



UNIVERSITY of
RWANDA

COLLEGE OF SCIENCE
AND TECHNOLOGY



AFRICAN CENTER OF
EXCELLENCE IN ENERGY FOR
SUSTAINABLE DEVELOPMENT

Title of the Project:

Assessment of Power Losses and Efficiency Improvement of Rwandan Transmission Line Using FACT Device

Case Study: Musha-Rwinkwavu Transmission Line

A dissertation submitted to:

African Center of Excellence in Energy for Sustainable Development (ACE-ESD)

In partial fulfillment of the requirement for the degree of:

Master of Science in Electrical Power System Engineering

By: Eng. Théophile NUMVIYINGOMA

Registration Number: 222022388

Advisor: Assoc. Prof. Getachew Biru

1st October, 2025

Kigali-Rwanda

Declaration

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

Names: Eng. Théophile NUMVIYINGOMA

Signature

APPROVAL

Date of Submission: 1st October 2025

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

Assoc. Prof. Getachew Biru

Thesis Advisor

Signature

ABSTRACT

The Rwandan power grid faces significant challenges related to power losses and inefficiencies across its entire system, from generation, transmission, and distribution. The grid consists of 36 substations and 49 power plants spread across various regions of the country. The transmission network primarily operates at 110 kV, with some lines at 220 kV.

Power losses are a critical issue that needs to be addressed to enhance the Available Transfer Capability of power systems. Mitigating these losses involves a two-stage process: The Planning phase and the Operational phase. In the Planning phase, strategies are developed to minimize losses before they occur. This includes the design and optimization of the power system infrastructure, such as selecting the appropriate size and type of conductors, transformers, and other equipment. Additionally, planning for future load growth and potential system expansions is crucial to ensure that the system can handle increased demand without significant losses. During the Operational phase, the focus shifts to real-time management and optimization of the power system. Techniques such as dynamic power flow control, real-time monitoring, and load balancing are employed to minimize losses as electricity is transmitted from generation points to end-users. As the load on the transmission system varies, the system operates under stressed conditions, which can lead to potential failures and increased losses. Effective power flow control techniques help to manage these variations and maintain system reliability.

This research evaluates the efficiency of Transmission line Musha-Rwinkwavu according to accepted standards. This involves determining the amount of power lost during the transfer of energy through the electrical network from generation to distribution. By quantifying these losses, improvements opportunities have been studied. Additionally, techniques for mitigating power losses and enhancing voltage profile by including STATCOM were explored.

Addressing the challenges of power losses and inefficiency on transmission line Musha-Rwinkwavu if feasible by using a STATCOM of 1.3MVA and losses which are on 4% reduced up to 3%.

Key Words: Static Synchronous Compensator, Losses, Voltage Profile, Efficiency, Line

Table of Contents

Declaration	ii
APPROVAL.....	ii
ABSTRACT	iii
List of FIGURES	vi
List of Tables	vii
List of ACRONYMS	viii
Acknowledgement	x
1. INTRODUCTION	11
1.1. Motivation and Background	11
1.2. Problem Statement	12
1.3. Objectives	13
1.3.1. General Objectives.....	13
1.3.2. Specific Objectives	13
1.4. Scope and Limitation of the Study.....	14
1.5. Expected Outcomes and significance of the study	14
1.6. Organization of Thesis.....	15
2. Literature Review.....	17
2.1. Introduction to Electrical Power System	17
2.2. Configuration of Electrical Power System.....	17
2.3. Overview of Rwandan Transmission System	21
2.4. Loss in Electrical Power System.....	22
2.4.10. Transformer Loss Mechanisms.....	26
2.4.11. Strategies for Reducing Power Losses.....	27
2.5.1. Power Electronics in Transmission of Electrical Power	27
2.6. FACTS Devices	28
2.6.1 Types of FACTs Devices.....	28
2.7 Power system stability	36
2.8. Rwanda's Grid Losses	37
2.9 Reasons for choosing STATCOM	39
3. DATA COLLECTION AND ANALYSIS	41
3.1. Methodology	41

3.3. Collected Data.....	50
3.4. Analytical Techniques.....	51
3.5. Loss Calculation.....	53
4. MODELING AND SIMULATION.....	55
4.1. Modeling Transmission Line	56
4.2. Modeling Power Transformers	60
4.3. Modeling Load.....	61
4.4. Modeling STATCOM.....	62
4.5. RESULTS	64
5. CONCLUSION AND RECOMANDATIONS.....	67
5.1. Conclusion	67
5.2. Recommendations	68
REFERENCES.....	69
Appendices.....	71
1. Network Results without STATCOM	71
2. Network Results with STATCOM Set to Default Values	72
3. Network Results with STATCOM Set to 1.3MVar.....	73

List of FIGURES

Figure 1. Schematic Diagram of Electrical Power System Configuration	18
Figure 2. Transmission line model.....	25
Figure 3. Power transformer model	26
Figure 4 . Serie FACTs Device.....	29
Figure 5. Series FACTs Devices.....	29
Figure 6. Shunt Device.....	31
Figure 7. Shunt Device.....	32
Figure 8. STATCOM on Grid.....	35
Figure 9. Combined Series-Series Devices.....	36
Figure 10. Series-Shunt Device	36
Figure 11. Musha Substation Single line diagram	42
Figure 12. Musha Substation	44
Figure 13. Kabarondo Substation Single line diagram	45
Figure 14. 5 Year Trend of Active Power at Kabarondo Substation	46
Figure 15. Single line Diagram of Rwinkwavu	47
Figure 16. 5 Year Trend of Active Power at Rwinkwavu Substation.....	48
Figure 17. Rwinkwavu Substation	49
Figure 18. Map of Musha - Rwinkwavu Transmission line with Distribution Feeders.....	49
Figure 19. Voltage Profile for Musha-Kabarondo-Rwinkwavu Substation	50
Figure 20. Active & Reactive Power During Peak Hours	52
Figure 21. Energy trend for Musha-Rwinkwavu	52
Figure 22. Single line diagram of Musha-Kabarondo-Rwinkwavu N/W in PSSE.....	56
Figure 23. Equivalent circuit of a transmission line	58
Figure 24. Musha-Kabarondo Transmission Line Parameters.....	59
Figure 25. Kabarondo-Rwinkwamvu Transmission line parameters.....	59
Figure 26. Parameters of Kabarondo and Rwinkwavu Transformers.....	60
Figure 27. Configuration of a STATCOM.....	62
Figure 28. Loss for different scenarios	66

List of Tables

Table 1. Cost comparison of shunt devices.....	39
Table 2. Comparison of SVC and STATCOM.....	40
Table 3. Some Electrical Quantities Musha-Karando-Rwinkwavu N/W	41
Table 4. Electrical Parameters of Kabarondo Bay in Musha Substation	43
Table 5. Energy Consumption Musaha-Kabarondo-Rwinkwavu	51
Table 6. Network Results without STATCOM	64
Table 7. Network Results with STATCOM Set to Default Values	65
Table 8. Network Results without STATCOM Set to 1.3MVar.....	65

List of ACRONYMS

Terms	Explanation / Definition
PQ	Power Quality
SVC	Static Var Compensator
AC	Alternating Current
ACE-ESD	African Center of Excellence in Energy of sustainable development
REG	Rwanda Energy Group Limited
EUCL	Energy Utility Corporation Limited
FACTS	Flexible Alternating Current Transmission system
VAR	Volt –Ampere reactive
KV	Kilo-volt
HV	High Voltage
DC	Direct Current
IEEE	Institute of Electrical and Electronics Engineer
STATCOM	Static Synchronous Compensator
SSSC	Static Synchronous Series Compensator
TCSC	Thyristor Controlled Series Compensator
Q, P&S	Reactive power, Active Power& Apparent Power
TSC	Thyristor Switched Capacitor
PSSE	Power system Simulation for Engineering
V _s	Sending Voltage
V _r	Receiving Voltage
X	Reactance
R	Resistance
MW	Megawatt
MVAR	Mega-Volt –Ampere reactive
AVR	Automatic Voltage regulation
HV	High Voltage
OHL _s	Overhead lines

IEC	International Electro-Technical Commission
VBE	Valve base Electronics
VCU	Valve control unit
TCU	Thyristor control unit
WECC	Western Electricity Coordinating Council
UDMs	User-defined models
DLL	Dynamically Linked Library
ACSR	Aluminum Conductor Steel Reinforced
VSC	Voltage Source Converter
GTO	Gate Turn-Off Thyristor
IGBT	Integrated Gate Bipolar Thyristor
IGCT	Integrated Gate Commutated Thyristor
IEGT	Injection Enhanced Gate Transistor
PCC	Point of common coupling
PWM	Pulse Width Modulation
TSA	Trajectory Sensitivity Analysis
TSSC	Thyristor Switched Series Capacitor
GTO	Gate Turn-Off
DSSC	Distributed Static Series Compensator
PLC	Power Line Communication

Acknowledgement

Firstly, I would like to give thanks to the Almighty God, for only with Him, everything is possible.

Secondly, I would like to thank so much my supervisor Assoc. Prof GETACHEW Biru for his guidance and support.

Thirdly, I would like to thank the African Center of Excellence for giving me the opportunity and support to pursue my Master's studies with them.

Lastly, I say thank you to my family and relatives together with my workmate, especially my supervisor for the support and encouragement throughout my studies.

1. INTRODUCTION

1.1. Motivation and Background

Electricity losses occur at each stage of the power system, starting from the step-up transformers that connect power plants to the transmission system and ending with the customer wiring beyond the retail meter. The system includes several key components: step-up transformers, transmission lines, substations, step-down transformers. These losses are often generically referred to as “line losses,” although the conductor lines themselves account for only one type of electricity loss during the transmission process.

System average line losses in Rwanda’s utility grids are around 18.5%, but they can increase exponentially as power lines become heavily loaded. Reducing electricity demand during peak hours can significantly decrease losses. High levels of losses mean that disproportionately more generation resources are required to deliver the same amount of electricity to end-users. A one-kilowatt (kW) load reduction at the customer’s end can result in a greater than one-kW load reduction upstream in transmission level due to compounding losses.

Focusing on the various components of the transmission system can help optimize and reduce line losses. For instance, step-up transformers are used to increase the voltage of electricity generated at power plants for efficient transmission over long distances. However, they can also be a source of losses if not properly maintained or if outdated technology is used. Upgrading these transformers to more efficient models can reduce losses significantly.

Transmission lines, which carry high-voltage electricity from power plants to substations, also contribute to power losses [1]. These losses can be minimized by using conductors with lower resistance, optimizing the physical layout of the transmission network, and employing technologies such as high-temperature superconductors and using STATCOM.

Substations play a crucial role in stepping down the voltage for distribution to end-users. Losses at this stage can be mitigated by using high-efficiency transformers and implementing advanced monitoring systems to detect and address inefficiencies promptly. Primary voltage distribution lines carry electricity from substations to local transformers, and their efficiency can be improved by optimizing their length and routing, as well as by using materials with better

conductivity[2]. Each component of power system presents opportunities for reducing line losses and improving overall efficiency. By optimizing equipment choices and implementing advanced technologies, significant reductions in power losses can be achieved, ultimately leading to a more reliable and efficient power grid.

1.2. Problem Statement

The transmission line Musha-Rwinkwavu faces critical challenges related to power losses and inefficiencies due to its topology as it is far from generation sources and being radial.

One of the most pressing issues is the instability of voltage during periods of low load, particularly during off-peak hours. This instability often leads to sudden increases in system voltage to unacceptable levels, triggered by an accumulation of events within the grid. The problem is exacerbated by the relatively long transmission line that is lightly loaded. This deficiency not only results in high power losses but also threatens the reliability and stability of the supply. To address these issues, a comprehensive assessment of power losses and identify potential efficiency improvements was conducted on that transmission line. Power loss is highly related to the increase of load and overvoltage is related to under-load condition.

This research aims to evaluate the efficiency of that particular transmission network according to accepted international standards, determine the power lost during energy transfer from one point to the end, and explore solutions to reduce power losses.

Key aspects investigated include:

1. **Quantification of Power Losses:** Assessment was done at the extent of power losses at each stage of the transmission process.
2. **Power Loss Reduction:** Identifying opportunities for optimizing the physical layout of the transmission network, upgrading equipment, and employing advanced monitoring and control systems to enhance overall efficiency.
3. **Reactive Power Compensation:** Evaluating the effectiveness of implementing reactive power compensation techniques to stabilize voltage levels and reduce power losses.

By addressing these areas, this research provides actionable recommendations for reducing power losses, improving voltage stability, and enhancing the efficiency and reliability of Musha-Rwinkwavu transmission system. This will ultimately contribute to a more stable and efficient power supply for the country, supporting its economic growth and development.

1.3. Objectives

1.3.1. General Objectives

The general objective of this research is to evaluate the current state of power losses within Musha-Rwinkwavu transmission system, identify and recommend technological methods and strategies for efficiency improvements. This was achieved through a detailed analysis of the transmission network, reactive power compensation, and system optimization by integrating STATCOM as a reactive power compensation device.

1.3.2. Specific Objectives

The specific objectives of this thesis are:

1. **Data Collection:** Relevant data of the transmission line, like line parameters, voltage variations versus load variation and others collected for the analysis work.
2. **Evaluate Power Losses Across the Transmission Network:** Conduct a comprehensive assessment of power losses at various stages of the transmission process, identifying the most significant sources of inefficiency.
3. **Analyze Voltage Variations and Its Impact on Power Losses:** Investigate the factors contributing to voltage instability and its impact on overall power losses. This includes analyzing voltage violations and their correlation with power losses.
4. **Assess the Effectiveness of Reactive Power Compensation:** Evaluate the potential benefits of implementing reactive power compensation techniques, such as STATCOM, to enhance voltage stability and reduce power losses in the transmission network.
5. **Develop Actionable Recommendations for Policy and Implementation:** Formulate practical recommendations for utility operators based on the findings. These recommendations focus on strategies to reduce power losses, enhance voltage stability, and improve the overall efficiency and reliability of the Musha-Rwinkwavu transmission system.

1.4. Scope and Limitation of the Study

Scope: This study aims at evaluating power losses and propose efficiency improvements for Musha-Rwinkwavu transmission system. The research focuses on the transmission stage, identifying and quantifying power losses on that stage. Key areas of investigation include voltage stability during low load periods, particularly during off-peak hours, and the effectiveness of reactive power compensation techniques. The study also explores opportunities for system optimization, including the physical layout of the network, equipment upgrades, and the integration of advanced monitoring, FACTS Devices and control systems. Practical recommendations for utility was formulated to improve the efficiency and reliability of the transmission system.

Limitation: The study faces several limitations, including the availability and accuracy of data, which may impact the analysis. Technological constraints and financial resources may limit the feasibility of implementing advanced solutions. External factors such as weather conditions, geopolitical events, and economic fluctuations can affect the transmission system's performance. Additionally, regulatory hurdles, stakeholder resistance, and logistical issues may pose challenges to the practical implementation of recommendations. The study's timeframe may also limit the ability to capture long-term trends and variations in power losses and voltage stability. Despite these limitations, the study aims to provide valuable insights for enhancing power infrastructure.

1.5. Expected Outcomes and significance of the study

Expected Outcomes:

This study expects to quantify and analyze power losses within Musha-Rwinkwavu transmission system, identifying critical areas for efficiency improvements. By evaluating voltage stability and the effectiveness of reactive power compensation techniques, the study aims to recommend strategies to mitigate losses and enhance system reliability. It anticipates proposing optimized system layouts, equipment upgrades, and advanced monitoring systems to reduce inefficiencies.

Significance:

The significance of this study lies in its potential to quantify the transmission losses and identify methods for improving the power losses. By reducing power losses and enhancing efficiency in the transmission system, the study aims to Enhance Energy Security by improving system reliability and stability, ensuring consistent power supply. Contribute to Economic Impact by Lowering operational costs and reducing the need for additional generation capacity. This study seeks to contribute to Rwanda's socioeconomic development by ensuring a more efficient and reliable electricity supply, crucial for industrial growth, public services, and quality of life improvements for its citizens.

1.6. Organization of Thesis

This structured approach ensures a thorough exploration of power losses and efficiency improvements on Musha-Rwinkwavu transmission system, from foundational research and data collection through to analysis, findings, and actionable recommendations. And below are how chapters will be organized and its contents.

Chapter 1: Introduction

- Overview of Rwanda's transmission system.
- Importance of assessing power losses and efficiency improvements.
- Objectives and scope of the thesis.
- Structure of the thesis.

Chapter 2: Literature Review

- Review of literature on power losses in transmission systems.
- Best practices in improving transmission efficiency globally.
- Theoretical background on voltage stability and reactive power compensation.

Chapter 3: Data Collection and Analysis

- Description of research design and approach.
- Data collection methods, sources, and tools used.
- Analysis techniques for evaluating power losses, voltage stability, and efficiency improvements.

Chapter 4: Modeling and Simulation

- Quantification and analysis of power losses on Musha-Rwinkwavu transmission system.
- Examination of voltage stability issues during varying load conditions.
- Assessment of the effectiveness of reactive power compensation techniques.

Chapter 5: Conclusion and Recommendations

- Recommendations for improving efficiency and reducing power losses.
- Summary of findings and their implications.
- Future directions for research and development in Rwanda's transmission system.

2. Literature Review

2.1. Introduction to Electrical Power System

The demand for electrical power has been rising significantly for a long time, and as a result, electrical power transmission networks are having trouble transmitting electricity. These restrictions result from supply balance, the permitted voltage level, and network stability maintenance. As a result, the power systems' practical operating capacity is lower than their full capacity. As a result, the power transmission systems do not operate at their best. In developing countries like Rwanda, addressing these losses is crucial for improving overall system efficiency and reliability. Building brand-new transmission lines is one of the numerous solutions to the growing issue of electricity transmission capacity, but this is neither feasible nor profitable.

Over the past years, researchers have been working to create new algorithms and models for power system stability that use Flexible AC Transmission System (FACTS) devices[3]. This allows for dependable, quick, and continuous control of the transmission system's power flow. To make power available to consumers without going against system constraints, these devices have been used in a variety of power system research areas, such as power quality, voltage stability, optimal power flow, power system security, and improving the power system's damping ratio and economic power dispatch[4]. This chapter compiles data from earlier academic research that has been analyzed by other academics to advance the investigation of using FACTS devices to improve power system stability and reduce power losses.

2.2. Configuration of Electrical Power System

An electrical power system's main objective is to deliver electrical energy to the load in a safe, cost-effective, and dependable way. Electrical power must be produced and then transported before the loads may use this energy. Electricity can be transported in two ways: distribution and transmission. Electrical power generation, transmission, and distribution are the main functions of a power system. In addition to the three primary functions, there is a supplementary responsibility that involves protection and metering. The primary and secondary systems, respectively, are responsible for completing these responsibilities.

Electrical power networks are far more sophisticated than the graphic portrayal, because they consist of a network of meshed transmission lines that cut across areas and to which a significant number of power plants and loads are connected as per in below figure.

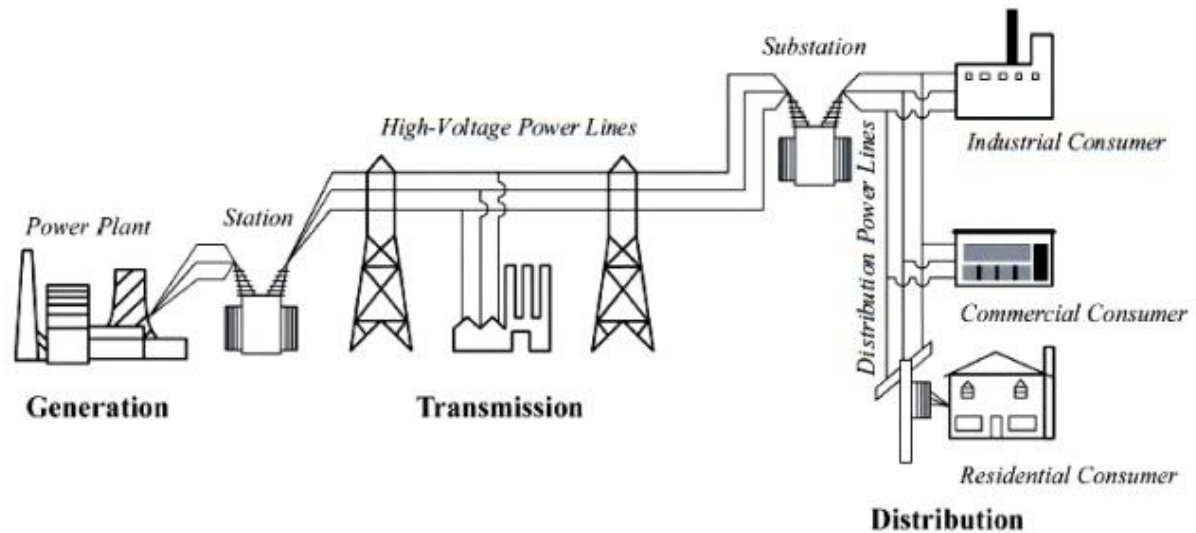


Figure 1. Schematic Diagram of Electrical Power System Configuration[5]

a. Generation of Electrical Power.

Electricity generation refers to the process of converting primary energy sources into electrical power, a critical step in ensuring the availability of electricity for consumption. In the context of the electric power industry, this stage precedes the delivery of electricity to consumers via transmission and distribution networks or its storage through methods like pumped-storage hydropower. This storage approach uses surplus electricity to pump water to a higher elevation, later releasing it to generate electricity during peak demand periods.

Unlike some forms of energy available in nature, electricity does not exist in a readily usable form and must be produced through the transformation of other energy types. This production occurs in facilities known as power stations or power plants. These plants employ electromechanical generators to produce electricity. These generators are commonly driven by heat engines powered by the combustion of fossil fuels such as coal, natural gas, or oil, or

through nuclear fission in nuclear power plants[6]. These traditional methods account for a significant share of global electricity generation.

In addition to conventional techniques, renewable energy sources play an increasingly vital role in electricity production. Hydropower, which harnesses the kinetic energy of flowing water, and wind power, utilizing turbines spun by wind, are prominent examples. Solar energy, captured through photovoltaic cells, and geothermal energy, derived from the Earth's internal heat, provide sustainable alternatives that reduce greenhouse gas emissions.

b. Transmission of Electrical Power.

Electric power transmission refers to the large-scale movement of electrical energy from generating facilities, such as power plants, to electrical substations, where the voltage is prepared for further distribution[7]. This crucial process ensures that electricity produced at centralized locations can reach distant areas where it is consumed. The network of interconnected high-voltage transmission lines responsible for this bulk transfer forms what is known as the transmission network or grid. This system is distinct from the lower-voltage local wiring that connects substations to homes, businesses, and other end users, a process referred to as electric power distribution. Together, the transmission and distribution systems form an integrated framework for electricity delivery, collectively referred to as the electrical grid.

To enable the efficient long-distance transmission of electricity, high voltage levels are employed. The reason for this lies in the relationship between voltage, current, and power loss: increasing the voltage reduces the current for the same power level, thereby minimizing resistive losses in the transmission lines. These losses, known as I^2R losses, can be substantial over long distances, making high-voltage transmission essential for maintaining efficiency.

Transmission systems use two main types of current: alternating current (AC) and direct current (DC). AC is more commonly used due to the ease of transforming its voltage levels with transformers. During transmission, the voltage is stepped up to hundreds of kilovolts to reduce

energy loss. Once the electricity reaches its destination substation, transformers step down the voltage to safer levels suitable for distribution and eventual use by consumers.

In some cases, high-voltage direct current (HVDC) systems are used for very long distances or undersea cables, as they can be more efficient and reduce certain losses associated with AC systems.

c. Distribution of Electrical Power

Electric power distribution represents the final and critical stage in the delivery of electricity, bridging the high-voltage transmission system and individual consumers. This stage ensures that electricity reaches end-users safely and efficiently, whether they are residential, commercial, or industrial customers.

The process begins at distribution substations, which are connected to the high-voltage transmission network. These substations reduce the transmission voltage, typically ranging from hundreds of kilovolts to medium voltage levels between 6.6kV and 30kV using step-down transformers. This medium-voltage electricity is then carried via primary distribution lines to distribution transformers strategically located near customer premises.

Distribution transformers perform a second voltage reduction, stepping down the medium voltage to the lower utilization voltages required for end-use applications. These voltages are typically suitable for powering lighting systems, household appliances, industrial machinery, and other electrical equipment. Secondary distribution lines then deliver this lower-voltage electricity to consumers. In many cases, a single distribution transformer serves multiple customers through shared secondary distribution lines.

Connections to end-users vary based on their power needs. Residential and small commercial customers are typically linked to secondary distribution lines through service drops, which are the final segment of the distribution network leading directly to the customer's property. However, large commercial or industrial users with higher power demands may bypass

secondary distribution lines altogether, connecting directly to the primary distribution network or even to the sub transmission level to access medium or high-voltage power more efficiently.

Modern distribution systems often include advanced technologies such as automated switches, smart meters, and distributed energy resources to enhance reliability, reduce losses, and facilitate better demand management[8]. These innovations contribute to creating a smarter and more sustainable electric grid while ensuring that electricity delivery remains safe and efficient

2.3. Overview of Rwandan Transmission System

Rwanda's transmission system encounters a range of unique challenges shaped by its geographical, economic, and infrastructural context. Despite considerable progress in electrification and energy access, the system struggles to operate efficiently and reliably, hindering its ability to meet the growing energy demands of the population and industrial sectors.

A key issue in the system is its minimal reserve margins, which leave little room for flexibility in managing fluctuations in demand or unexpected outages. This limitation increases the risk of supply interruptions and reduces the system's ability to support economic growth and industrial expansion. Additionally, most transmission lines in Rwanda are underutilized, operating at only about 20% of their capacity. While this underutilization may initially seem to provide a buffer for future load growth, it paradoxically contributes to inefficiencies. For instance, low load levels on transmission lines can result in higher relative line losses and reduced voltage stability, further complicating network performance.

Another significant concern is the system's vulnerability to power angle variations during load changes or faults. Power angle stability is a critical factor in maintaining synchronism between generating units and ensuring uninterrupted power supply[9]. In Rwanda, variations in load demand, especially during peak hours, can cause oscillations in power angles. These oscillations, if not controlled, can lead to partial or total system instability. Similarly, in the event of faults such as short circuits or equipment failures, the transmission system's limited redundancy exacerbates the risk of widespread outages.

Furthermore, Rwanda's predominantly mountainous terrain presents logistical and technical challenges for building and maintaining transmission infrastructure. The steep and rugged landscape complicates line routing, increases construction costs, and heightens the risk of environmental and weather-related disruptions. Economic constraints also limit the pace of upgrading and expanding the transmission network, making it difficult to keep up with the country's ambitious electrification goals.

Addressing these challenges requires targeted interventions, including the optimization of transmission line utilization, the adoption of advanced grid technologies like Flexible AC Transmission Systems (FACTS), and increased investment in grid infrastructure. Enhancing reserve margins, implementing robust fault detection systems, and prioritizing grid automation can also improve the stability and resilience of Rwanda's transmission system, supporting its sustainable energy future

2.4. Loss in Electrical Power System

Losses occur in both transmission and distribution lines and in transformers, the fundamental components of the electricity power system. Some losses, called no-load losses, are incurred to energize transformers in substations. A larger share is labeled copper losses; these losses reflect the resistance of the materials themselves to the flow of electricity. Copper losses are typically 25 to 30 percent of total distribution losses, and do not change with changes in load[10]. They are largely influenced by the characteristics of the steel laminations used to manufacture the core of transformers.

Resistive losses are analogous to friction losses in the lines and transformers. As loads increase, the wires get hotter, the material becomes more resistive, and line losses increase. For this reason, resistive losses increase exponentially with the current on a line. At low-load periods, system losses are almost entirely copper losses and may be lower. At the highest load hours, average line losses increased. Therefore, line loss reduction is partly a function of system design and construction but is also heavily affected by operation of the underlying electrical loads and by how well peak loads are managed.

2.4.1 Resistance and Power Loss

The primary source of transmission losses is the resistance of conductors. When current flows through a conductor, it encounters resistance, leading to power dissipation in the form of heat. This power loss is directly proportional to the square of the rms current traveling through the line:

$$P_{\text{loss}}=I^2R \quad (2.1)$$

To minimize resistive losses, transmission voltage is increased, thereby reducing current for the same power level. However, raising voltage requires expensive transformers and insulation, imposing economic limits.

2.4.2 Conductance and Leakage Current

Conductance represents energy losses due to leakage currents flowing through insulation materials. Leakage can occur between transmission lines or between a line and the ground. While conductance values are affected by atmospheric conditions like humidity and pollution, overhead transmission lines generally have negligible leakage losses and can be ignored in most calculations.

2.4.3 Capacitance and Charging Current

Capacitive effects arise from electric field interactions between conductors and between conductors and the ground. Even when a transmission line is open-circuited, alternating voltage variations cause a charging current to flow, affecting power transmission. This effect becomes more pronounced in high-voltage and long-distance transmission lines.

2.4.4 Inductance and Magnetic Coupling

Alternating currents in a transmission system create time-varying magnetic fields, inducing voltages in adjacent conductors. The mutual coupling between these lines can lead to unwanted voltage imbalances in a three-phase system.

- Unbalanced phases increase power losses because current distribution becomes uneven, with higher current in some conductors leading to higher resistive losses.

- Transposition of transmission lines is used to counteract inductance effects. Conductors are periodically repositioned to balance mutual coupling effects and reduce reactance.

2.4.5. Voltage Regulation and Efficiency

The efficiency of a transmission line is defined as:

$$\eta = 100\% \times P_{\text{load}} / (P_{\text{load}} + P_{\text{loss}}) \quad (2.3)$$

Voltage regulation, which measures voltage drop from the sending end to the receiving end, is given by:

$$\text{Percent Regulation} = 100\% \times (|V_{R,NL}| - |V_{R,FL}|) / |V_{R,FL}| \quad (2.4)$$

where $V_{R,NLV}$ and $V_{R,FLV}$ are the receiving-end voltages at no load and full load, respectively.

2.4.6. Skin Effect and its Impact on Resistance

The skin effect causes alternating current (AC) to concentrate near the conductor's surface, reducing effective cross-sectional area for current flow. This occurs because:

1. Magnetic flux within the conductor induces voltage variations across its cross-section.
2. The induced voltage opposes the current flow, pushing current density towards the conductor's outer surface.
3. Higher resistance at higher frequencies increases power losses.

The skin depth, which determines how far current penetrates a conductor, depends on material properties and frequency. For a copper conductor at 50 Hz, the skin depth is approximately 0.75 cm[11]. Aluminum conductors have greater penetration depth, allowing them to be reinforced with a steel core without significantly reducing current-carrying capacity.

2.4.7. Transmission Line Models

For power system analysis, transmission lines are categorized into short, medium, and long lines based on length and operating voltage.

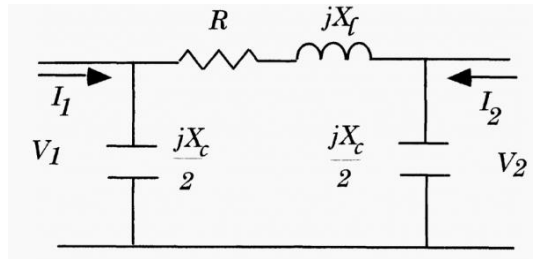


Figure 2. Transmission line model

Short Transmission Line Model

In short transmission lines (less than 80 km, voltage below 69 kV), capacitance is negligible, and only resistance R and inductance L are considered. The voltage drop is calculated using:

$$V_R = V_S - I(R + j\omega L) \quad (2.5)$$

Where V_S and V_R are sending and receiving voltage and I its current

where V_S and V_R are sending and receiving voltages, and I is current.

Medium and Long Transmission Line Models

- Medium lines (80–250 km, 69–200 kV) incorporate shunt capacitance effects.
- Long transmission lines (above 250 km, voltage exceeding 200 kV) require distributed parameter models due to significant inductance and capacitance effects.

2.4.8 Induced Voltage

Induced voltage per unit length is given by:

$$V_{do} = 21.2 m_0 \delta r \ln \left(\frac{d}{r} \right) \quad (2.6)$$

where d is conductor spacing, r is conductor radius, δ air density factor and m_0 is surface roughness

The load power factor influences voltage regulation, with lagging power factors experiencing the greatest voltage drop.

2.4.9. Corona Loss and Electromagnetic Interference

Corona discharge occurs when the electric field around a conductor ionizes surrounding air, leading to energy loss and radio interference.

- **Critical voltage:** Corona begins when the field strength reaches 3000 kV/m, leading to an avalanche effect where free electrons collide with air molecules, ionizing them.
- **Factors affecting corona loss** are Conductor diameter and spacing, Line voltage and its temperature and humidity
- Since corona loss is associated with high-frequency oscillations, it also contributes to electromagnetic interference (EMI), affecting communication systems.

2.4.10. Transformer Loss Mechanisms

1. **Copper losses (I^2R):** Caused by resistance in transformer windings.
2. **Core losses:**

Hysteresis loss: Energy dissipated in the magnetic core due to repeated magnetization cycles.

Eddy current loss: Circulating currents in the core induced by changing magnetic fields.

Hysteresis and eddy current losses depend on frequency and core material flux density B :

$$P_{\text{core}} \propto fB^{1.6-2.0}$$

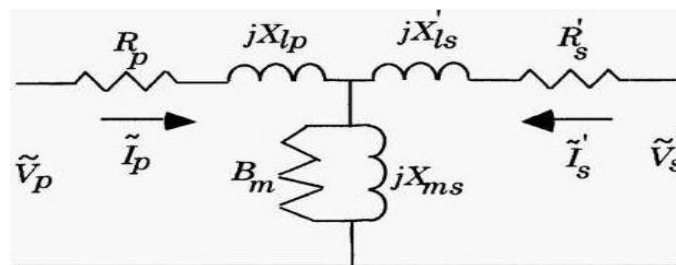


Figure 3. Power transformer model

2.4.11. Strategies for Reducing Power Losses

To improve the efficiency of the Rwandan transmission system, several strategies can be employed:

Reactive Power Compensation: Installing FACTS devices can help manage voltage levels and reduce losses due to reactive power. This approach helps in stabilizing the power angle during disturbances

Grid Reinforcement: Upgrading transmission lines and substations to handle higher loads can reduce resistive losses and improve overall efficiency. This involves both physical infrastructure improvements and optimization of operational practices.

Dynamic Simulations and Modeling: Utilizing software tools like PSS/E and MATLAB for dynamic simulations allows for a better understanding of system behavior under different scenarios. This helps in predicting potential stability issues and planning appropriate mitigation measures.

Reducing Transformer Losses

- **Optimized winding design:** Reducing leakage flux by using thin, long windings.
- **Improved core materials:** Using high-permeability materials to reduce eddy currents.
- **Electromagnetic shielding:** Placing shorted coil windings to counteract EMI effects

2.5.1. Power Electronics in Transmission of Electrical Power

The first power electronics device on a transmission line was the HVDC transmission system[12]. As an alternate method of power transportation, the HVDC is more useful in long-distance overhead and subterranean transmission networks. Connecting AC systems with varying frequencies is another use for it. When it is necessary to increase the system's capacity for power delivery, FACTS devices are used to improve and compensate for an existing AC transmission system[13].

It has been demonstrated that the transmission system is becoming more complex because of the sharply rising demand for electrical power. FACTS is a feasible and alluring substitute when considering the time and expense required to construct a new transmission line. It is possible to connect FACTS devices in shunt, mixed, or series mode.

2.6. FACTS Devices

Conventional and power electronics-based devices are two types of power flow control devices. There are three different ways to arrange this technology in the network: shunt, series, and combined

2.6.1 Types of FACTs Devices

Reactive power compensation devices come in two varieties. A Gate Turn-Off (GTO) thyristor, an Integrated Gate Bipolar Transistor (IGBT), an Integrated Gate Commutated Thyristor (IGCT), and an Injection Enhanced Gate Transistor (IEGT) converter are used as voltage source converters (VSC) in the second type, whereas the first type uses conventional thyristor switched reactors and capacitors[14]. To enhance the control of system characteristics and the power transfer capability of an electric power transmission system, FACTS and its controllers were defined as an alternating current transmission system composed of power electronic-based static controllers. Based on electronics The management and control of contemporary power systems are greatly aided by FACTS devices, which have supplanted several mechanically operated reactive power compensators.

Four categories can be used to classify FACTS devices:

- a. Devices in series
- b. Shunt apparatus
- c. Devices with a combination of series
- d. Devices that combine series and shunt

2.6.1.1 Series Devices

As seen in figure 4, these devices may be power electronics-based variable sources that inject voltage in series with the line, or they may be variable impedance devices like thyristor switches,

capacitors, reactors, or other devices. The variable impedance multiplied by the current passing across the wire represents the injected variable series voltage. In this instance, the gadget needs an outside power supply. When the voltage is more or less than 90^0 out of phase with the line current, this device either produces or absorbs variable reactive power.

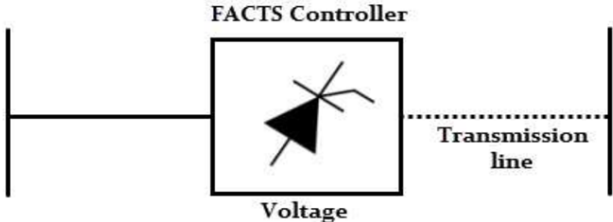


Figure 4 . Serie FACTs Device

As illustrated in figure 5, the series FACTS devices are used to improve loadability and stability in the power system. They function as a variable capacitive or inductive impedance that can be altered in series with the transmission line to reduce system oscillation. A suitable voltage phasor, which is represented as the voltage across an impedance in series with the transmission line, is injected in series with the line to achieve this. The controller sinks or generates reactive power if the line voltage and current are in phase quadrature; otherwise, the devices sink or produce both active and reactive power. Equations (2) and (3) below govern the management of the power flow.

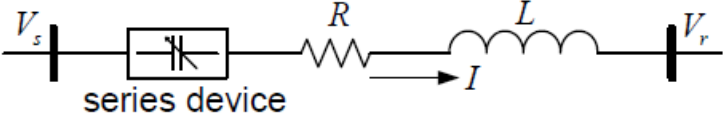


Figure 5. Series FACTs Devices

A portion of the transmission line reactance is balanced when the device operates in capacitive mode. To restrict the power flow in the event of an inductive mode, the reactance will be raised.

a. Thyristor Controlled Series Capacitor (TCSC)

The IEEE defines a Thyristor Controlled Switched Capacitor (TCSC) as "a capacitive reactance compensator which consists of a series capacitor bank in order to provide a smoothly variable series capacitive reactance". The Thyristor Controlled Reactor (TCR) branch reactance is controlled by TCSC using inverse-parallel thyristors, and the total impedance of TCSC is changed using a fixed capacitor. TCSC provides faster system control than a mechanically switched device since it can change line impedance in a single cycle. TCSC setup is depicted in the image below. The transient stability of a power system with TCSC under varied operating conditions was evaluated using Trajectory Sensitivity Analysis (TSA) methodologies.

b. Thyristor Switched Series Controller (TSSC)

In order to enable step-wise control of series capacitive reactance, a thyristor switched reactor switches a bank of series capacitors to create a Thyristor Switched Series Capacitor (TSSC). The TSSC has a quicker response time than mechanically switched compensators since it uses a thyristor to alter the capacitor bank. The TSSC, depicted in the image below, is only able to introduce capacitance into the lines; it is unable to regulate the line current.

c. Static Synchronous Series Compensator (SSSC)

The Static Synchronous Series Compensator (SSSC) is a series-connected FACTS device that injects a controlled voltage magnitude at a specific angle into the transmission line to regulate power flow. Operating without an external energy source, it produces a voltage in quadrature with the line current, allowing independent control of reactive voltage drop and power flow. This capability enhances system stability and power delivery efficiency.

SSSC employs a synchronous voltage source, typically implemented using a Gate Turn-Off (GTO) thyristor-based voltage-sourced inverter, for precise series compensation. It provides symmetrical voltage compensation across capacitive and inductive ranges, regardless of line current magnitude. Studies have demonstrated that a non-linear control method for SSSC significantly improves system stability compared to traditional linear controls. This makes SSSC

an effective solution for dynamic power flow management and voltage stability in modern power systems.

d. Distributed Static Series Controller (DSSC)

The Distributed Static Series Compensator (DSSC) consists of multiple low-rated, single-phase Voltage Source Converters (VSCs) connected to the grid via single-turn transformers. These transformers use the transmission line as their secondary winding, injecting controllable voltage directly into the line in quadrature with the current to mimic capacitive or inductive impedance. DSSCs are remotely controlled via wireless or Power Line Communication (PLC), offering high reliability at a low cost. As single-phase devices clamped onto transmission lines, DSSCs require no additional land or phase-ground isolation, making them suitable for any transmission voltage level.

2.6.1.2. Shunt Devices:

As seen in figure 6, shunt devices can be capacitors, reactors, variable medance, variable current or voltage sources, or power electronic-based variable sources that are onnected to the system in a shunt fashion to introduce variable current into the line. When the injected current is more or less than 900 out of phase with the line voltage, the shunt device either absorbs or provides variable reactive power.

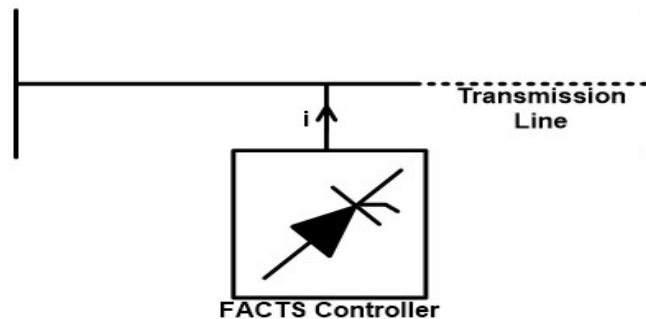


Figure 6. Shunt Device

A shunt device works by injecting reactive current I_{sh} , which indirectly controls the line current I , by altering its impedance to provide the reactive power needed at the load. According to Ohm's law, the line current I is equal to the voltage drop over the transmission line, which is the difference between the transmitting and receiving end voltages, or $V_s - V_r$. A shunt device can

regulate the magnitude of the voltage at the receiving end $|V_r|$, while we can assume that the voltage at the transmitting end (V_s) is constant[5].

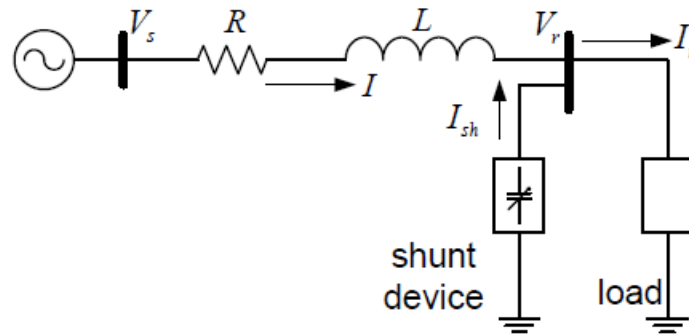


Figure 7. Shunt Device

The following equation shows the relationship between the voltage at the receiving end V_r and the injected current I_{sh} by the shunt device:

$$V_r = V_s - IZ$$

$$= V_s - (I_r - I_{sh})Z \quad (2.7)$$

Where $Z = R + j\omega L$

By altering its impedance, the shunt device may regulate the voltage magnitude. The shunt current I_{sh} partially compensates for the huge load current I_r by reducing the line current I , which causes a voltage drop under heavy load conditions. Shunt controllers come in three different varieties: shunt switch inductor and capacitor devices, Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM).

a. Static VAR Compensator (VAR)

A Static Var Compensator (SVC) is a static reactive power device designed to maintain or control specific parameters, such as bus voltage or reactive power, in electrical power systems. SVCs are shunt-connected devices comprising Thyristor Switched Capacitors (TSC) and Thyristor-Controlled Reactors (TCR). They work by exchanging inductive or capacitive current to stabilize bus voltages. The TCR includes a fixed reactor in series with a bi-directional thyristor valve, where inductance is symmetrically divided. In contrast, the TSC consists of a

capacitor, thyristor valve, and a damping reactor that mitigates inrush currents during severe transients. The shunt reactance in a Fixed Capacitor Thyristor Controlled Reactor (TCR-FC) is controlled by adjusting the thyristor valve firing angle.

SVCs are extensively studied for damping low-frequency inter-area oscillations in large interconnected power systems. Studies utilizing modal analysis identify oscillation patterns and inform control design. Coordinated controllers combining power system stabilizers and SVC damping controllers, optimized through techniques like Particle Swarm Optimization (PSO), demonstrate effective oscillation damping. Advanced approaches, including fuzzy logic and genetic algorithms, further enhance SVC performance by addressing nonlinear modal interactions in stressed systems.

Research also emphasizes optimal SVC placement to improve voltage stability, reduce power losses, and enhance system efficiency. A method utilizing Voltage Stability Limit (VSL) assesses controller performance by varying TCR impedance through thyristor firing angle adjustments. The Coordinated Transformation method, validated through MATLAB simulations, has proven cost-effective, accurate, and responsive for SVC voltage regulation.

SVC applications in power systems enhance real power transfer capabilities and stabilize bus voltage profiles. Post-fault stability analyses confirm improved power flow and system resilience. These findings underscore SVCs' significance in modern power systems, supporting voltage control, oscillation damping, and enhanced operational efficiency.

b. Static Synchronous Compensator (STATCOM)

The Static Synchronous Compensator (STATCOM) is a power electronics-based Synchronous Voltage Generator (SVG) and a shunt-connected Flexible AC Transmission System (FACTS) device. It provides reactive power compensation to stabilize and manage voltage fluctuations in power systems, independent of AC system voltage. The STATCOM operates using a DC Voltage Source Converter (VSC), which generates a three-phase voltage synchronized with the grid through a coupling transformer. Its primary components include a DC capacitor, Gate

Commutated Turn-off (GCT) thyristors, and a step-up transformer. STATCOM improves both static and dynamic voltage stability while maintaining the electric system's operational mode.

STATCOM controls reactive power by injecting AC current either leading or lagging the grid voltage, acting as inductive or capacitive impedance at the connection point. If its voltage is lower than the transmission line voltage, it mimics an inductive load and absorbs reactive power. Conversely, when its voltage is higher, it behaves as a capacitive load and supplies reactive power. Its reactive power generation is independent of the transmission line voltage magnitude, making it highly versatile for voltage regulation and power quality improvement. Techniques like Multi-phase, Multi-level, or Pulse-Width Modulated (PWM) converters further reduce current distortion, enhancing its efficiency.

Applications of STATCOM in improving power system stability have been widely researched. Studies emphasize the coordination between STATCOM damping stabilizers and internal voltage controllers to enhance dynamic stability and voltage regulation. Optimized STATCOM designs using Genetic Algorithms show significant improvements in voltage stability, maintaining voltages closer to nominal levels. Advanced control schemes, such as decoupled current control strategies, have demonstrated high efficiency in both inductive and capacitive modes for voltage regulation and reactive power compensation.

Digital simulations in MATLAB/Simulink validate STATCOM's performance under various operating conditions. Novel control designs, such as a Current Source Inverter (CSI)-based STATCOM, incorporate fast AC current inner loops and slower DC current outer loops. Experimental validations confirm that STATCOM effectively enhances system voltage profiles and reduces power losses.

STATCOM also plays a crucial role in renewable energy integration, particularly in wind farms, by supporting steady-state and transient voltage stability. Unlike thyristor-based Static Var Compensators (SVC), STATCOM's compensating current remains unaffected by voltage drops, providing an advantage in voltage support. Its typical applications include improving system

stability, damping low-frequency oscillations, enhancing transient stability, controlling voltage flicker, and improving overall power quality.

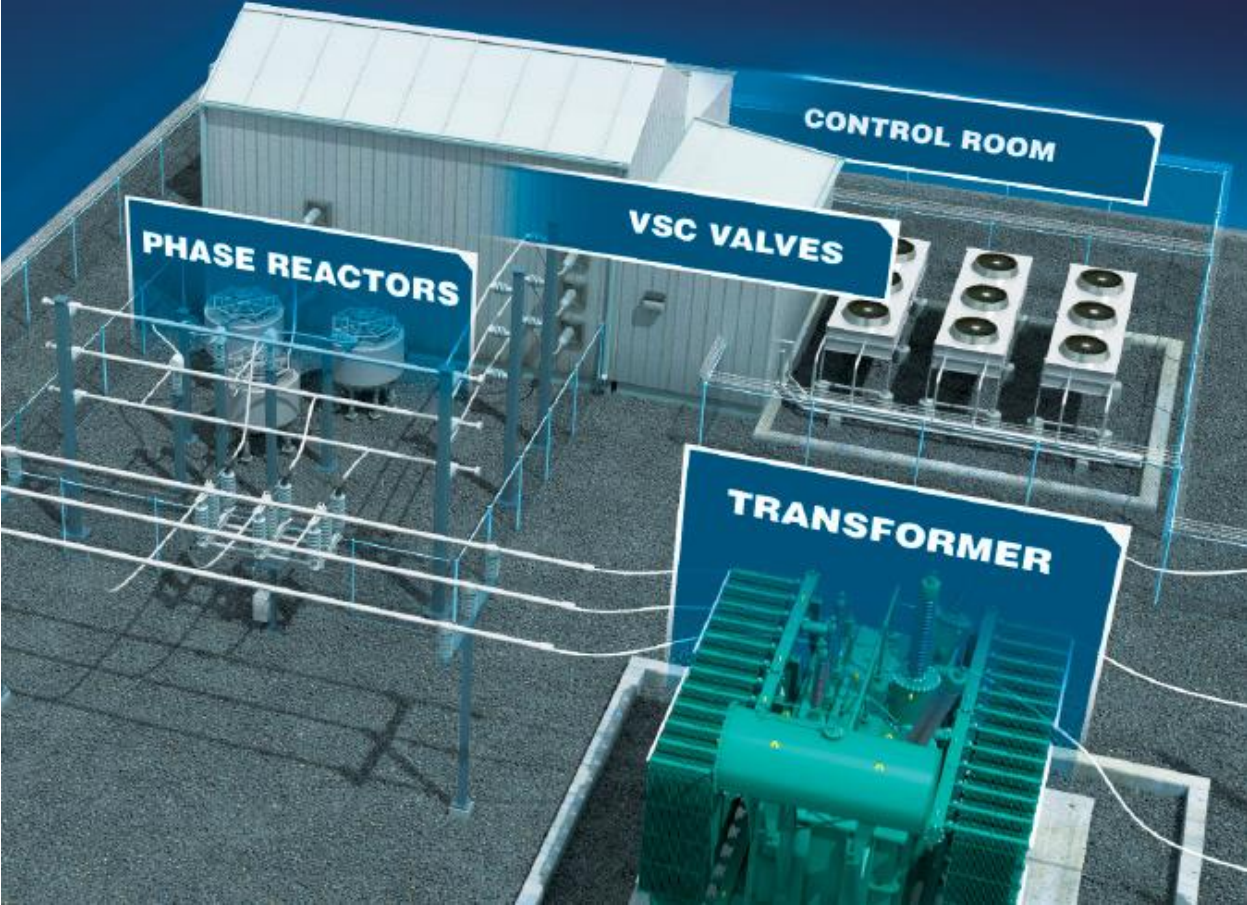


Figure 8. STATCOM on Grid[15]

In conclusion, STATCOM is an advanced FACTS device that significantly enhances voltage stability, power delivery, and system efficiency. Its ability to operate independently of transmission line voltage, coupled with advanced control strategies, makes it an essential component in modern power systems, especially for renewable energy integration and power quality improvement.

2.6.1.3 Combined Series-Series Devices

Devices that integrate two or more independent series devices under coordinated control are known as combined series-series devices. By using the DC link, these devices may balance the flow of both real and reactive power in the line, maximizing the use of the transmission system. It is known as a Unified Power Flow Controller (UPFC) because all the device converters' DC

terminals are coupled together for actual power transmission. Figure 9 depicts the series-series device.

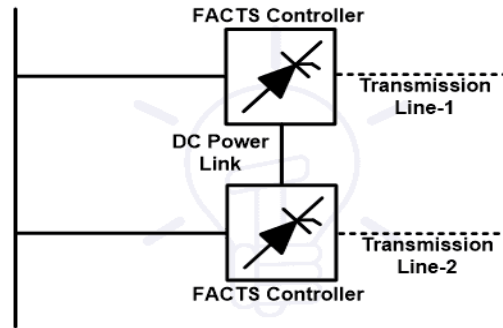


Figure 9. Combined Series-Series Devices

2.6.1.4 Combined Series-Shunt Devices

These are gadgets that synchronize disparate shunt and series controllers. With the series component, the combined series and shunt controllers inject voltage in the line, and with the shunt part, they inject current into the system. Figure 10 depicts the series-shunt device.

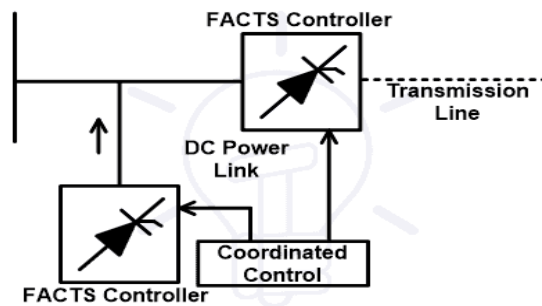


Figure 10. Series-Shunt Device

2.7 Power system stability

Power system stability refers to a system's ability to maintain equilibrium during normal operations and return to equilibrium after disturbances. Stability depends on synchronization forces overcoming disturbances, and instability results in loss of synchronism. Stability is a key consideration in power system planning, especially as growing load demands and interconnected systems increase stress on existing networks. Without new investments in transmission lines, the network faces greater instability risks during disturbances or sudden load increases. FACTS

devices have proven effective in managing stressed networks while maintaining stability margins.

Stability is categorized into three types:

1. **Steady-State Stability:** This measures a system's ability to return to equilibrium after minor disturbances. It is defined by the maximum power transfer limit without losing synchronism. Steady-state stability is influenced by load angles, and instability occurs if the load angle exceeds 90° . Operating within safe load angles prevents instability.
2. **Dynamic Stability:** This refers to a system's ability to maintain equilibrium after short-term small disturbances. Ignoring dynamic instability can lead to generators falling out of step.
3. **Transient Stability:** This describes a system's ability to regain synchronism after severe disturbances such as sudden load changes, line outages, or system faults. Transient stability is critical for managing major disruptions in power systems.

2.8. Rwanda's Grid Losses

A detailed study on the Rwandan grid involved creating a model using PSS/E and validating it. A comprehensive study of the Rwandan transmission grid was conducted by developing a detailed simulation model using Power System Simulator for Engineering (PSS/E), a widely recognized tool for analyzing power systems. This model was carefully designed and validated against actual network parameters, ensuring that the simulation accurately reflected the operational characteristics and constraints of the Rwandan grid. By incorporating real-world data such as line impedances, transformer ratings, and load profiles, the model provided an in-depth representation of the system's dynamics.

The findings from the study highlighted a critical aspect of the grid's performance: its point of stability loss during power angle variations could be precisely identified through simulation. This point of stability loss is a vital metric, as it signifies the conditions under which the grid becomes unstable due to excessive power angle deviations. These deviations, often caused by sudden load changes, faults, or generation fluctuations, can result in a loss of synchronism

between different parts of the system, potentially leading to cascading outages or system-wide blackouts.

Power system efficiency can be notably improved by controlling and reducing losses. REG's efforts to reduce network losses are commendable. However, due to the low consumption per customer in Rwanda today and considering the increase in the number of connections and the growth of consumptions the losses could increase in the coming years. Therefore, solid actions must be taken as of today in order to control this potential increase and anticipate it.

In electricity supply to final consumers, losses refer to the amounts of electricity injected into the transmission and distribution grids that are not paid for by users. Losses occur naturally and consist mainly of power dissipation in electricity system components such as transmission and distribution lines, transformers, and measurement systems.

The study underscored the importance of deploying active devices to address these challenges. Devices such as Flexible AC Transmission Systems (FACTS), Static Synchronous Compensators (STATCOMs), and Phasor Measurement Units (PMUs) are particularly effective in managing power angle variations. These technologies enhance the grid's ability to maintain synchronism by dynamically regulating voltage, reactive power, and power flow. For instance, FACTS devices can quickly respond to disturbances by injecting or absorbing reactive power, thus stabilizing power angles and improving the grid's overall resilience.

Moreover, the study emphasized that the use of active devices would not only mitigate stability issues but also enable better utilization of existing transmission lines. By maintaining optimal power and voltage levels, these devices can reduce line losses and enhance the grid's efficiency, aligning with Rwanda's goals for sustainable energy development. This approach is particularly crucial for a system like Rwanda's, which operates with minimal reserve margins and underutilized transmission capacity. Implementing such advanced solutions is a key step toward improving the reliability, efficiency, and stability of the Rwandan transmission grid, directly supporting the objectives of your thesis on power losses and efficiency improvements

2.9 Reasons for choosing STATCOM

Shunt compensators, such as shunt capacitors and FACTS devices, are commonly used for reactive power compensation to enhance grid voltage stability. Among these, shunt capacitors are cost-effective compared to other shunt FACTS devices, as shown in Table 1, and provide voltage stability.

STATCOM, a Voltage Source Converter (VSC)-based device, addresses these limitations. It converts DC input to AC output, compensating for both active and reactive power. Unlike SVC, STATCOM's compensating current remains unaffected by voltage levels, maintaining constant current even during voltage dips[16]. This characteristic ensures superior voltage regulation and system stability.

Additionally, STATCOM's use of self-commutating power semiconductors like IGBTs enables faster response times and reduced harmonic emissions compared to SVC[17]. Its compact design eliminates large passive components, reducing space requirements and maintenance needs while avoiding synchronism issues.

Reactive power imbalance can destabilize the power system, making fast, efficient compensation essential. STATCOM's advantages make it ideal for addressing such imbalances. In this dissertation, a STATCOM employing VSC PWM techniques is proposed to mitigate power losses and enhance system performance, leveraging its reliability and operational benefits over traditional compensators.

Table 1. Cost comparison of shunt devices

Shunt Device	Cost (US \$)
Shunt Capacitor	8 / kVAr
SVC	40 / kVAr
STATCOM	50 / kVAr

To reduce power losses on a power transmission line, a voltage source converter (VSC) PWM technique-based STATCOM is suggested in this research. Although the basic operating principles of SVC and STATCOM appear to be similar, table 2 below illustrates how the two devices differ from one another.

Table 2. Comparison of SVC and STATCOM

SVC (Thyristor Based Shunt Compensator)	STATCOM (VSC Based Shunt Compensator)
SVC operates as a shunt connected to control reactive admittance	STATCOM functions as a shunt connected synchronous voltage source
SVC does not produce active power compensation	STATCOM provides active power and reactive power compensation

These distinctions explain why STATCOM has stronger functional qualities than SVC, including higher performance and more adaptability in applications. STATCOM improves power system performance and flexibility, detects voltage disturbances instantly, and quickly corrects by injecting leading or lagging reactive power. With its sophisticated controls, STATCOM helps utilities recover from system voltage collapse incidents and removes power transfer restrictions linked to stability. The fact that it is an affordable solution with a small environmental impact is more significant.

3. DATA COLLECTION AND ANALYSIS

3.1. Methodology

Data collection for this study involved acquiring critical transmission line parameters such as line length, conductor type, line resistance and reactance, voltage levels, and load data at Bus of Musha, Kabarondo and Rwinkwavu Substation. These parameters were essential for conducting Load Flow Analysis, which examined voltage profiles, active and reactive power flows, and losses across that. The analysis employed PSSE tools which is industry-standard platform for power system modeling and optimization and some data are presented in below table.

Table 3. Some Electrical Quantities Musha-Karando-Rwinkwavu N/W

Study Project Tasks		Network data x															
Bus	Section	Substation	Bus	Base kV	Area	Area	Zone	Zone	Owner	Owner	Code	Voltage	Angle	Normal	Normal	Emergency	Emergency
1			MUSHA	110.0	1		1		1		3	1.0000	-6.30	1.1000	0.9000	1.1000	0.9000
2			KABARONDO	110.0	1		1		1		1	0.9949	-6.63	1.1000	0.9000	1.1000	0.9000
3			RWINKWAVU	110.0	1		1		1		1	0.9944	-6.66	1.1000	0.9000	1.1000	0.9000
11			MUSHA-15	15.0	1		1		1		1	0.9440	-8.97	1.1000	0.9000	1.1000	0.9000
12			GIGAWATT	15.0	1		1		1		-2	1.0162	4.00	1.1000	0.9000	1.1000	0.9000
21			KABARONDO-30	30.0	1		1		1		-2	0.9847	-8.77	1.1000	0.9000	1.1000	0.9000
31			RWINKWAVU-15	15.0	1		1		1		1	0.9883	-7.24	1.1000	0.9000	1.1000	0.9000
*																	

3.2. Site Description

Musha substation:

It is located in the Eastern Province, Rwamagana District. It receives power primarily from Gasogi substation, situated in Kigali, Gasabo District, through a 110kV transmission line with a length of 16.5 km. This transmission line has a power transfer capacity of 100MW and is constructed using an ACSR conductor of 240/40mm².

Musha substation is equipped with two power transformers, each rated at 20MVA, 110/15kV ensuring reliable voltage transformation for onward power distribution. Additionally, Musha substation receives power from Gabiro substation, which is located in the Eastern Province, Nyagatare District. This connection is facilitated by another 110kV transmission line spanning a distance of 45 km, also with a power transfer capacity of 100MW and constructed using an ACSR conductor of 240/40mm².

Furthermore, Musha substation integrates an embedded generation source from renewable energy: the Gigawatt Solar Power Plant. This solar farm, located in the same region, supplies power through 9.4km distribution of line, operating on 15kV. The line is constructed with an

ACSR conductor of 120/20mm² its resistance of 0.404Ω/km and reactance of 0.371Ω/km and has a maximum generation capacity of 8MW, contributing to grid stability and reducing dependency on conventional sources.

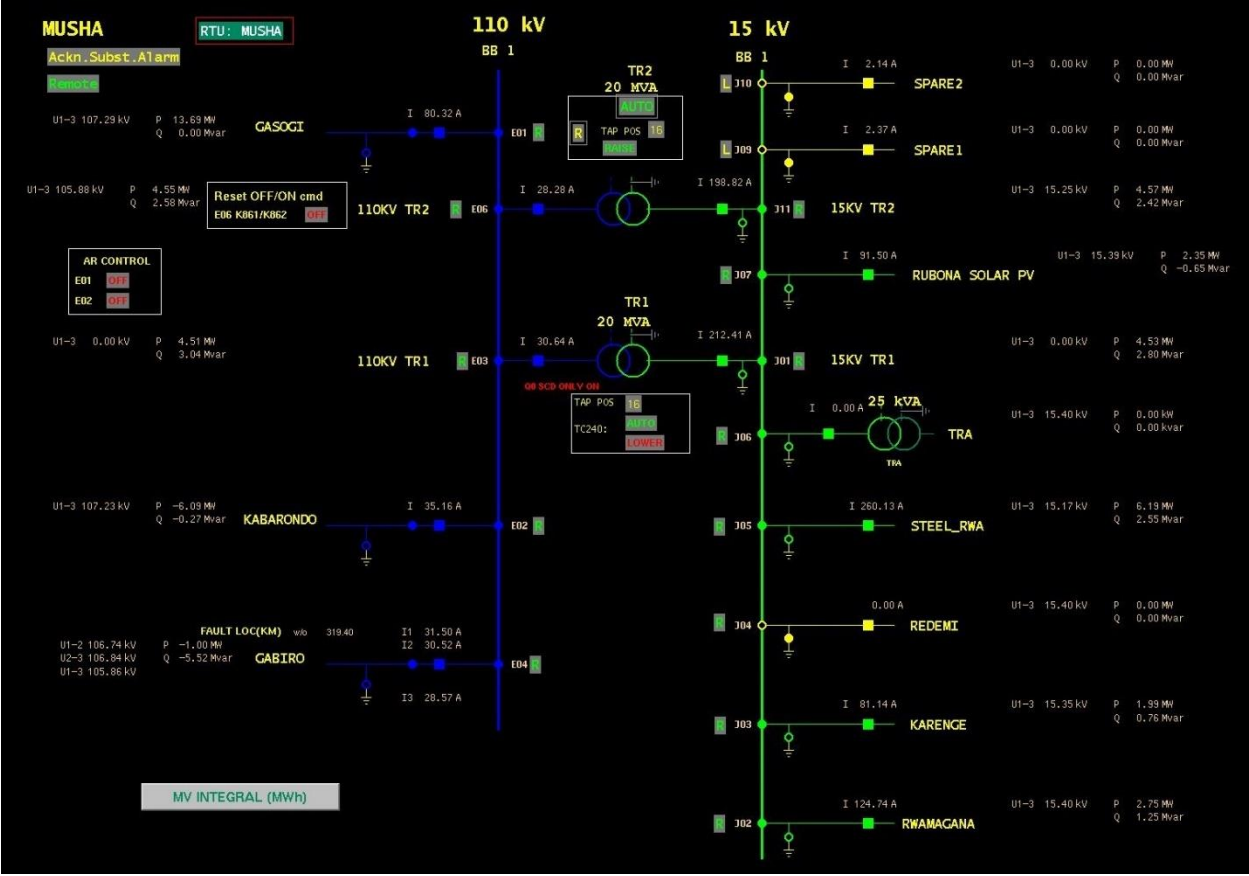


Figure 11. Musha Substation Single line diagram

Power from Musha substation is transmitted to Kabando and Rwinkwavu substations, both located in the Eastern Province, Kayonza District. The transmission lines connecting these substations operate at 110kV, with a length of 25 km to Kabando and 8.5 km to Rwinkwavu. Each of these lines are designed to transfer up to 100MW and are constructed with ACSR conductor of 240/40mm², ensuring robust power delivery and network reliability.

In 2024, the peak power distributed from Musha substation was recorded at 18.57MW, delivered through four medium-voltage (MV) distribution feeders. These feeders and their respective peak loads were as follows:

- Rwamagana Feeder – Peak load: 5.3MW
- Karenge Feeder – Peak load: 2.64MW

- SteelRwa Feeder – Peak load: 10.83MW
- Redemi Feeder – Peak load: 0.51MW

Table 4. Electrical Parameters of Kabarondo Bay in Musha Substation

KABARONDO BAY IN MUSHA SUBSTATION											
		CURRENT			VOLTAGE			POWERS		FREQUENCY	COS ϕ
		L1	L2	L3	L12	L23	L31	Active	Reactive		
		A	A	A	KV	KV	KV	P	Q	f	PF
DATE	Hrs	A	A	A	KV	KV	KV	MW	Mvar	Hz	Cos
29/4/2021	1:00	27	27	28	110.6	110.4	109.7	-3.5	3.8	49.8	-0.7
	2:00	28	27	27	110.9	110.9	110.6	-3.5	3.6	50	-0.7
	3:00	27	27	27	111.1	110.9	110	-3.7	3.3	50	-0.7
	4:00	27	27	28	111.4	111	110.3	-3.3	3.8	50	-0.64
	5:00	28	28	27	108.5	108.9	108	-3.8	3.6	49.5	-0.7
	6:00	27	27	28	110.2	110.5	109.2	-3.7	3.5	49.7	-0.7
	7:00	22	21	22	108.3	107.6	106.9	-2.9	2.6	50	-0.76
	8:00	23	21	23	103.7	104.7	103.5	-3.3	1.6	49.5	-0.88
	9:00	25	23	24	104.7	106.1	105.4	-4.2	1.2	49.4	-0.94
	10:00	23	22	23	107	106.2	106.5	-4	1.2	49.4	-0.94
	11:00	19	19	18	106.5	106.5	106.1	-3.4	0.8	50	-0.94
	12:00	24	24	25	107.6	107.6	107.1	-4.2	1.3	49.7	-1
	13:00	23	22	23	108.9	109	108.4	-4	1.6	50	-0.94
	14:00	21	20	21	108.5	108.5	108	-3.3	1.4	50	-0.94
	15:00	22	22	23	107.6	107.5	107.8	-3.8	1.7	50.6	-0.94
	16:00	19	17	18	105.6	105.9	106.1	-2.9	0.3	49.8	-1
	17:00	24	24	24	106.8	106.6	106.3	-4.4	0.5	50.2	-1
	18:00	31	30	30	106.6	108.1	107.5	-5.3	1.1	49.3	-1
	19:00	41	40	42	108.9	109.2	108.7	-5.8	4.9	50	-0.76
	20:00	41	39	40	110.9	111.1	110.5	-5.4	5.1	49.6	-0.7
21:00	37	35	37	117.1	117.2	116.6	-5	5.1	50	-0.7	
22:00	31	31	32	113.6	113.7	113.1	-4	4.3	49.9	-0.7	
23:00	26	26	27	113.5	113.7	112.7	-3.2	3.8	49.8	-0.64	
0:00	26	26	27	113.2	113.2	112.4	-3.3	3.8	49.8	-0.64	

These feeders play a crucial role in supplying power to industrial, commercial, and residential consumers in the region, ensuring a stable and efficient distribution network. The integration of

renewable energy and robust transmission infrastructure contributes to enhancing the overall efficiency of the Rwandan power system.



Figure 12. Musha Substation

Kabarondo Substation:

It is located in the Eastern Province, Kayonza District. It is a tie substation connected on transmission line of 110kV from Musha to Rwinkwavu at a length of 25 km. Kabarondo substation is equipped with one power transformers, rated at 10MVA, 110/30kV ensuring reliable voltage transformation for onward power distribution.

Currently, Kabarondo substation has no alternative power supply in case of a fault or outage on the incoming transmission line. The substation is primarily feed from one 110kV transmission line from Musha. However, any failure on that line or associated equipment, such as switchgear, would result in a complete loss of power supply to the substation, disrupting both agriculture farm, commercial and residential consumers.

Additionally, Kabarondo substation integrates an embedded generation source from renewable energy: the Nasho Solar Power Plant. This solar farm, located in Kirehe, supplies power through an 26km distribution line operating at 30kV. The line is constructed with an ACSR conductor of

150/25mm² and has a maximum generation capacity of 3.3MW, contributing to grid stability and reducing dependency on conventional sources.

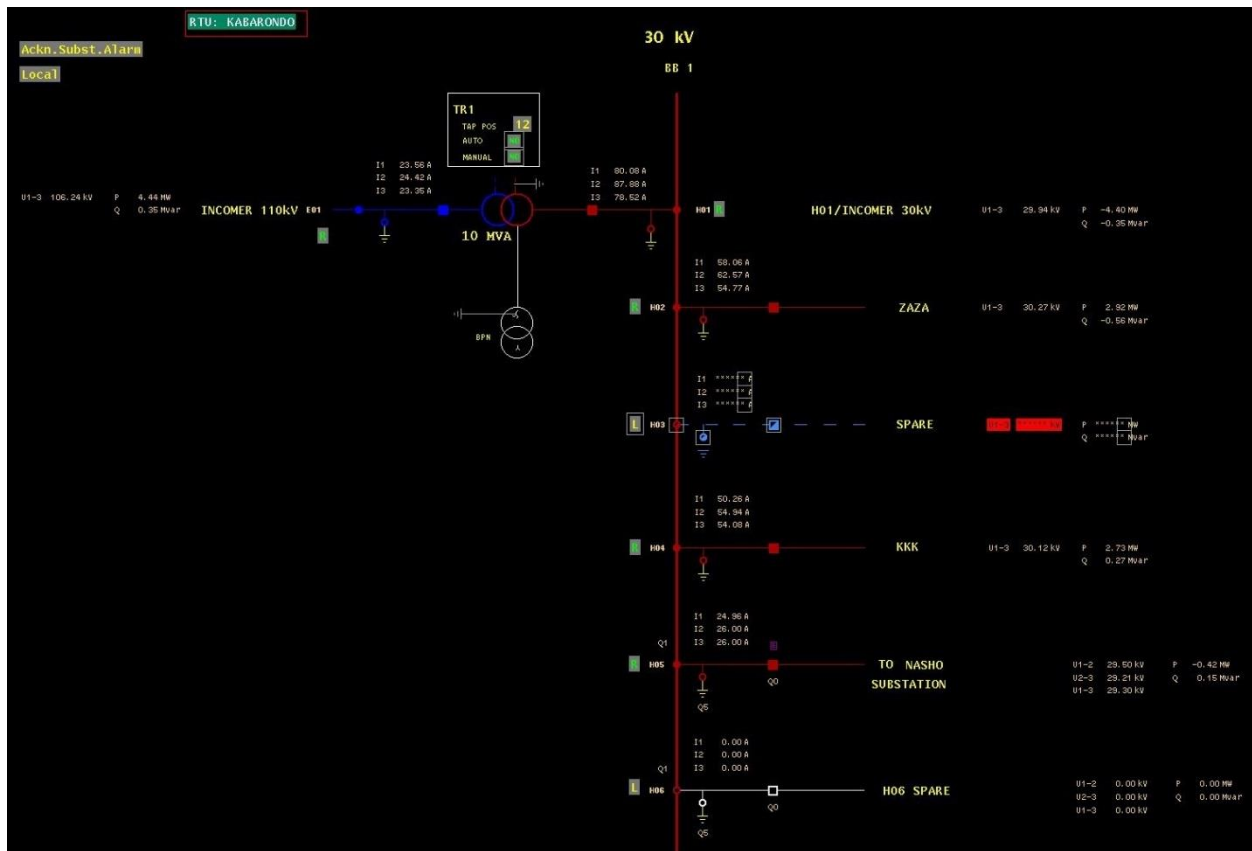


Figure 13. Kabarondo Substation Single line diagram

In 2024, the peak power distributed from Kabarondo substation was recorded at 9.48MW, delivered through two medium-voltage (MV) distribution feeders. These feeders and their respective peak loads were as follows:

- Zaza Feeder – Peak load: 5.1MW
- KKK Feeder – Peak load: 5.47MW

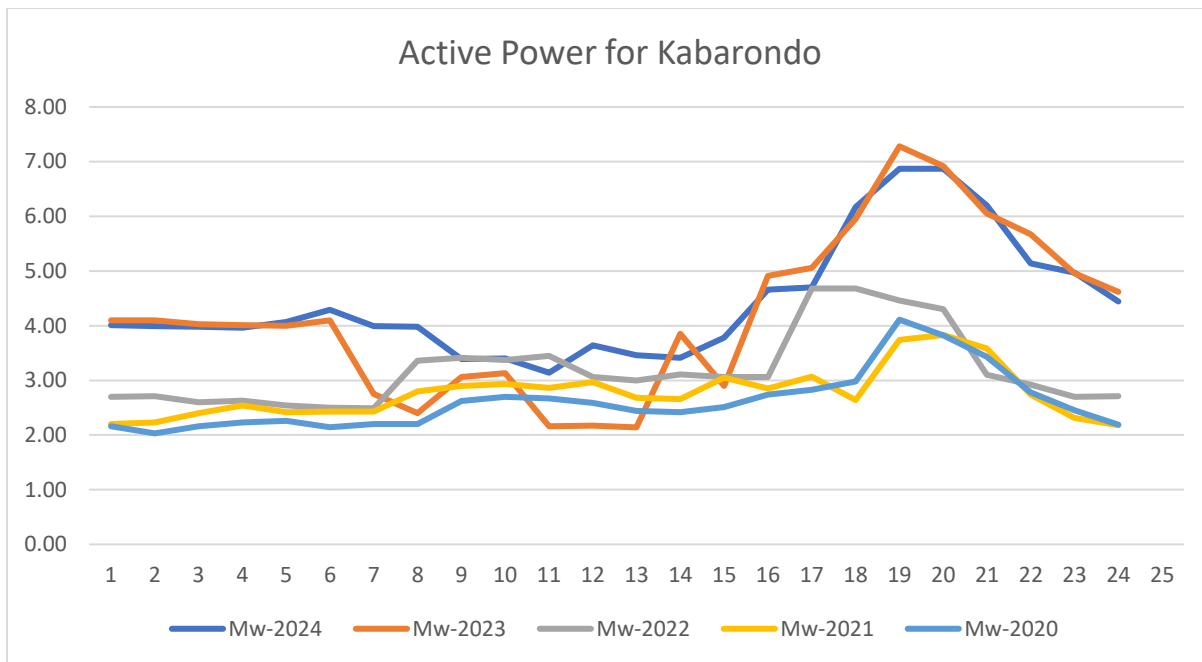


Figure 14. 5 Year Trend of Active Power at Kabarondo Substation

These feeders serve a significant role in supplying power to industrial, commercial, and residential consumers in the region, guaranteeing a stable and efficient distribution network. The region's total efficiency is improved by the combination of reliable transmission infrastructure and renewable energy.

Rwinkwavu Substation:

Rwinkwavu substation is located in the Eastern Province, Kayonza District. This substation is positioned at the terminal end of a 110kV transmission line from Musha, with a total length of 33.5 km. The transmission line has a power transfer capacity of 100MW and is constructed using an ACSR conductor of 240/40mm², ensuring efficient power transmission.

Rwinkwavu substation is equipped with one power transformer, rated at 6MVA, 110/15kV, facilitating voltage transformation for medium-voltage (MV) distribution to local consumers. Despite its critical role in supplying power to the region, the substation faces a major reliability concern due to the lack of an alternative power supply. Currently, Rwinkwavu substation is solely dependent on a single 110kV transmission line from Musha, meaning that any fault or

disruption on this line whether due to equipment failure, conductor faults, or adverse weather conditions would lead to a complete loss of power supply.

This reliability issue has significant implications for agriculture-based industries, irrigation systems, commercial activities, and residential consumers in the region. The agricultural sector, particularly large-scale farms and irrigation projects, heavily relies on uninterrupted power supply. Any outages at Rwinkwavu substation could directly impact agricultural production, food processing facilities, and rural electrification efforts, causing economic losses and reduced productivity.

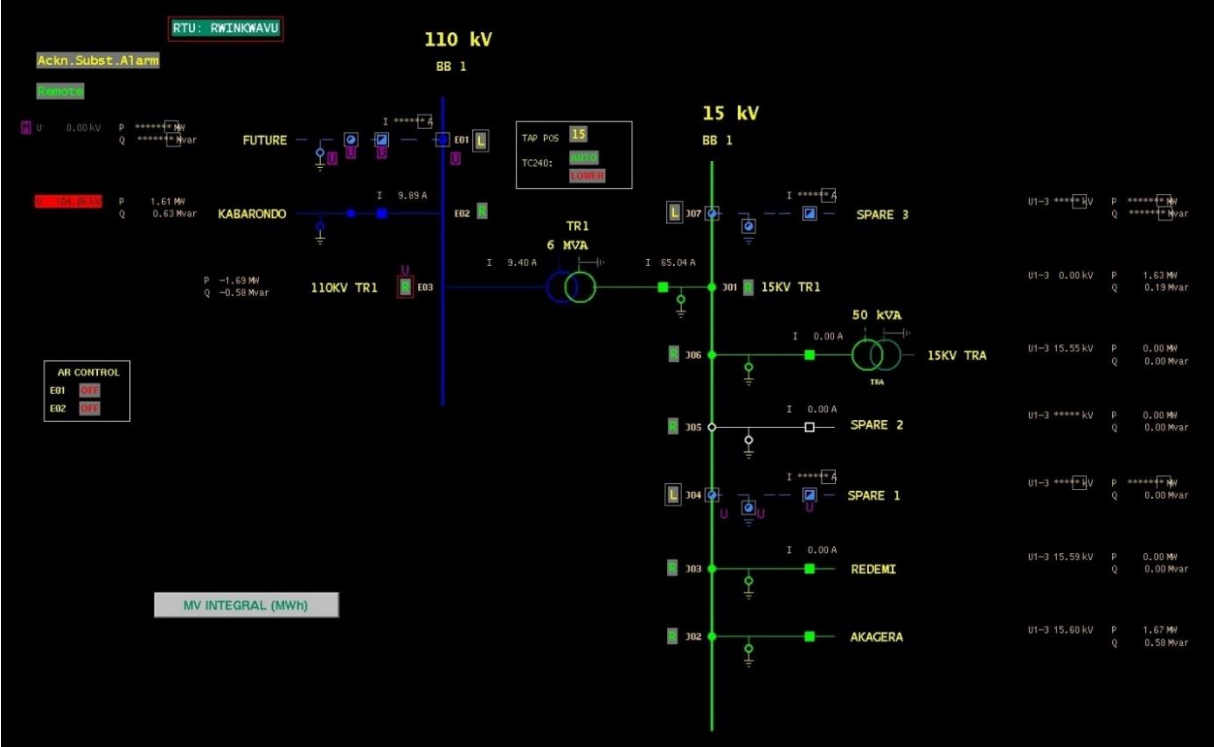


Figure 15. Single line Diagram of Rwinkwavu

In 2024, the peak power distributed from Rwinkwavu substation was recorded at 2.22MW, delivered through a single medium-voltage (MV) distribution feeder, known as Akagera Feeder.

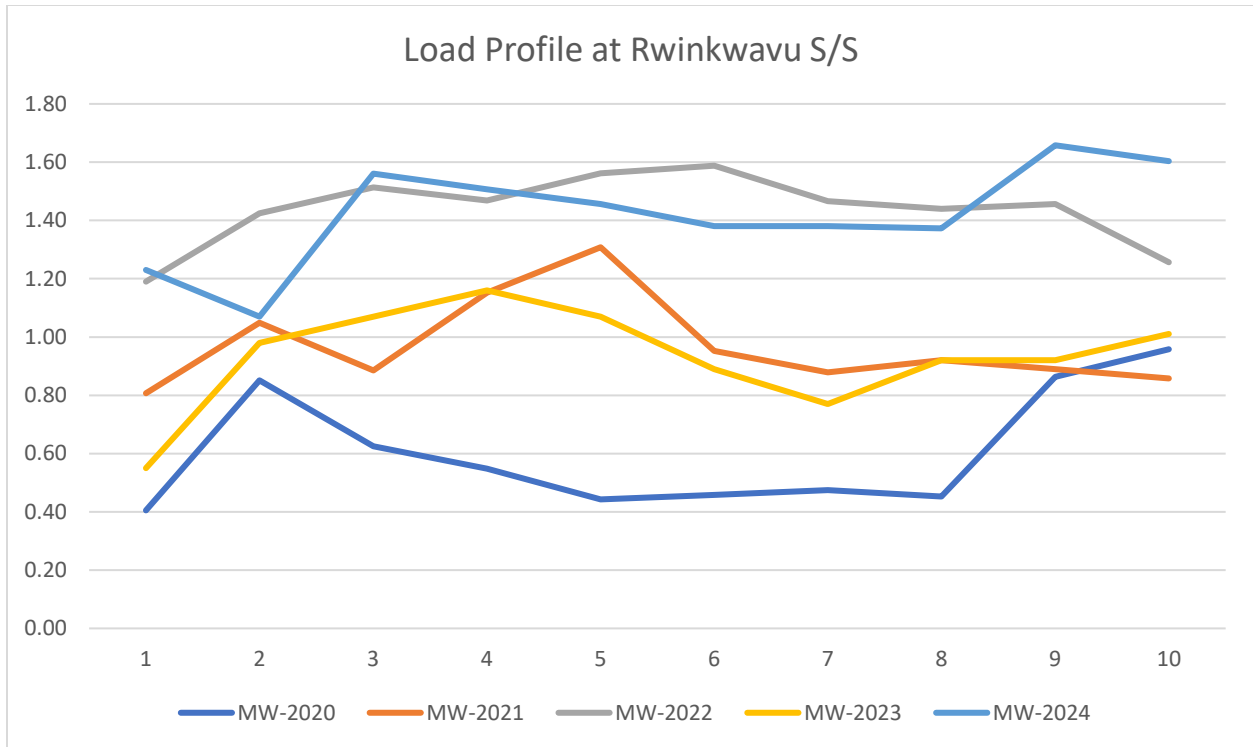


Figure 16. 5 Year Trend of Active Power at Rwinkwavu Substation

This feeder plays a crucial role in supplying power to:

- Agricultural consumers, including irrigation systems and agro-processing plants, supporting the region’s farming activities and mining
- Commercial consumers, such as local businesses and service providers, ensuring economic growth.
- Residential consumers, improving rural electrification and access to essential services.



Figure 17. Rwinkwavu Substation

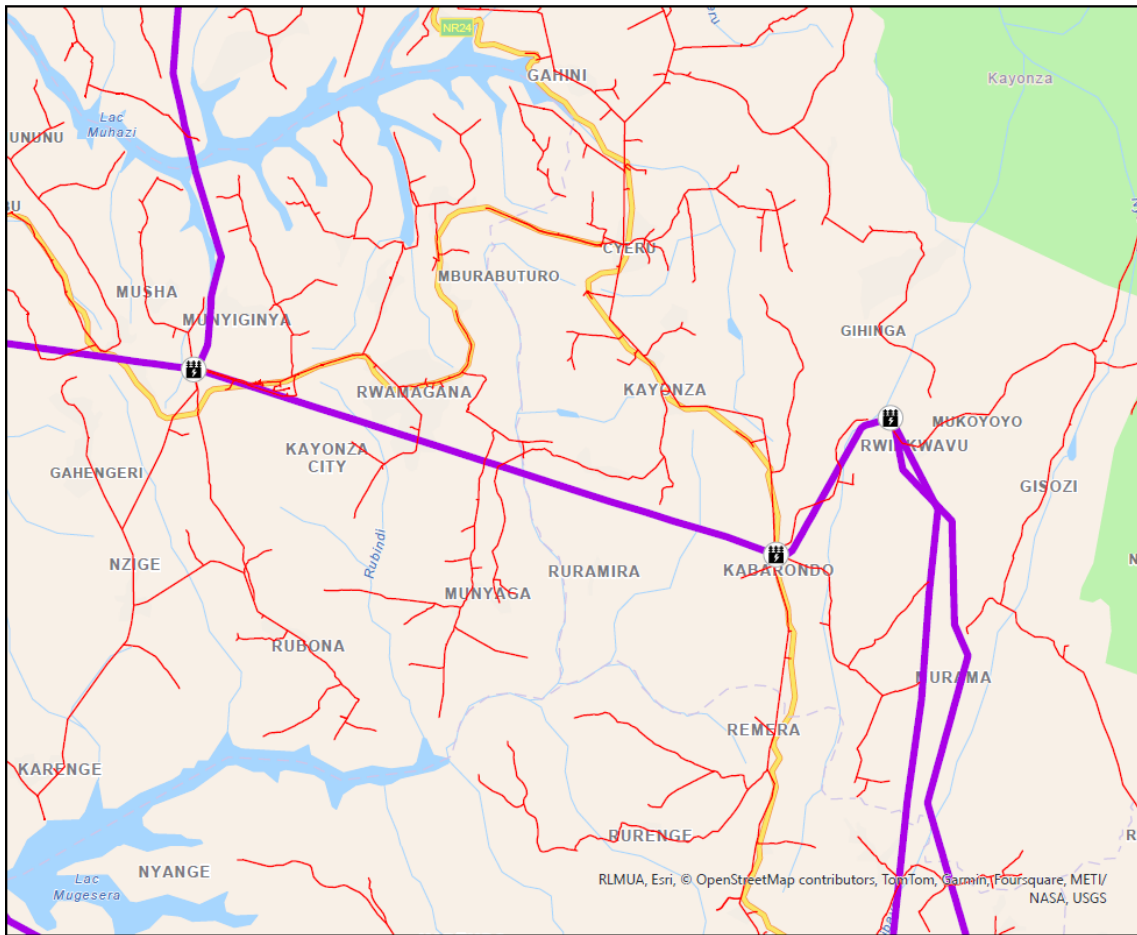


Figure 18. Map of Musha - Rwinkwavu Transmission line with Distribution Feeders

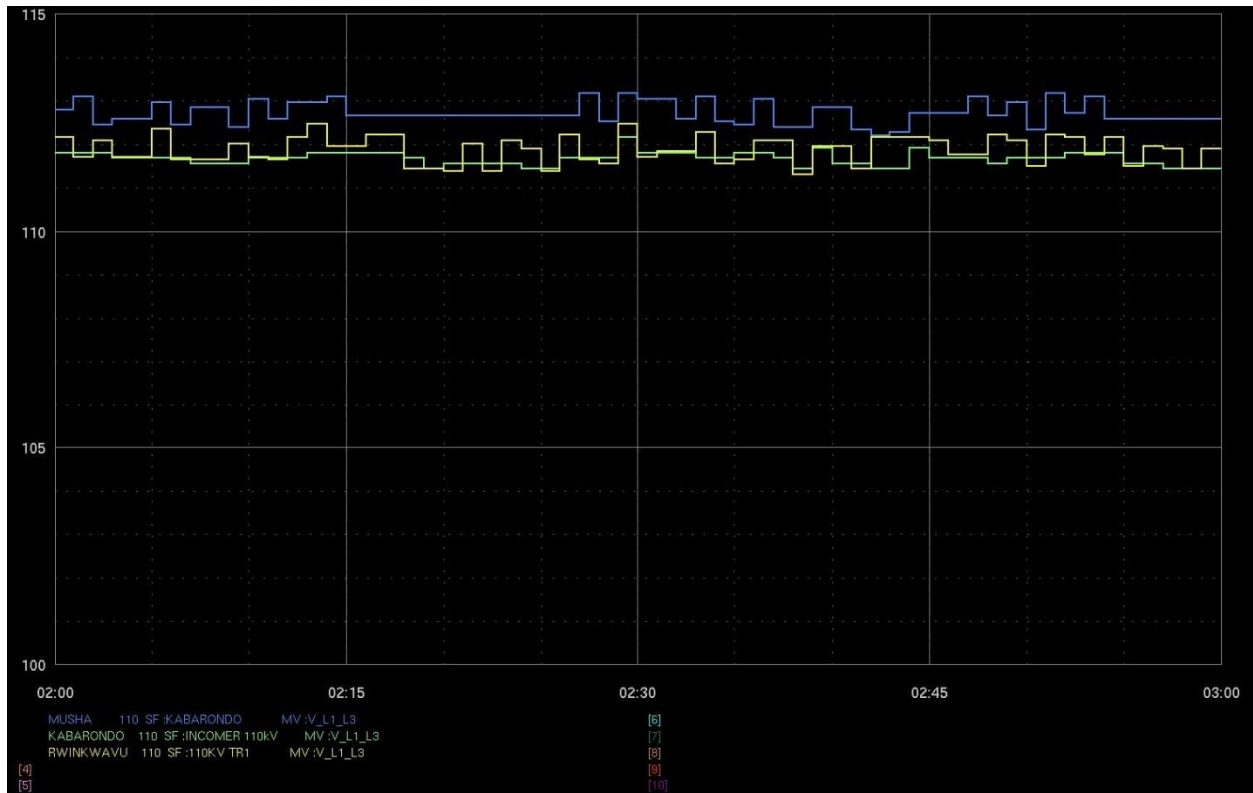


Figure 19. Voltage Profile for Musha-Kabarondo-Rwinkwavu Substation

3.3. Collected Data

The Musha-Rwinkwavu transmission line was constructed in 1982 and operates at a voltage level of 70 kV and later in 2008 upgraded to 110kV, is a critical component of Rwanda’s high-voltage transmission network as it is radial with tie line of Kabarondo.

The analysis of Musha-Rwinkwavu transmission line offers crucial insights into the factors influencing power losses and the efficiency of the system. This line has a length of 25 km from Musha to Kabarondo and 8.3 km from Kabarondo to Rwinkwavu located in eastern province.

The line's parameters are $R= 0.231\Omega/\text{km}$ and $X= 0.437\Omega/\text{km}$ for the line Musha – Kabarondo while for Kabarondo-Rwinkwavu are $R= 0.231\Omega/\text{km}$ and $X= 0.437\Omega/\text{km}$, significantly this contributes to power losses due to resistive heating.

The transmission line uses Aluminum Conductor Steel Reinforced (ACSR) conductors with a cross-sectional area of 240/40 mm². This choice enhances efficiency by striking an optimal balance between the current-carrying capacity and the conductor's resistance. Additionally, the

high voltage level of 110 kV effectively reduces current flow, thereby minimizing resistive losses and improving the line's efficiency in long-distance transmission.

This analysis underscores the importance of transmission line parameters, such as conductor type, cross-sectional area, and operating voltage, mitigating power losses and optimizing system performance. The insights gained contribute to the overall objective of improving the reliability and efficiency of Rwanda's transmission network, specifically Musha-Rwinkwavu

3.4. Analytical Techniques

Transmission losses occur due to the resistance and reactance of the transmission lines. Losses are calculated as the difference between the power sent into the system and the power delivered to the loads.

By conducting load flow analysis or power flow analysis the computational technique in power system engineering used to determine the operating conditions of an electrical power system under a steady state. It helps in evaluation of the performance of the system, plan expansions, and ensure the system operates reliably and efficiently. Below table show energy loss records in December 2024, while others figure show energy trend in 2024.

Table 5. Energy Consumption Musaha-Kabarondo-Rwinkwavu

KABARONDO SUBSTATION	Feeder	Kwh	Kvarh
	Entrée TR	3,939,830	849,800
	Sortie TR	3,945,920	1,081,830
	KIZIGURO (KKK)	2,125,380	87,700
	ZAZA	2,024,790	1,051,830
	NASHO	-147,170	71,740
	Auxiliaire	1,786.5	789.00
RWINKWAVU SUBSTATION	Feeder	Kwh	Kvarh
	Entrée TR	630,220	213,140
	Sortie TR	768,610	205,730
	AKAGERA	759,860	181,990
	Auxiliaire	2,945.00	1,256.50
Musha Substation	Kabarondo TL	4,749,370	1,434,920
	Total Export	4,561,270	1,127,270
	Total Loss	188,100	
	Loss in %	4%	

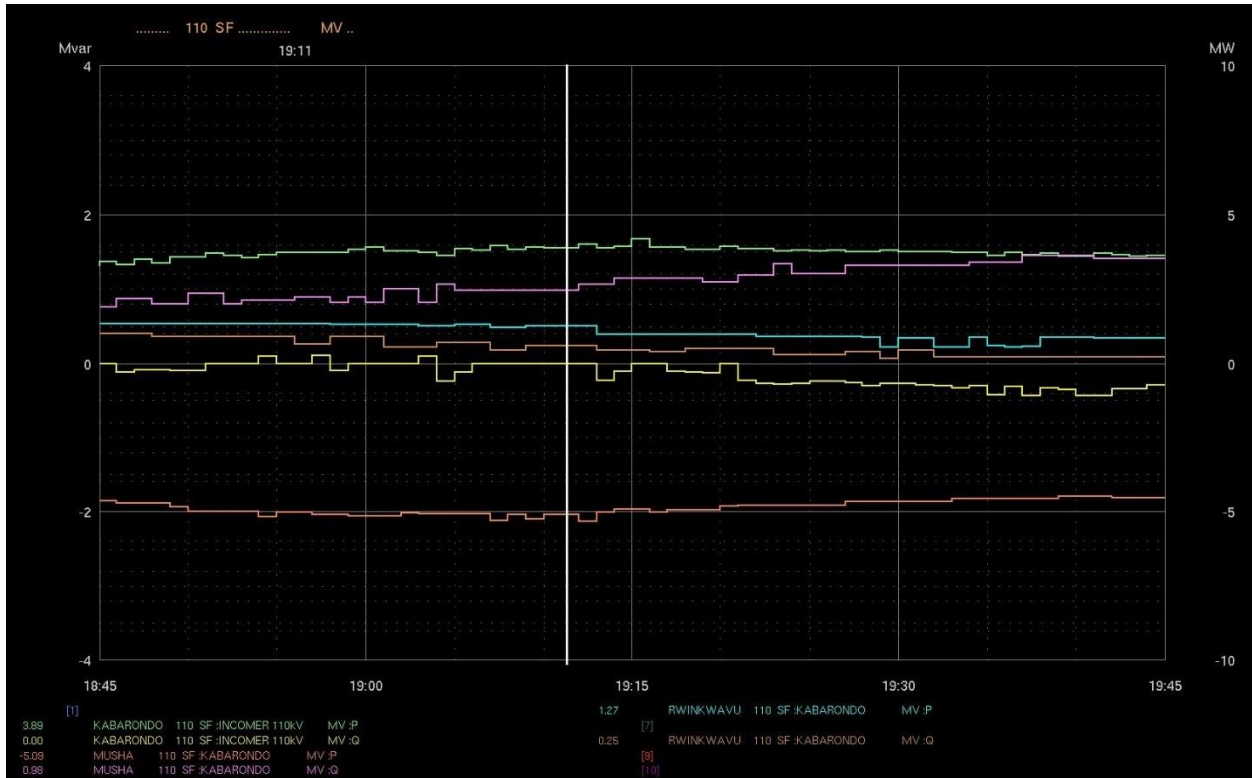


Figure 20. Active & Reactive Power During Peak Hours

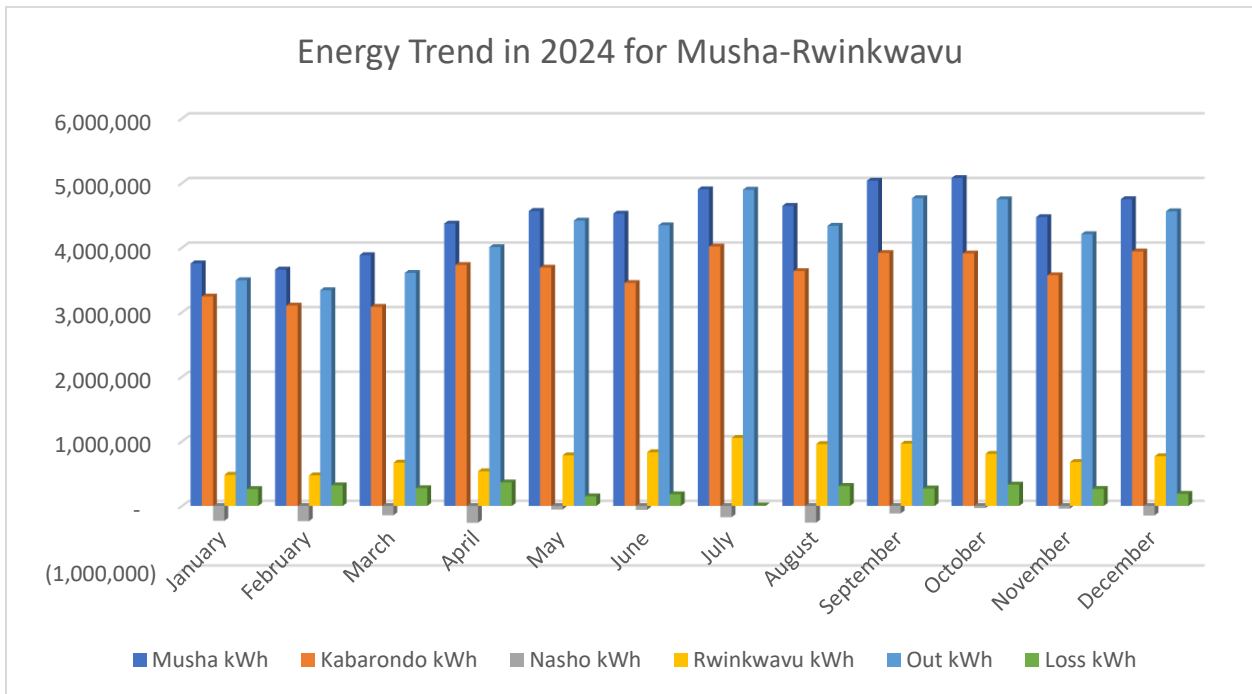


Figure 21. Energy trend for Musha-Rwinkwavu

For a trend of 5 Years the average loss recorded was 5.4%

Power losses (P_{loss}) for three phase system:

$$P_{\text{loss}} = 3 \cdot I^2 \cdot R_{\text{total}} = 3 \cdot (10.5)^2 \cdot 1.96 = 0.648 \text{ kW}$$

Corona Loss Calculations (P_c)

Line voltage: 110 kV

$$P_c = 244 \times (f + 25) / \delta \times \sqrt{\frac{r}{d}} (V - V_{\text{do}})^2 \times 10^{-5} = 292.73 \text{ kW}$$

Where:

$$f = 50 \text{ Hz,}$$

$$V = 63.5 \text{ kV (Phase voltage)}$$

$$D = 1 \text{ m (spacing between conductors)}$$

$$r = 0.87 \text{ cm (conductor radius)}$$

$$\delta = 0.95 \text{ (air density factor)}$$

$$V_{\text{do}} = 21.2 m \delta r \ln \left(\frac{d}{r} \right) \dots \dots \text{Disruption critical voltage}$$

$$V_{\text{do}} = 21.2 \times 0.83 \times 0.95 \times 0.76 \ln \left(\frac{100}{0.76} \right) = 61.99 \text{ kV}$$

$$P_c = 244 \times (50 + 25) / 0.95 \times \sqrt{\frac{0.76}{100}} (63.5 - 61.99)^2 \times 10^{-5} = \frac{0.037 \text{ kW}}{\text{km}} / \text{phase}$$

$$P_c = 3 \times 0.037 \times (25 + 8.5) = 3.8 \text{ kW}$$

The total power losses include:

$$P_{\text{loss}} = 14 \text{ kW} + 56.416 \text{ kW} + 11.5 \text{ kW} + 43.350 \text{ kW} + 59.088 \text{ kW} + 0.648 \text{ kW} + 3.8 \text{ kW} = 188.8 \text{ kW}$$

$$\text{Total efficiency } (\eta) = \left(\frac{P_{\text{civling}}}{P_{\text{civling}} + P_{\text{loss}}} \right) \times 100$$

$$\eta = \left(\frac{5191}{5191 + 188.8} \right) \times 100 = 96.5\%$$

4. MODELING AND SIMULATION

Power system studies require performing complex calculations and utilizing a range of advanced functions to analyze and optimize grid performance. One of the most widely used tools for these analyses is PSSE (Power System Simulator for Engineering), a powerful software suite designed for modeling, simulating, and evaluating electrical networks. PSSE offers various essential functions, including power flow analysis, which determines voltage levels, power losses, and load distribution across the network; dynamic simulations, which assess transient and steady-state stability in response to disturbances such as generator outages or sudden load changes; network equivalent modeling, which simplifies large power networks into reduced models for efficient computation while preserving essential characteristics; and fault and contingency analysis, which simulates short circuits, equipment failures, and other system disturbances to evaluate resilience and develop mitigation strategies. Many power utilities, consulting firms, and research institutions rely on PSSE for feasibility studies, particularly when integrating new electrical components such as power plants, substations, or renewable energy sources into the existing grid. The software helps identify potential operational challenges, ensure grid stability, and optimize system performance before implementation.

PSSE supports two primary types of models used in power system simulations. The first type consists of built-in library models, which are pre-programmed and available within the software. These models include industry-standard representations, such as those developed by the Western Electricity Coordinating Council (WECC) and other regulatory bodies, which define generator, load, and system behavior under different conditions. These pre-defined models provide a standardized approach for simulating and analyzing power system dynamics. The second type includes user-defined models (UDMs), which allow engineers to create custom models for specific power system components that are not available in the built-in library. These models are typically written in Fortran, a high-performance programming language widely used for numerical and engineering computations. Once developed, the Fortran-based models are compiled into Dynamically Linked Library (DLL) files, which are then imported into PSSE for execution. This capability enables engineers and researchers to simulate unique system

behaviors, incorporate proprietary control algorithms, and test innovative power system solutions[18].

By employing this methodologies and tool, the research provides a thorough understanding of power loss dynamics within Musha – Rwinkwavu transmission line. The insights gained from this analysis support the development of targeted solutions to improve reliability, efficiency, and overall effectiveness. This approach aligns with the broader goal of advancing the performance and sustainability of Rwanda’s power infrastructure.

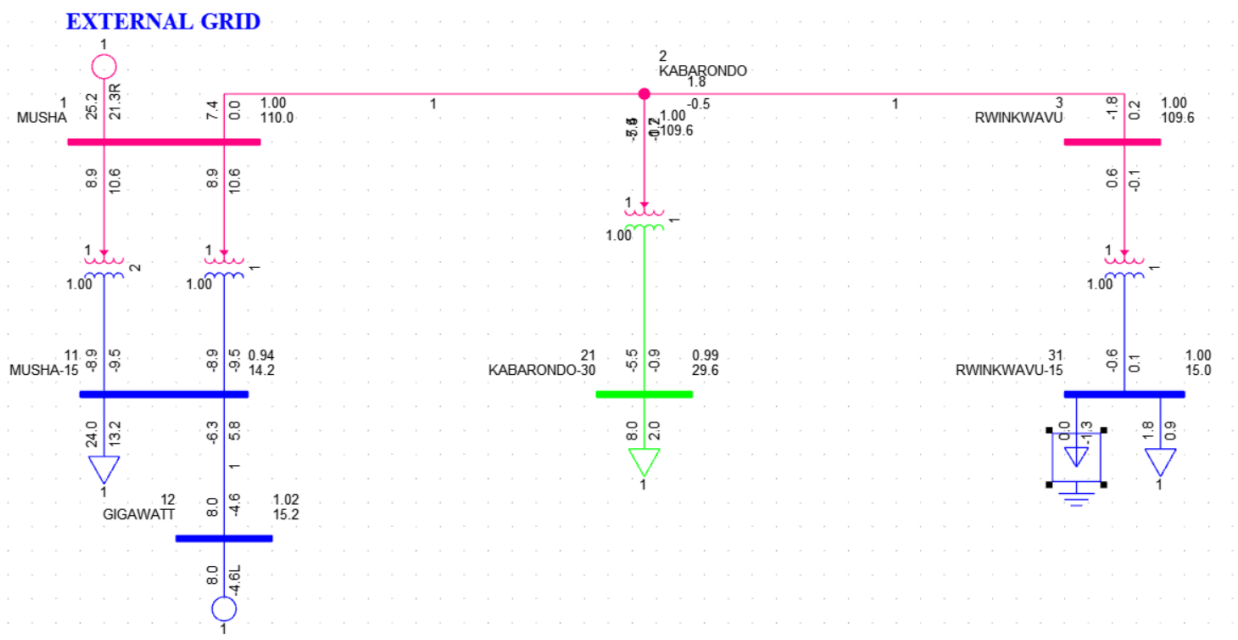


Figure 22. Single line diagram of Musha-Kabarondo-Rwinkwavu N/W in PSSE

4.1. Modeling Transmission Line

A transmission line is a fundamental component of the power system infrastructure, specifically designed to transport electrical power from generation sources to substations and distribution networks over long distances while minimizing power losses and maintaining voltage stability. Efficient transmission line operation is crucial for ensuring power quality, system reliability, and economic efficiency.

In load flow analysis, which is essential for assessing power system performance, the electrical characteristics of a transmission line are defined by four fundamental parameters:

1. Resistance (R)
2. Inductance (L)
3. Capacitance (C)
4. Conductance (G)

These parameters collectively determine the power transfer capacity, voltage regulation, and stability of the transmission network. However, in most practical power system studies, conductance is often neglected because its contribution to shunt admittance is typically minimal [19].

Key Transmission Line Parameters and Their Impact

1. Resistance (R): A Measure of Power Losses

- Resistance represents the real power losses in a transmission line due to Joule heating (I^2R).
- It depends on factors such as the material, cross-sectional area, length, and temperature of the conductor.
- The effective resistance (R_{eff}) is defined as:

$$R_{eff} = P_{loss} / I^2R \quad (4.1)$$

- Higher resistance leads to greater power dissipation, reducing system efficiency and requiring compensation techniques such as series capacitors or higher voltage transmission to minimize losses.

2. Inductance (L): Impact on Voltage Drop and Stability

- Inductance is associated with the magnetic field generated around the conductor when the current flows.
- It contributes to reactive power flow, influencing voltage regulation and stability.
- High inductance can lead to excessive voltage drop, necessitating reactive power compensation using FACTS devices.

The inductance of the line is measured by the induced electrical voltage compared to the rate of electric current change. It is an electrical property which represents the flux linkage in conductors.

$$L = \lambda / I \quad (4.2)$$

Where: L: Inductance [H] ; I: Current [A] ; λ : Instantaneous flux linkages [Wb]

3. Capacitance (C): Role in Charging Currents and Ferranti Effect

Line capacitance is defined as the charge on the conductors caused by the voltage differential between the transmission line's conductors and ground.

$$C=q/v \tag{4.3}$$

Where: C: Capacitance [F]; q: Charge on the conductor [C]; v: Potential difference between conductors [V]

- Capacitance arises due to the electric field between conductors and ground.
- It becomes significant in long transmission lines, causing the Ferranti effect, where voltage at the receiving end exceeds the sending-end voltage under no-load or light-load conditions.
- This requires voltage control measures, such as shunt reactors to absorb excess reactive power.

For these three fundamental line properties, the unit length is used to quantify resistance (Ω/km), inductance (mH/km), and capacitance ($\mu\text{F}/\text{km}$)[20]. A transmission line is reduced to several distinct "lumps" using the lumped parameter model, which assumes that electrical changes within each lump are ignored. The parameters are then implemented within the PSSE tool. Its parameters (R, L, and C) are estimated using this approach for load flow and transient analysis.

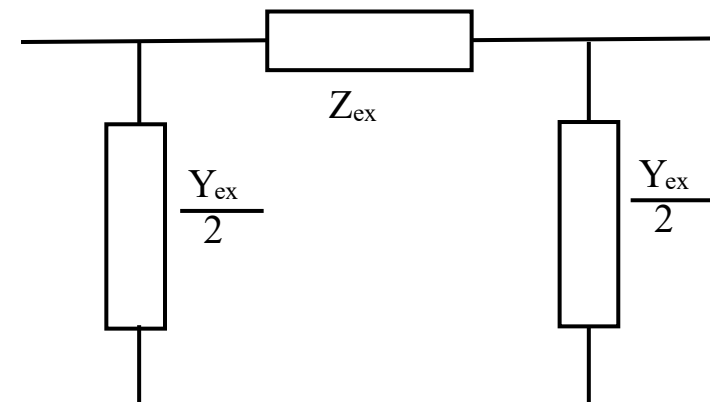


Figure 23. Equivalent circuit of a transmission line

Branch Data Record

Power Flow Short Circuit

Basic Data

From Bus Number: 1 From Bus Name: MUSHA 110.0 In Service

To Bus Number: 2 To Bus Name: KABARONDO 110.0 Bypass

Branch ID: 1 Branch Name: Metered on From end

Branch Data

Line R (pu)	Line X (pu)	Ratings (I as MVA)
0.047727	0.090289	
Charging B (pu)	Length	
0.007600	25.000	
Line G From (pu)	Line B From (pu)	
0.00000	0.00000	
Line G To (pu)	Line B To (pu)	
0.00000	0.00000	

Owner Data

Owner	Fraction
1 <input type="text"/> Select ...	1.000 <input type="text"/>
0 <input type="text"/> Select ...	1.000 <input type="text"/>
0 <input type="text"/> Select ...	1.000 <input type="text"/>
0 <input type="text"/> Select ...	1.000 <input type="text"/>

OK Cancel

Figure 24. Musha-Kabarondo Transmission Line Parameters

Branch Data Record

Power Flow Short Circuit

Basic Data

From Bus Number: 2 From Bus Name: KABARONDO 110.0 In Service

To Bus Number: 3 To Bus Name: RWINKWAVU 110.0 Bypass

Branch ID: 1 Branch Name: Metered on From end

Branch Data

Line R (pu)	Line X (pu)	Ratings (I as MVA)
0.016227	0.030698	
Charging B (pu)	Length	
0.002500	8.500	
Line G From (pu)	Line B From (pu)	
0.00000	0.00000	
Line G To (pu)	Line B To (pu)	
0.00000	0.00000	

Owner Data

Owner	Fraction
1 <input type="text"/> Select ...	1.000 <input type="text"/>
0 <input type="text"/> Select ...	1.000 <input type="text"/>
0 <input type="text"/> Select ...	1.000 <input type="text"/>
0 <input type="text"/> Select ...	1.000 <input type="text"/>

OK Cancel

Figure 25. Kabarondo-Rwinkwamvu Transmission line parameters

4.2. Modeling Power Transformers

Power transformers play a critical role in the electrical power system by serving as an interconnection point between transmission and distribution networks. Its primary function is to modify voltage levels, ensuring efficient power transfer while minimizing transmission losses. At the distribution stage, transformers step down voltage to levels suitable for consumer usage, to 30kV or 15kV. This voltage transformation process enhances system efficiency, stability, and reliability, which are key aspects in assessing power losses and improving.

For accurate simulation and analysis in PSSE, transformers are characterized using nine essential parameters, which define their electrical behavior and impact on system performance:

The figure displays two side-by-side screenshots of the 'Two Winding Transformer Data Record' dialog box in PSSE. The left window is for the 'KABARONDO' transformer, and the right window is for the 'RWINKWAVU' transformer. Both windows are divided into several sections:

- Line Data:** Includes fields for From Bus Number, To Bus Number, Branch ID, From Bus Name, To Bus Name, Transformer Name, Vector Group, and checkboxes for 'In Service', 'Metered on From end', and 'Winding 1 on From end'.
- I/O Data:** Includes dropdown menus for Winding I/O Code, Impedance I/O Code, and Admittance I/O Code.
- Transformer Impedance Data:** Includes input fields for Load loss (W), No load loss (W), Impedance Table, Load loss table corrected (W), Specified I Z I (pu), and Exciting I (pu).
- Transformer Nominal Ratings Data:** Includes input fields for Winding 1 Voltage (kV), Winding 2 Voltage (kV), Winding 1 Nominal kV, Winding 2 Nominal kV, Winding (1-2) Angle (degrees), Winding MVA, and a list of Ratings (MVA) with a scrollable dropdown menu.
- Control Data:** Includes input fields for Controlled Bus Number, Controlled Bus Name, Control Mode, and checkboxes for 'Controlled Bus On Winding Side', 'Auto Adjust', and 'Wind Connect Angle'.
- Owner Data:** Includes a table with columns for Owner and Fraction, with 'Select...' buttons for each owner.

Figure 26. Parameters of Kabarondo and Rwinkwavu Transformers

1. Nominal Voltages at Primary and Secondary Side (V_1 , V_2): Determines the voltage transformation ratio, essential for grid compatibility.
2. Rated Power (S): Specifies the maximum apparent power capacity of the transformer under normal operating conditions.
3. Operating Frequency (f): Typically, 50Hz,

4. Connection Configuration: Defines the transformer's winding connections which is Star-Delta (Y- Δ)
5. Short Circuit Voltage ($U_k\%$): Represents the impedance voltage required to drive rated current under short-circuit conditions, impacting system fault levels and stability.
6. Copper Losses (P_{cu}): Accounts for I^2R losses in the windings, directly affecting transformer efficiency and energy dissipation.
7. No-Load Current (I_0): Reflects the magnetizing current drawn by the transformer under open-circuit conditions, impacting power quality.
8. No-Load Power Losses (P_0): Includes core (iron) losses caused by hysteresis and eddy currents, which contribute to overall power system inefficiencies.
9. Tap Changer Settings: Defines on-load and off-load tap positions, essential for voltage regulation and reactive power control to optimize grid performance.

4.3. Modeling Load

In a power system, electrical loads represent the total energy consumption by end-users and the losses that occur within the transmission and distribution network. Accurate load modeling is crucial for power flow studies, stability analysis, and loss evaluation, particularly in assessing power losses and efficiency improvements.

Types of Load Models in PSSE:

In PSSE loads are categorized based on their electrical characteristics and response to voltage and frequency variations:

1. Y-Load (Admittance Load – Star or Unbalanced Connection):
 - Represents voltage-dependent loads, where power consumption is influenced by changes in system voltage.
 - Typically used in unbalanced network studies, such as those involving single-phase loads or weak distribution networks.
2. I-Load (Constant Current Load – Balanced Load):
 - Maintains a constant current draw, independent of voltage fluctuations.
 - Suitable for modeling loads with stable current characteristics, such as industrial processes with well-regulated power supplies.

3. P-Q Load (Constant Power Load – Active and Reactive Power Load):

- Maintains fixed active (P) and reactive (Q) power, regardless of voltage variations.
- This is the most used load model in power system studies, as it accurately represents residential, commercial, and industrial loads.

4.4. Modeling STATCOM

For this project, a STATCOM was modeled using PSSE for reactive power compensation and loss reduction in the transmission network. The appropriate STATCOM rating was determined based on system requirements, particularly the amount of reactive power needed to be injected or absorbed. The grid summary of the case study, obtained from PSSE simulations, provided crucial insights into the optimal STATCOM capacity for integration into the transmission system.

A Voltage Source Converter (VSC)-based STATCOM was implemented with a decoupled control scheme for active and reactive power exchange between the VSC and the power system. This control strategy ensures DC capacitor voltage stability during transient conditions, enabling efficient reactive power regulation. The STATCOM structure consists of a shunt converter modeled as a controllable voltage source, a connection filter, and a coupling transformer, which was represented in PSSE using its equivalent resistance and inductive impedance. The converter regulates the current injected into the system, allowing precise voltage and reactive power control.

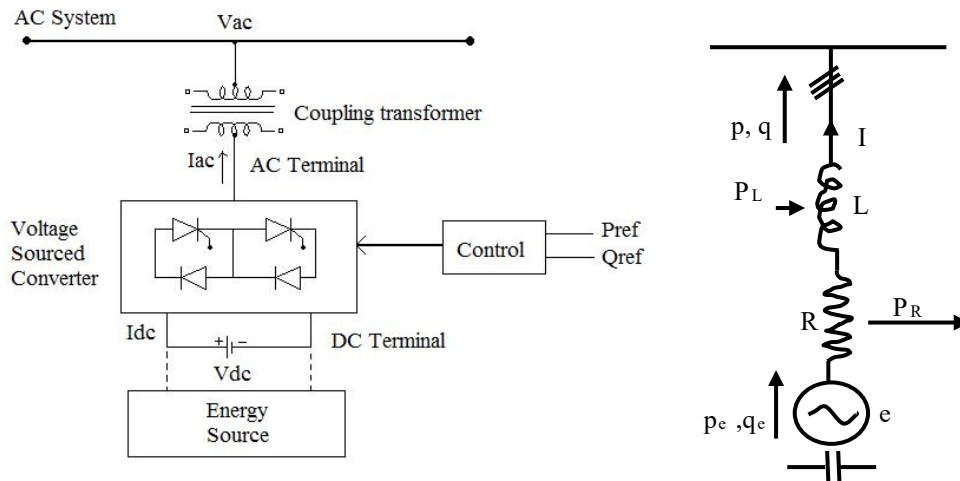


Figure 27. Configuration of a STATCOM

As illustrated in Figure 24, the STATCOM facilitates active (P) and reactive (Q) power exchange at V_{ac} . The power loss in the filter resistance (P_R), as well as the losses in the filter and transformer inductance (P_L), were considered during modeling. Additionally, the active and reactive power exchanged between the converter and the AC system (P_e and Q_e) were accounted for in the PSSE simulation framework. The DC-side power of the converter feeds the PWM-VSC, which transforms it into AC before injecting it into the transmission network.

To achieve effective STATCOM control, the d-q transformation reference frame was utilized in conjunction with Park's transformation, allowing for independent control of active and reactive power. This approach is fundamental in PSSE modeling, as it simplifies the representation of three-phase variables within the STATCOM control logic. Considering a balanced three-phase operation, the equations governing STATCOM behavior is here below

$$\begin{aligned} V_d &= \sqrt{V_d^2} = \sqrt{V} = V \\ V_q &= \sqrt{V_q^2} = 0 \end{aligned} \tag{4.4}$$

The system control equations incorporate the d-axis (V_d) and q-axis (V_q) voltage vectors, along with their corresponding current components (I_d and I_q). By regulating these current components, the STATCOM provides independent control of active and reactive power (P and Q), ensuring dynamic voltage support and power factor correction at the load end of the system and are described by below equations

$$P = V_i (I_d \cos \theta_i + I_q \sin \theta_i) = V_d I_d + V_q I_q \tag{4.5}$$

$$Q = V_i (I_d \sin \theta_i + I_q \cos \theta_i) = -V_d I_q + V_q I_d \tag{4.6}$$

The STATCOM control strategy employed in this study follows Pulse Width Modulation (PWM) principles for the VSC, specifically using a multi-pulse VSC approach[21]. The efficiency of the VSC in PSSE modeling is influenced by its control strategy, which is crucial for minimizing switching losses. The implemented strategy, Sinusoidal PWM (SPWM), enhances the efficiency of the system by optimizing switching sequences. The modeled STATCOM system comprises a three-phase step-down transformer, a PWM rectifier/inverter bridge, a three-phase filter, line inductors, a controller, and a DC link capacitor. The PWM Voltage Source Converter (VSC) offers key advantages such as power factor correction, bidirectional power flow, and DC voltage regulation.

4.5. RESULTS

By utilizing load flow study results in PSSE, the compliance of system power and voltages to the allowable maximum limits at a given point in the network was determined. The primary objective of the road flow analysis is to assess the following:

- Voltage magnitude at the buses.
- Line flow of active power, reactive power, current, and power factor in each section of the power system.
- Power losses in every line segment and the total power losses in the system.

The simulation and results analysis were conducted using PSSE based on a system rating to default MVar, on Rwinkwavu bus designated as the reference bus. To verify the model and outline the effect of STATCOM, 3 scenarios were considered. The system load data were set to default without STATCOM, then with STATCOM set to default values and voltage set to 1pu to ascertain the loss-mitigating effect of STATCOM on the grid finally the STATCOM was set to the values equal to the required MVar. The power flow results for each scenario were obtained and compared with the initial power flow result of standard load on the system.

Before the integration of the STATCOM at any point in the system, the following results were recorded. The voltage magnitude profile experienced a decline, reaching a value of 0.96364 pu at Rwinkwavu Substation. Additionally, the reactive power demand of the system increased significantly, with a total consumption of 1.3 MVar, contributing to unnecessary power losses and reduced system efficiency. This excessive reactive power demand can lead to increased transmission losses, reduced power transfer capability, and potential voltage collapse if not properly compensated. For this case evaluated losses were up to 276kW which is equivalent to 4% as shown in Table 6. These findings highlight the system's losses and to overcome this through a solution of STATCOM will minimize losses in that transmission system.

Table 6. Network Results without STATCOM

	Bus Name	MW	MVAR	MVA	Percent	Voltage/ratio	Angle (De	Losses (MW)	Losses (MVAR)
1	MUSHA 110.00	0.0000	0.0000	0.0000	0	1.0000PU	-6.2972	0.0000	0.0000
	FROM GENERATION	25.2571	22.6054	33.8958	34	110.00KV	0.0000	0.0000	0.0000
▶	TO 2 KABARONDO 110.00 1	7.4120	1.3310	7.5306	7		0.0000	0.0276	0.0522

When the STATCOM was connected to the system, with the voltage reference set to 1pu and the STATCOM's reactive power compensation capacity set to its default values, the following results were obtained. The voltage magnitude profile improved considerably compared to the scenario without STATCOM integration. The voltage at Rwinkwavu substation reached the desired value of 1pu, indicating enhanced voltage stability. Simultaneously, the reactive power flow at the sending point shifted to -3.2MVAR as shown in table 10 and evaluated losses were up to 294kW which is equivalent to 3.5%, signifying that the STATCOM was injecting reactive power of 4.3MVAR into the system. This reactive power injection not only mitigated the previous reactive power demand but also contributed to voltage support and improved power factor. These findings demonstrate the effectiveness of STATCOM in enhancing the operational efficiency and overall stability of the transmission network.

Table 7. Network Results with STATCOM Set to Default Values

	Bus Name	MW	MVAR	MVA	Percent	Voltage/ratio	Angle (Deg)	Losses (MW)	Losses (MVAR)
1	MUSHA 110.00	0.0000	0.0000	0.0000	0	1.0000PU	-6.2972	0.0000	0.0000
	FROM GENERATION	25.1408	18.0060	30.9237	31	110.00KV	0.0000	0.0000	0.0000
▶	TO 2 KABARONDO 110.00	7.2958	-3.2683	7.9944	7		0.0000	0.0294	0.0556

Another scenario was also considered where the STATCOM was connected to the system with the voltage reference set to 1pu and the reactive power injection from the STATCOM set to 1.3 MVAR, matching the reactive power demand previously observed at the sending point before STATCOM integration. The following results were obtained: the voltage magnitude profile showed a noticeable improvement compared to the case without STATCOM, with the voltage at Rwinkwavu substation increasing to 0.964645pu. Additionally, the reactive power at the sending point was significantly reduced to 0.0247MVAR referring to table 8 with evaluated losses up to 262kW which is equivalent to 3.7%, indicating a substantial reduction in reactive power losses.

Table 8. Network Results without STATCOM Set to 1.3MVAR

	Bus Name	MW	MVAR	MVA	Percent	Voltage/ratio	Angle (Deg)	Losses (MW)	Losses (MVAR)
1	MUSHA 110.00	0.0000	0.0000	0.0000	0	1.0000PU	-6.2972	0.0000	0.0000
	FROM GENERATION	25.2498	21.2991	33.0334	33	110.00KV	0.0000	0.0000	0.0000
▶	TO 2 KABARONDO 110.00	7.4048	0.0247	7.4048	7		0.0000	0.0262	0.0497

Since reactive power represents the portion of energy lost in transmission, these results confirm that a STATCOM capacity of 1.3 MVar is the optimal requirement to mitigate reactive power losses along the Musha-Rwinkwavu transmission line. This finding underscores the critical role of reactive power compensation in minimizing transmission losses, enhancing voltage stability, and improving overall system efficiency.

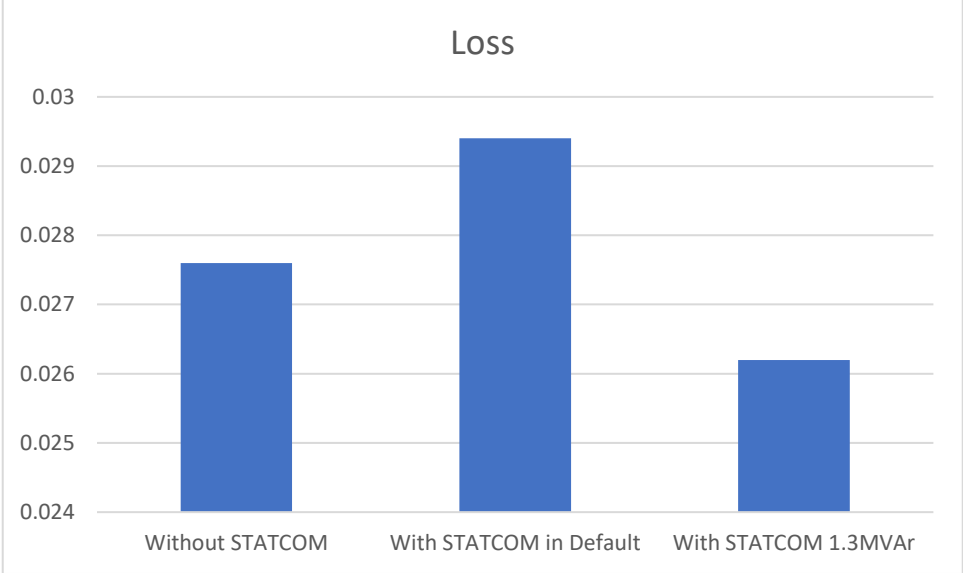


Figure 28. Loss for different scenarios

5. CONCLUSION AND RECOMANDATIONS

5.1. Conclusion

The effectiveness of the Static Synchronous Compensator (STATCOM) in mitigating power losses and enhancing voltage stability was validated through simulations using the bus test system in PSSE. The results demonstrated that the STATCOM controller simultaneously improved voltage profiles and minimized active and reactive power losses, contributing to greater system efficiency and stability.

To conduct this analysis, the bus system was first modeled in PSSE under standard loading conditions. Evaluation of key system parameters, including voltage magnitudes, active power losses, and reactive power losses, under steady-state conditions before the incorporation of STATCOM. After obtaining baseline results, STATCOM was integrated into the system, and the power flow study was repeated to assess its impact.

In conclusion, the analysis presented in this thesis highlights the impact of STATCOM deployment on reducing power losses and improving voltage regulation in transmission network. By strategically integrating STATCOM at key locations, such as the Musha-Rwinkwavu transmission line, the power system can achieve better stability, increased efficiency, and reduced energy wastage. These insights provide a strong foundation for future grid optimization strategies aimed at enhancing the reliability and sustainability of Rwanda's power transmission system.

5.2. Recommendations

This study highlights the significance of the Static Synchronous Compensator (STATCOM) as a crucial technology for loss reduction in transmission line of Musha-Rwinkwavu. Utilities and service providers should explore its potential for enhancing power system stability and improving power quality delivering reliable and efficient electricity to consumers

Future research on STATCOM should focus on evaluating its performance under various fault conditions to better understand its dynamic response and operational resilience. Additionally, advanced methodologies for optimal placement of STATCOMs in extensive power networks should be investigated. Analytical techniques with greater precision, such as statistical inference and pattern recognition, can be utilized to enhance result interpretation and improve decision-making.

For the Rwandan transmission system, integrating STATCOM could be particularly beneficial in mitigating voltage fluctuations, reducing reactive power losses, and improving overall system efficiency. Given Rwanda's expanding power grid and the increasing integration of renewable energy sources, STATCOM could help manage reactive power more effectively, ensuring a stable voltage profile while minimizing power dissipation.

Further studies could explore the economic feasibility, real-time control strategies to optimize power transmission in Rwanda's evolving energy landscape.

By leveraging PSSE for advanced power system modeling, Rwanda's transmission network can be optimized to enhance efficiency and reliability, aligning with national goals for a more resilient and sustainable power infrastructure.

REFERENCES

- [1] C. Ding, Y. Zhou, Q. Ding, and Z. Wang, “Loss Prediction of Ultrahigh Voltage Transmission Lines Based on EEMD–LSTM–SVR Algorithm,” *Front. Energy Res.*, vol. 10, no. March, pp. 1–19, 2022, doi: 10.3389/fenrg.2022.811745.
- [2] J. Sabattin, G. Fuertes, M. Alfaro, L. Quezada, and M. Vargas, “Optimization of large electric power distribution using a parallel genetic algorithm with dandelion strategy,” *Turkish J. Electr. Eng. Comput. Sci.*, vol. 26, no. 5, pp. 2648–2660, 2018, doi: 10.3906/elk-1801-261.
- [3] I. O. Ozioko, C. C. Okoli, N. G. Ajah, and N. S. Ugwuanyi, “Enhancement of Power System Transmission Using Static Synchronous Compensator (STATCOM),” in *2019 IEEE PES/IAS PowerAfrica*, 2019, pp. 482–486. doi: 10.1109/PowerAfrica.2019.8928629.
- [4] A. K. Roy, “Review on Stability and Power Quality Problem and Mitigation on Renewable Energy Penetration in Grid System,” *Int. J. Res. Appl. Sci. Eng. Technol.*, vol. 10, no. 1, pp. 1500–1513, 2022, doi: 10.22214/ijraset.2022.40088.
- [5] X. Ke *et al.*, “Coordinative real-time sub-transmission volt-var control for reactive power regulation between transmission and distribution systems,” *IET Gener. Transm. Distrib.*, vol. 13, no. 11, pp. 2190–2198, 2019, doi: 10.1049/iet-gtd.2018.5850.
- [6] C. A. Buckner *et al.*, “We are IntechOpen , the world ’ s leading publisher of Open Access books Built by scientists , for scientists TOP 1 %,” *Intech*, vol. 11, no. tourism, p. 13, 2016, [Online]. Available: <https://www.intechopen.com/books/advanced-biometric-technologies/liveness-detection-in-biometrics>
- [7] F. Alcayde-García, E. Salmerón-Manzano, M. A. Montero, A. Alcayde, and F. Manzano-Agugliaro, “Power Transmission Lines: Worldwide Research Trends,” *Energies*, vol. 15, no. 16, pp. 1–21, 2022, doi: 10.3390/en15165777.
- [8] T. Navidi, A. El Gamal, and R. Rajagopal, “Coordinating distributed energy resources for reliability can significantly reduce future distribution grid upgrades and peak load,” *Joule*, vol. 7, no. 8, pp. 1769–1792, 2023, doi: 10.1016/j.joule.2023.06.015.

- [9] A. Of and R. I. D. P. Of, "ASEAN Engineering Journal," vol. 3, pp. 1–14, 2023.
- [10] R. Losses, "10. Reduce Losses in the Transmission and Distribution System 1.," pp. 1–10.
- [11] P. Stucky and W. Lord, "Skin Depth Considerations in Eddy Current NDT," *Rev. Prog. Quant. Nondestruct. Eval.*, vol. 11, pp. 299–306, 1992, doi: 10.1007/978-1-4615-3344-3_37.
- [12] I. M.K and P. S, "Practical Investigations on SCR Based HVDC Power Transmission Systems," 2021, doi: 10.4108/eai.7-6-2021.2308652.
- [13] D. Sutanto, "A review of new innovations in power system control," 1995.
- [14] U. Vemulapati, T. Stiasny, T. Wikstrom, N. Lophitis, and F. Udrea, "Integrated Gate Commutated Thyristor: From Trench to Planar," *Proc. Int. Symp. Power Semicond. Devices ICs*, vol. 2020-Septe, no. iii, pp. 490–493, 2020, doi: 10.1109/ISPSD46842.2020.9170102.
- [15] G. Solutions, "GE Grid Solutions Static Synchronous Compensator (STATCOM) Solutions".
- [16] E. Engineers and M. Nadarajah, "Comparison of shunt capacitor , SVC and STATCOM in static voltage stability margin," no. April 2004, 2014, doi: 10.7227/IJEEE.41.2.7.
- [17] S. V. Compensator and S. S. Compensator, "Power Conversion SVC and STATCOM".
- [18] A. Mikwar, "Modeling of Hybrid STATCOM in PSSE KTH Royal Institute of Technology," 2017.
- [19] N. E. Vvedensky, V. P. Golov, A. S. Kazarin, D. N. Kormilitsyn, I. A. Moskvina, and S. D. Nikitina, "Regulation of shunt reactor power for improving stability of electrical power systems with a controlled series compensation device," *Vestn. IGEU*, no. 6, pp. 49–56, 2016, doi: 10.17588/2072-2672.2016.6.049-056.
- [20] F. Broydé and E. Clavelier, "A simple computation of the high-frequency per-unit-length resistance matrix," *2011 IEEE 15th Work. Signal Propag. Interconnects, SPI 2011 - Proc.*, no. 3, pp. 121–124, 2011, doi: 10.1109/SPI.2011.5898854.
- [21] L. Eriksson, "Development of PSS / E Model for Enhanced STATCOM Master ' s thesis in Electric Power Engineering," 2023.

Appendices

1. Network Results without STATCOM

	Bus Name	MW	MVAR	MVA	Percent	Voltage/ratio	Angle (Deg)	Losses (MW)	Losses (MVAR)
1	MUSHA 110.00	0.0000	0.0000	0.0000	0	1.0000PU	-6.2972	0.0000	0.0000
	FROM GENERATION	25.2571	22.6054	33.8958	34	110.00KV	0.0000	0.0000	0.0000
	TO 2 KABARONDO 110.00	7.4120	1.3310	7.5306	7		0.0000	0.0276	0.0522
	TO 11 MUSHA-15 15.000	8.9225	10.6372	13.8838	69	1.0000LK	0.0000	0.0455	0.9900
	TO 11 MUSHA-15 15.000	8.9225	10.6372	13.8838	69	1.0000LK	0.0000	0.0455	0.9900
		0.0000	0.0000	0.0000	0		0.0000	0.0000	0.0000
2	KABARONDO 110.00	0.0000	0.0000	0.0000	0	0.9949PU	-6.6356	0.0000	0.0000
		0.0000	0.0000	0.0000	0	109.44KV	0.0000	0.0000	0.0000
	TO 1 MUSHA 110.00	-7.3844	-2.0349	7.6597	7		0.0000	0.0276	0.0522
	TO 3 RWINKWAVU 110.00	1.8647	0.8086	2.0325	2		0.0000	0.0007	0.0013
	TO 21 KABARONDO-3030.000	5.5338	1.2251	5.6678	57	1.0000LK	0.0000	0.0181	0.2168
		0.0000	0.0000	0.0000	0		0.0000	0.0000	0.0000
3	RWINKWAVU 110.00	0.0000	0.0000	0.0000	0	0.9943PU	-6.6600	0.0000	0.0000
		0.0000	0.0000	0.0000	0	109.38KV	0.0000	0.0000	0.0000
	TO 2 KABARONDO 110.00	-1.8640	-1.0546	2.1417	2		0.0000	0.0007	0.0013
	TO 31 RWINKWAVU-1515.000	0.6150	0.3517	0.7084	12	1.0000LK	0.0000	0.0006	0.0080
	TO 31 RWINKWAVU-1515.000	0.6150	0.3517	0.7084	12	1.0000LK	0.0000	0.0006	0.0080
	TO 31 RWINKWAVU-1515.000	0.6150	0.3517	0.7084	12	1.0000LK	0.0000	0.0006	0.0080
		0.0000	0.0000	0.0000	0		0.0000	0.0000	0.0000
	11 MUSHA-15 15.000	0.0000	0.0000	0.0000	0	0.9440PU	-8.9684	0.0000	0.0000
		0.0000	0.0000	0.0000	0	14.161KV	0.0000	0.0000	0.0000
	TO LOAD-PQ	24.0000	13.1900	27.3857	0		0.0000	0.0000	0.0000
	TO 1 MUSHA 110.00	-8.8580	-9.5085	12.9952	65	1.0000UN	0.0000	0.0455	0.9900
	TO 1 MUSHA 110.00	-8.8580	-9.5085	12.9952	65	1.0000UN	0.0000	0.0455	0.9900
	TO 12 GIGAWATT 15.000	-6.2839	5.8270	8.5698	121		0.0000	1.7161	1.2333
		0.0000	0.0000	0.0000	0		0.0000	0.0000	0.0000
	12 GIGAWATT 15.000	0.0000	0.0000	0.0000	0	1.0161PU	4.0047	0.0000	0.0000
	FROM GENERATION	8.0000	-4.6000	9.2282	104	15.242KV	0.0000	0.0000	0.0000
	TO 11 MUSHA-15 15.000	8.0000	-4.6000	9.2282	121		0.0000	1.7161	1.2333
		0.0000	0.0000	0.0000	0		0.0000	0.0000	0.0000
	21 KABARONDO-3030.000	0.0000	0.0000	0.0000	0	0.9846PU	-8.7759	0.0000	0.0000
	FROM GENERATION	2.5100	1.0600	2.7246	83	29.539KV	0.0000	0.0000	0.0000
	TO LOAD-PQ	8.0000	2.0000	8.2462	0		0.0000	0.0000	0.0000
	TO 2 KABARONDO 110.00	-5.5018	-0.9404	5.5816	56	1.0000UN	0.0000	0.0181	0.2168
		0.0000	0.0000	0.0000	0		0.0000	0.0000	0.0000
	31 RWINKWAVU-1515.000	0.0000	0.0000	0.0000	0	0.9883PU	-7.2443	0.0000	0.0000
		0.0000	0.0000	0.0000	0	14.824KV	0.0000	0.0000	0.0000
	TO LOAD-PQ	1.8000	0.9100	2.0170	0		0.0000	0.0000	0.0000
	TO 3 RWINKWAVU 110.00	-0.6030	-0.3037	0.6752	11	1.0000UN	0.0000	0.0006	0.0080
	TO 3 RWINKWAVU 110.00	-0.6030	-0.3037	0.6752	11	1.0000UN	0.0000	0.0006	0.0080
	TO 3 RWINKWAVU 110.00	-0.6030	-0.3037	0.6752	11	1.0000UN	0.0000	0.0006	0.0080
		0.0000	0.0000	0.0000	0		0.0000	0.0000	0.0000

2. Network Results with STATCOM Set to Default Values

	Bus Name	MW	MVAR	MVA	Percent	Voltage/ratio	Angle (Deg)	Losses (MW)	Losses (MVAR)
▶ 1	MUSHA 110.00	0.0000	0.0000	0.0000	0	1.0000PU	-6.2972	0.0000	0.0000
	FROM GENERATION	25.2428	17.9535	30.9762	31	110.00KV	0.0000	0.0000	0.0000
	TO 2 KABARONDO 110.00	7.3977	-3.3208	8.1089	7		0.0000	0.0302	0.0572
	TO 11 MUSHA-15 15.000	8.9225	10.6372	13.8838	69	1.0000LK	0.0000	0.0455	0.9900
	TO 11 MUSHA-15 15.000	8.9225	10.6372	13.8838	69	1.0000LK	0.0000	0.0455	0.9900
		0.0000	0.0000	0.0000	0		0.0000	0.0000	0.0000
2	KABARONDO 110.00	0.0000	0.0000	0.0000	0	0.9992PU	-6.7607	0.0000	0.0000
		0.0000	0.0000	0.0000	0	109.91KV	0.0000	0.0000	0.0000
	TO 1 MUSHA 110.00	-7.3675	2.6187	7.8190	7		0.0000	0.0302	0.0572
	TO 3 RWINKWAVU 110.00	1.8456	-3.8412	4.2616	4		0.0000	0.0028	0.0053
	TO 21 KABARONDO-3030.000	5.5219	1.2225	5.6556	57	1.0000LK	0.0000	0.0179	0.2140
		0.0000	0.0000	0.0000	0		0.0000	0.0000	0.0000
3	RWINKWAVU 110.00	0.0000	0.0000	0.0000	0	1.0000PU	-6.8278	0.0000	0.0000
		0.0000	0.0000	0.0000	0	110.00KV	0.0000	0.0000	0.0000
	TO 2 KABARONDO 110.00	-1.8428	3.5967	4.0413	4		0.0000	0.0028	0.0053
	TO 31 RWINKWAVU-1515.000	0.6138	-1.1989	1.3469	22	1.0000LK	0.0000	0.0023	0.0327
	TO 31 RWINKWAVU-1515.000	0.6138	-1.1989	1.3469	22	1.0000LK	0.0000	0.0023	0.0327
	TO 31 RWINKWAVU-1515.000	0.6138	-1.1989	1.3469	22	1.0000LK	0.0000	0.0023	0.0327
		0.0000	0.0000	0.0000	0		0.0000	0.0000	0.0000
11	MUSHA-15 15.000	0.0000	0.0000	0.0000	0	0.9440PU	-8.9684	0.0000	0.0000
		0.0000	0.0000	0.0000	0	14.161KV	0.0000	0.0000	0.0000
	TO LOAD-PQ	24.0000	13.1900	27.3857	0		0.0000	0.0000	0.0000
	TO 1 MUSHA 110.00	-8.8580	-9.5085	12.9952	65	1.0000UN	0.0000	0.0455	0.9900
	TO 1 MUSHA 110.00	-8.8580	-9.5085	12.9952	65	1.0000UN	0.0000	0.0455	0.9900
	TO 12 GIGAWATT 15.000	-6.2839	5.8270	8.5698	121		0.0000	1.7161	1.2333
		0.0000	0.0000	0.0000	0		0.0000	0.0000	0.0000
12	GIGAWATT 15.000	0.0000	0.0000	0.0000	0	1.0161PU	4.0047	0.0000	0.0000
	FROM GENERATION	8.0000	-4.6000	9.2282	104	15.242KV	0.0000	0.0000	0.0000
	TO 11 MUSHA-15 15.000	8.0000	-4.6000	9.2282	121		0.0000	1.7161	1.2333
		0.0000	0.0000	0.0000	0		0.0000	0.0000	0.0000
21	KABARONDO-3030.000	0.0000	0.0000	0.0000	0	0.9889PU	-8.8781	0.0000	0.0000
	FROM GENERATION	2.5100	1.0600	2.7246	83	29.668KV	0.0000	0.0000	0.0000
	TO LOAD-PQ	8.0000	2.0000	8.2462	0		0.0000	0.0000	0.0000
	TO 2 KABARONDO 110.00	-5.4900	-0.9400	5.5699	56	1.0000UN	0.0000	0.0179	0.2140
		0.0000	0.0000	0.0000	0		0.0000	0.0000	0.0000
31	RWINKWAVU-1515.000	0.0000	0.0000	0.0000	0	1.0207PU	-7.4940	0.0000	0.0000
		0.0000	0.0000	0.0000	0	15.310KV	0.0000	0.0000	0.0000
	TO LOAD-PQ	1.8000	0.9100	2.0170	0		0.0000	0.0000	0.0000
	TO STATCON SHUNT STA FACTS	0.0000	-4.7260	4.7260	46		0.0000	0.0000	0.0000
	TO 3 RWINKWAVU 110.00	-0.6001	1.2720	1.4065	23	1.0000UN	0.0000	0.0023	0.0327
	TO 3 RWINKWAVU 110.00	-0.6001	1.2720	1.4065	23	1.0000UN	0.0000	0.0023	0.0327
	TO 3 RWINKWAVU 110.00	-0.6001	1.2720	1.4065	23	1.0000UN	0.0000	0.0023	0.0327
		0.0000	0.0000	0.0000	0		0.0000	0.0000	0.0000

3. Network Results with STATCOM Set to 1.3MVar

	Bus Name	MW	MVAR	MVA	Percent	Voltage/ratio	Angle (Deg)	Losses (MW)	Losses (MVAR)
1	MUSHA 110.00	0.0000	0.0000	0.0000	0	1.0000PU	-6.2972	0.0000	0.0000
	FROM GENERATION	25.2498	21.2991	33.0334	33	110.00KV	0.0000	0.0000	0.0000
	TO 2 KABARONDO 110.00	7.4048	0.0247	7.4048	7		0.0000	0.0262	0.0497
	TO 11 MUSHA-15 15.000	8.9225	10.6372	13.8838	69	1.0000LK	0.0000	0.0455	0.9900
	TO 11 MUSHA-15 15.000	8.9225	10.6372	13.8838	69	1.0000LK	0.0000	0.0455	0.9900
		0.0000	0.0000	0.0000	0		0.0000	0.0000	0.0000
2	KABARONDO 110.00	0.0000	0.0000	0.0000	0	0.9961PU	-6.6707	0.0000	0.0000
		0.0000	0.0000	0.0000	0	109.57KV	0.0000	0.0000	0.0000
	TO 1 MUSHA 110.00	-7.3785	-0.7321	7.4147	7		0.0000	0.0262	0.0497
	TO 3 RWINKWAVU 110.00	1.8552	-0.4934	1.9197	2		0.0000	0.0006	0.0011
	TO 21 KABARONDO-3030.000	5.5304	1.2243	5.6643	57	1.0000LK	0.0000	0.0181	0.2160
		0.0000	0.0000	0.0000	0		0.0000	0.0000	0.0000
3	RWINKWAVU 110.00	0.0000	0.0000	0.0000	0	0.9959PU	-6.7070	0.0000	0.0000
		0.0000	0.0000	0.0000	0	109.55KV	0.0000	0.0000	0.0000
	TO 2 KABARONDO 110.00	-1.8546	0.2465	1.8710	2		0.0000	0.0006	0.0011
	TO 31 RWINKWAVU-1515.000	0.6139	-0.0820	0.6194	10	1.0000LK	0.0000	0.0005	0.0066
	TO 31 RWINKWAVU-1515.000	0.6139	-0.0820	0.6194	10	1.0000LK	0.0000	0.0005	0.0066
	TO 31 RWINKWAVU-1515.000	0.6139	-0.0820	0.6194	10	1.0000LK	0.0000	0.0005	0.0066
		0.0000	0.0000	0.0000	0		0.0000	0.0000	0.0000
11	MUSHA-15 15.000	0.0000	0.0000	0.0000	0	0.9440PU	-8.9684	0.0000	0.0000
		0.0000	0.0000	0.0000	0	14.161KV	0.0000	0.0000	0.0000
	TO LOAD-PQ	24.0000	13.1900	27.3857	0		0.0000	0.0000	0.0000
	TO 1 MUSHA 110.00	-8.8580	-9.5085	12.9952	65	1.0000UN	0.0000	0.0455	0.9900
	TO 1 MUSHA 110.00	-8.8580	-9.5085	12.9952	65	1.0000UN	0.0000	0.0455	0.9900
	TO 12 GIGAWATT 15.000	-6.2839	5.8270	8.5698	121		0.0000	1.7161	1.2333
		0.0000	0.0000	0.0000	0		0.0000	0.0000	0.0000
12	GIGAWATT 15.000	0.0000	0.0000	0.0000	0	1.0161PU	4.0047	0.0000	0.0000
	FROM GENERATION	8.0000	-4.6000	9.2282	104	15.242KV	0.0000	0.0000	0.0000
	TO 11 MUSHA-15 15.000	8.0000	-4.6000	9.2282	121		0.0000	1.7161	1.2333
		0.0000	0.0000	0.0000	0		0.0000	0.0000	0.0000
21	KABARONDO-3030.000	0.0000	0.0000	0.0000	0	0.9858PU	-8.8045	0.0000	0.0000
	FROM GENERATION	2.5100	1.0600	2.7246	83	29.575KV	0.0000	0.0000	0.0000
	TO LOAD-PQ	8.0000	2.0000	8.2462	0		0.0000	0.0000	0.0000
	TO 2 KABARONDO 110.00	-5.4984	-0.9403	5.5782	56	1.0000UN	0.0000	0.0181	0.2160
		0.0000	0.0000	0.0000	0		0.0000	0.0000	0.0000
31	RWINKWAVU-1515.000	0.0000	0.0000	0.0000	0	0.9974PU	-7.3141	0.0000	0.0000
		0.0000	0.0000	0.0000	0	14.961KV	0.0000	0.0000	0.0000
	TO LOAD-PQ	1.8000	0.9100	2.0170	0		0.0000	0.0000	0.0000
	TO STATCON SHUNT STA FACTS	0.0000	-1.2966	1.2966	100		0.0000	0.0000	0.0000
	TO 3 RWINKWAVU 110.00	-0.6021	0.1286	0.6156	10	1.0000UN	0.0000	0.0005	0.0066
	TO 3 RWINKWAVU 110.00	-0.6021	0.1286	0.6156	10	1.0000UN	0.0000	0.0005	0.0066
	TO 3 RWINKWAVU 110.00	-0.6021	0.1286	0.6156	10	1.0000UN	0.0000	0.0005	0.0066
		0.0000	0.0000	0.0000	0		0.0000	0.0000	0.0000