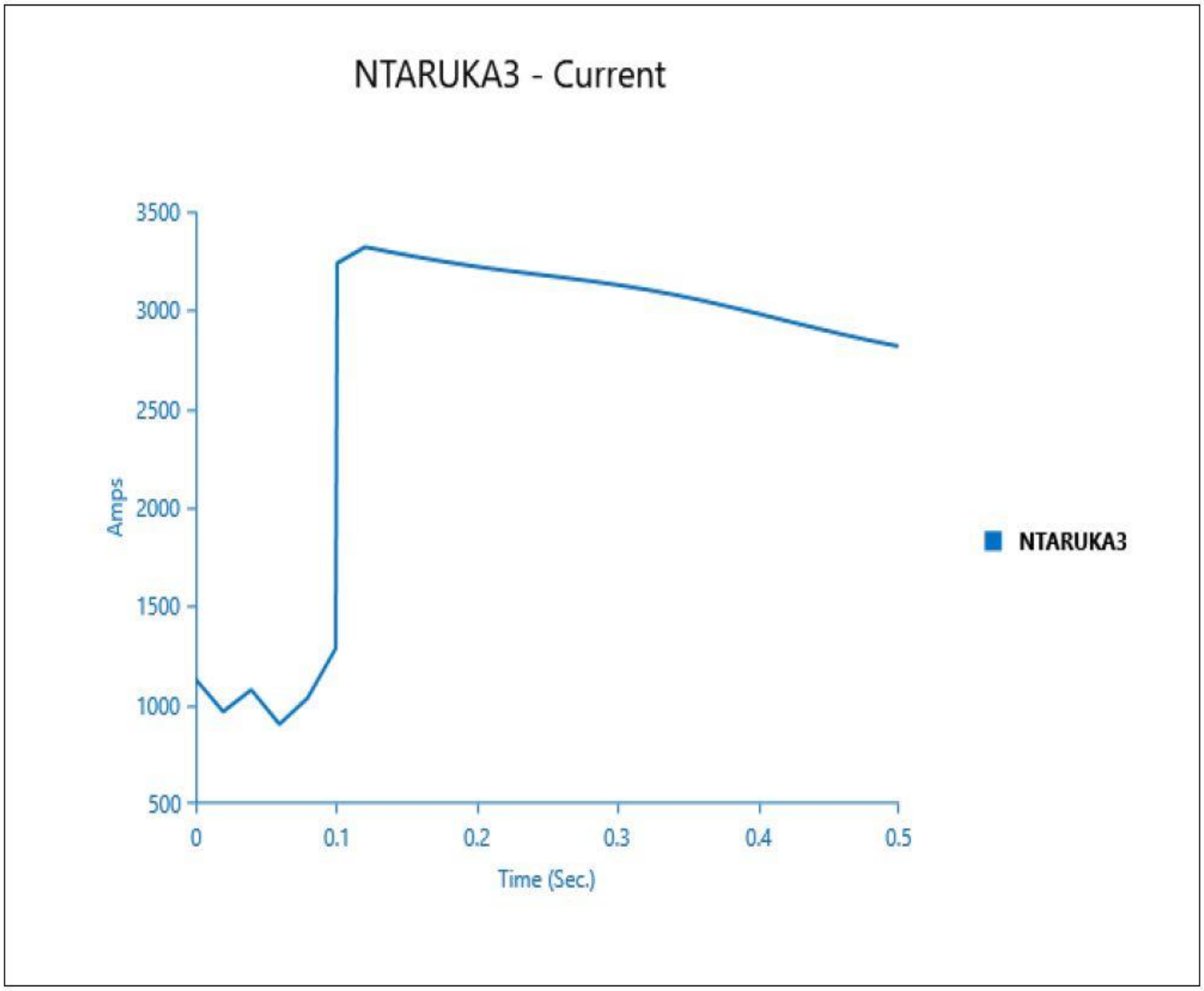

Figure 35: Increament of current at Ntaruka during a fault at Rulindo SS

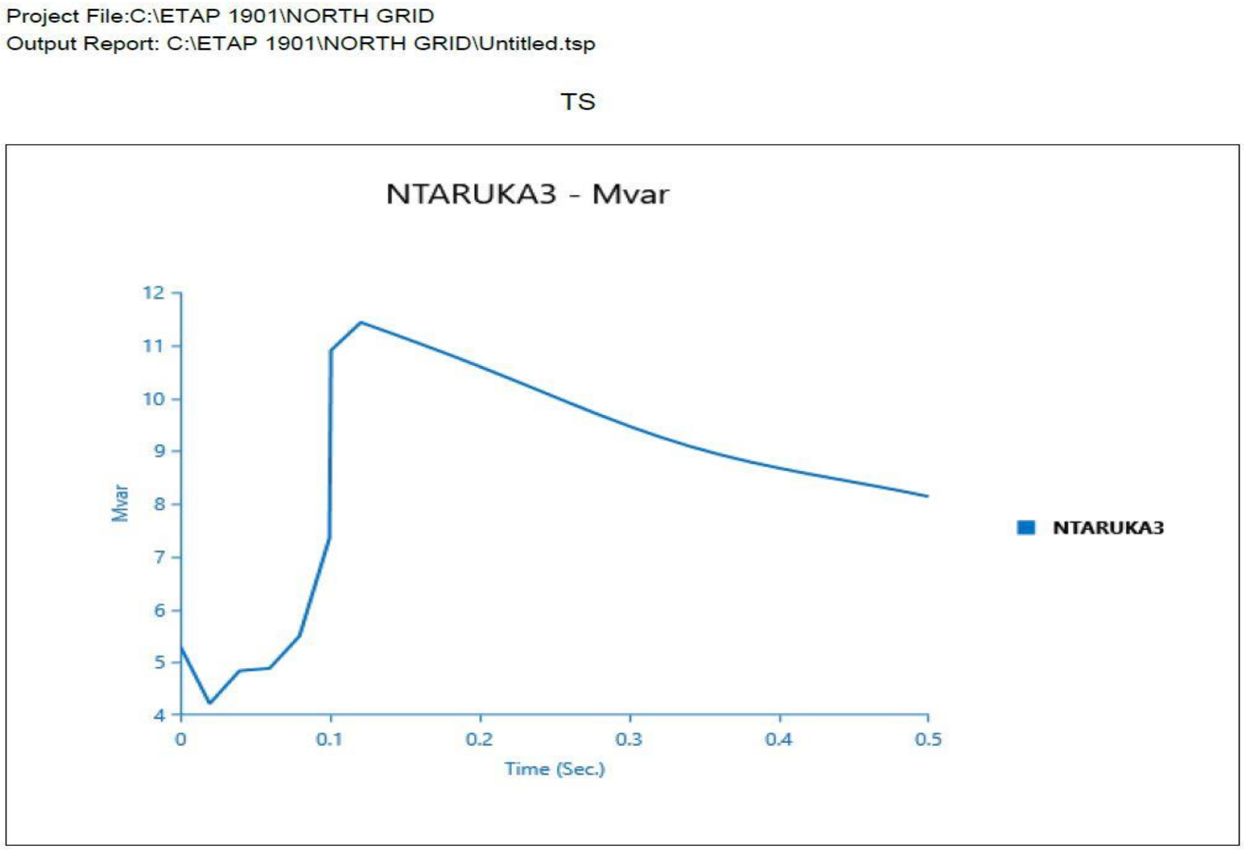

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Figure 36: Increament of Reactive Power at Ntaruka during a fault at Rulindo SS

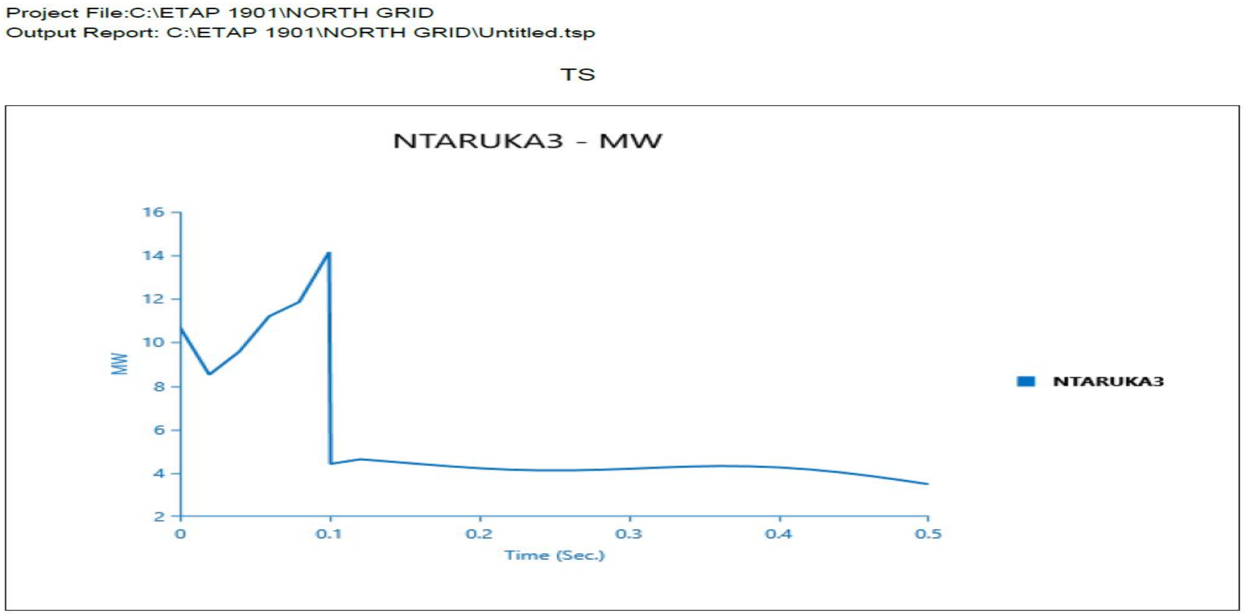

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Figure 37: Decrease of Active Power at Ntaruka during a fault at Rulindo SS

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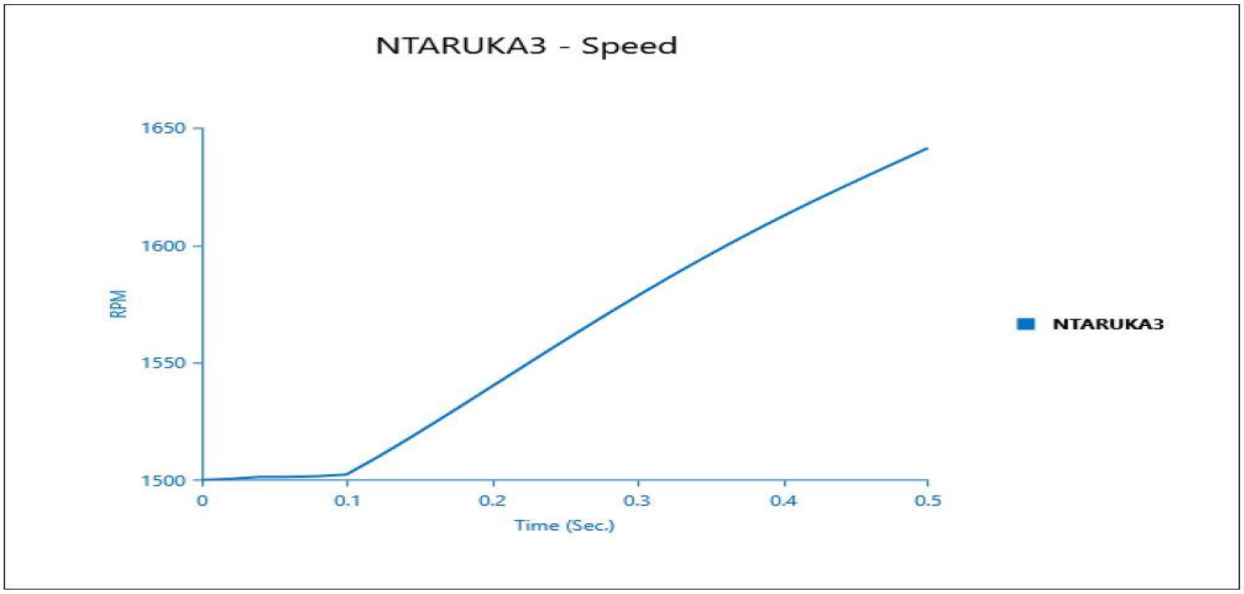

Figure 38: Increament of Generator Speed at Ntaruka during a fault at Rulindo SS

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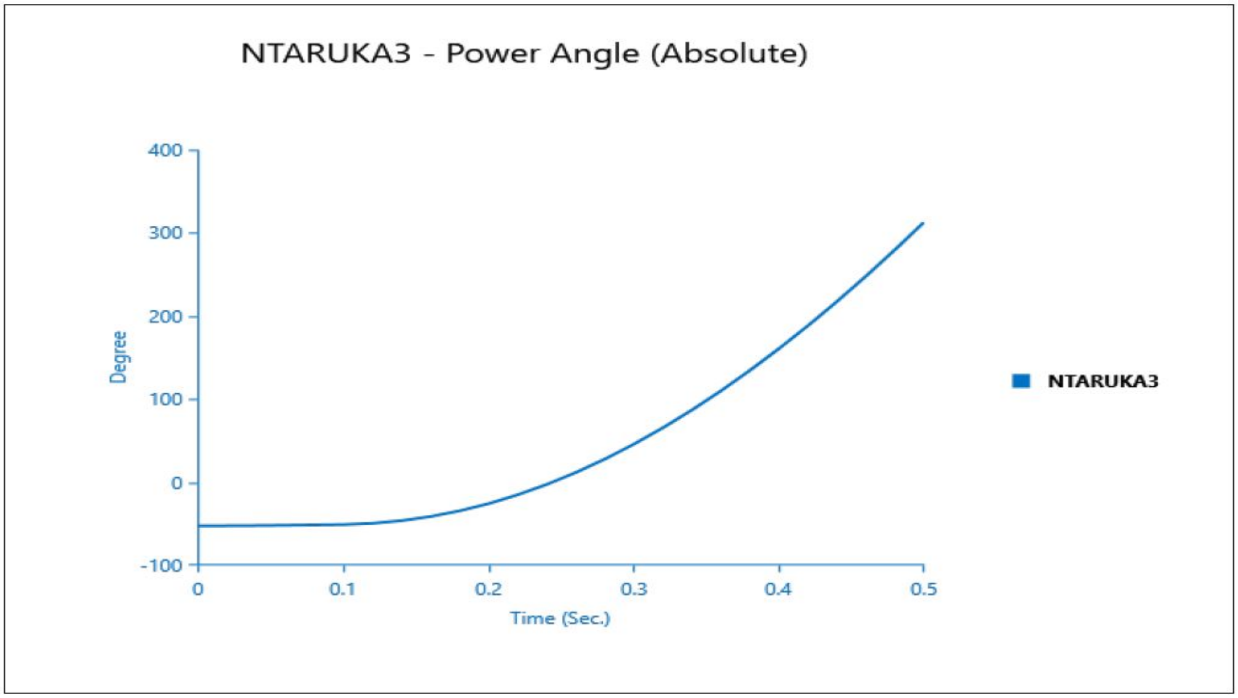

Figure 39: Increament of Power Angle at Ntaruka during a fault at Rulindo SS

4.6 Transient Analysis at Mukungwa and Ntaruka Generators when a fault occured at Rulindo ss

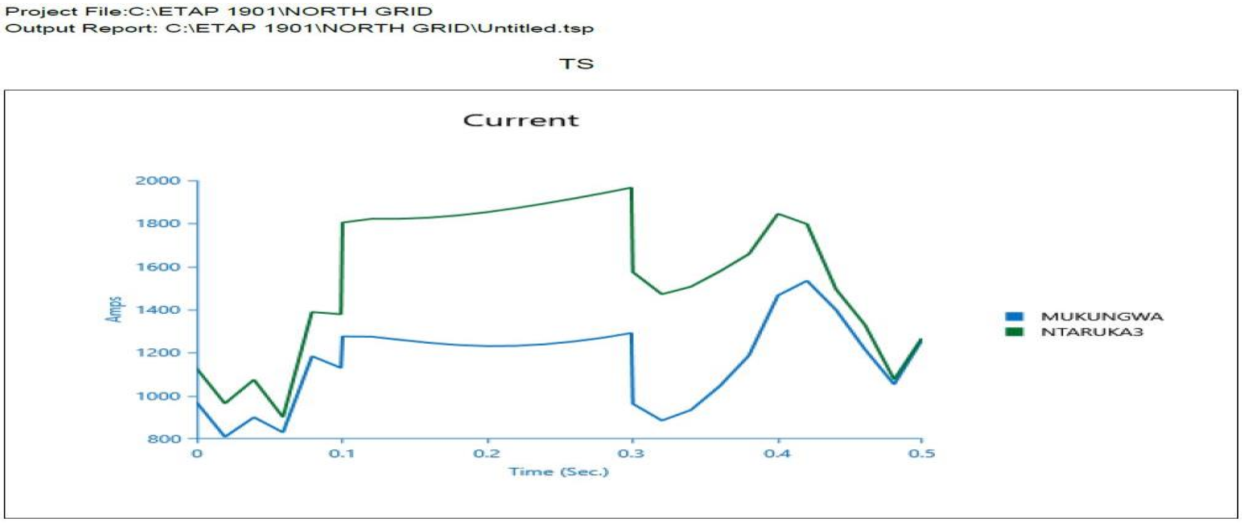
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Figure 40: Current at Mukungwa and Ntaruka during transient fault at Rulindo ss

When the fault happened, the current will fluctuate together with reactive power, and active power. This will cause the fluctuation of both reactive power, and active power as can be seen on figures 40-42.

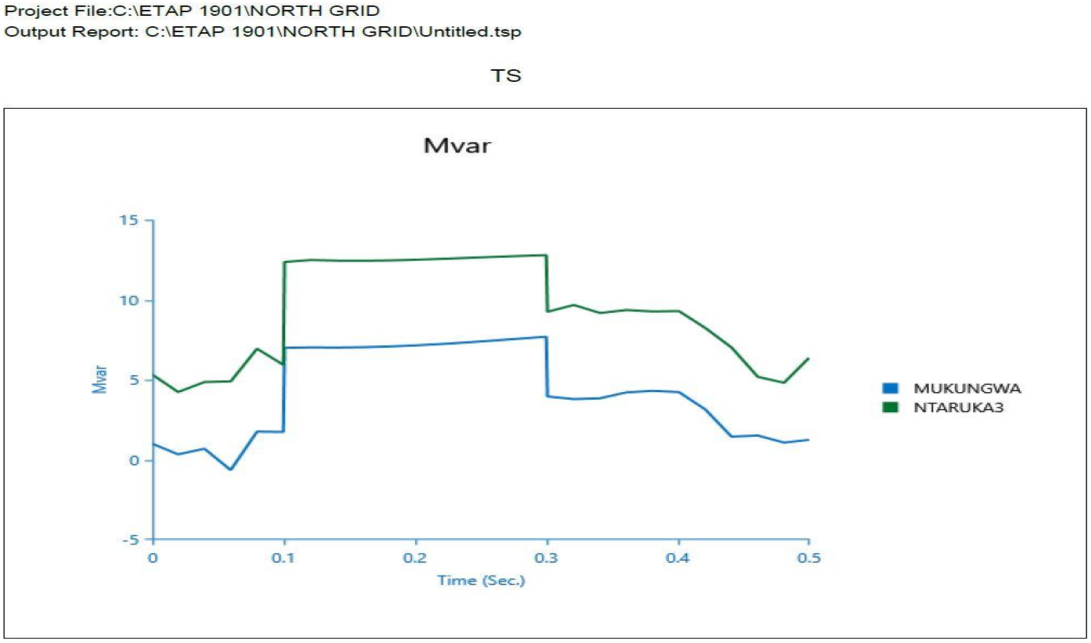
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Figure 41: Reactive Power fluctuation during transient fault at Rulindo SS

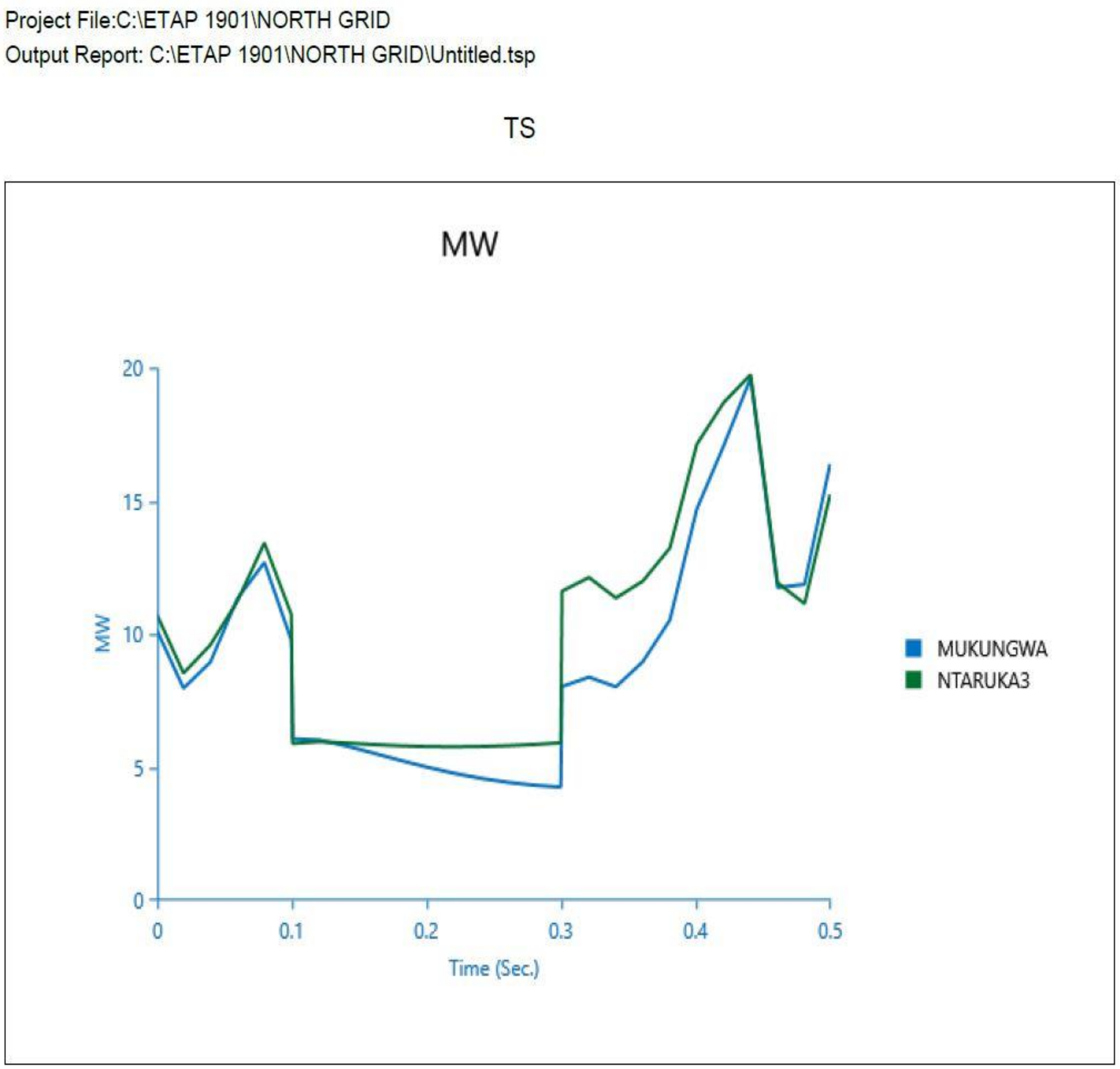

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Figure 42: Active Power fluctuation during transient fault at Rulindo SS

CHAP 5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In this thesis, Rwandan grid, with case study of northern part dynamic stability is analyzed considering the issues that can influence it. Based on simulation results obtained using real data collected, voltage phase angle, Voltage reactive and active power and Frequency at different substations during abnormal operation of the grid are presented.

It was noted that during fault or disconnection of some substation, the stability of the whole system is affected. Apart from fault, the long transmission lines, which influence the high voltage drop at some substations, also influence the voltage profile of the system.

The voltage profile on substations has assessed under different loading conditions such as line fault, disconnection of some feeders and the step increase of loads at some substations.

From the obtained results, it is shown that any disturbance in the northern part, affect the whole Rwandan network as the reference generators are in that area. This results in persisting blackout of the whole network.

5.2 Recommendation

To keep up with stable network, based on our findings; Rwandan Government is recommended to carry out the same study throughout whole network, to analyze vulnerable parts of the network.

Another recommendation is that some reference generators must in different area so that when one area is affected, the remaining reference generators can keep up the network stability.

Last but not least, it is recommended to upgrade the transmission lines in order to reduce the voltage drop by either adding some voltage compensating devices or supporting substations to reduce the length of line or by increasing the transmission voltage.

REFERENCES

[1] "REG," [Online]. Available: https://www.reg.rw/what-we-do/Distribution/transmission/Access. [Accessed Wednesday October 2023].

[2] REG, "Rwanda Energy Group," [Online]. Available: https://www.reg.rw/what-we-do/generation/. [Accessed Thursday 12th October 2023].

[3] B. Safari, "A review of energy in Rwanda," *Renewable and Sustainable Energy Reviews*, no. Volume 14, Issue 1, January 2010, Pages 524-529.

[4] "www.scribd.com," [Online]. Available: https://www.scribd.com/document/432720187/Advanced-Power-System-UNIT-II-Part-1-of-2.

[5] REG, "Rwanda Electricity Distribution Master Plan," REG, Kigali, 2023.

[6] "http://www.egr.unlv.edu," [Online]. Available: http://www.egr.unlv.edu/~eebag/Reliability_Indices_for_Utilities.pdf.

[7] REG, "https://www.reg.rw/customer-service/network-performance-indices/," REG, [Online]. Available: www.reg.rw.

[8] Wenzhou Yixing Electronic Technology Co., Ltd., "linkedin," Wenzhou Yixing Electronic Technology Co., Ltd., [Online]. Available: https://cn.linkedin.com/company/wenzhou-yixing-electronic-technology-co-ltd?trk=article-ssr-frontend-pulse_publisher-author-card. [Accessed Wednesday,18th October 2023].

[9] arath Perera, Sean Elphick, "Introduction to power quality in modern power systems," *Applied Power Quality*, pp. 1-17, 2023.

[10] Saurabh Ratra, Rajive Tiwari, Voltage stability assessment in power systems using line voltage stability index, ELSEVIER, 2018.

[11] M Kowsalya,Priya Vijaya, "Voltage stability indices for stability assessment: a review," *International Journal of Ambient Energy*, pp. 829-845, 2018.

[12] P. Tumino, "Frequency Control in a Power System," *EE POWER Technical Article*, October 15thh 2020.

[13] P. Tumino, "Learn about the primary, secondary and tertiary frequency control in a power system.," *Frequency Control in a Power System*, 2020,15th October.

[14] M. Krarti, "Harmonic distortion in an electrical system is the deviation of the voltage and current waveforms from a purely sinusoidal waveform.," *Harmonic Distortion*, 2017.

[15] N. Kolkowska, "Grid Integration of Renewable Energy," *ENERGY AND ENVIRONMENT*, June 2023.

[16] OLIVER SMITH, OLIVER CATTELL, "The effect of renewable energy incorporation on power grid stability and resilience," *Science Advences,* 2 March 2022.

[17] Mateusz Michalski,Grzegorz Wiczy´nski, Determination of the parameters of voltage variation, Institute of Electrical Engineering and Electronics, 2016.

[18] w. E. Reid, Power quality issues,standard and guidelines, IEEE, 1996.

[19] Gilbert Shyirambere, Kuo-Chi Chang, Kai-Chun Chu, Hsiao-Chuan Wang, AbdalazizAltayeb Ibrahim Omer, Governor David Kwabena Amesimenu & Fu-Hsiang Chang, "Study of Assessing the Stability of Rwanda's Power System from Big Data Based on Power Generation," Conference paper, 2021.

[20] E.B. Tchawou Tchuisseu, D. Gomila∗, P. Colet, Reduction of power grid fluctuations by communication between smart, Palma de Mallorca: Instituto de Física Interdisciplinar y Sistemas Complejos, IFISC (CSIC-UIB), Campus Universitat Illes Balears, E-07122 Palma de Mallorca, Spain, 2019.

[21] Uche Chinweoke Ogbuefi, Boniface Onyemaechi Anyaka, Reactive Power Loss Minimization,chap 16.

[22] Walid A. Omran, M. Kazerani, Senior Member, IEEE, and M. M. A. Salama, Fellow, IEEE, Investigation of Methods for Reduction of Power fluctuation generated from large grid connected photovoltaic system, IEEE, 2011.

[23] Umuhoza, Boniface Ntambara & Ritha, "https://link.springer.com/," [Online]. Available: https://link.springer.com/article/10.1007/s42452-022-05188-5. [Accessed Friday October 2023].

[24] t. f. e. From Wikipedia, "Wikipedia," [Online]. Available: https://en.wikipedia.org/wiki/Recloser. [Accessed Thursday October 2023].

[25] Tylor and Francis, Control and Dynamics in Power Systems and Microgrids, New York: CRC Press.

[26] Mehrdad Bagheri Sanjareh; Mohammad Hassan Nazari; Seyed Hossein Hosseinian; Seyyed Mohammad Sadegh Ghiasi, A New Strategy for Mitigating The Frequency Deviation in Distribution networks and Microgrids, IEEE, August 2021.

[27] E. Planning, "Rwanda Electricity Distribution Master Plan," REG, Kigali, 2023.

[28] Lockwill, [Online]. Available: https://www.cnrockwill.com/automatic-circuit-recloser/36kv-auto-recloser?gclid. [Accessed CHINA RECLOSER,TRANSFORMER,SWITCHGEAR,EV CHARGER,DIGITAL POWER STATION MANUFACTURER October 2023].

[29] R. Li, "Grid-connected power conversion of distributed resources," *Droop Speed Control,* 2019.

[30] Hari Santoso; Unggul Wibawa; Ramadhani Kurniawan Subroto; Lunde Ardhenta, Impact of load and speed variation to frequency variation on single-phase self-excited induction generator, IEEE.

[31] "Harmonic Distortion," in *Types of Disturbance*, pp. p 227-232.

[32] Paul Denholm,1 Trieu Mai,1 Rick Wallace Kenyon,2 Ben Kroposki,1 and Mark O’Malley1, "Inertia and the Power Grid: A Guide Without the Spin," National Renewable Energy Laboratory (NREL), Colorado, May 2020.