



UNIVERSITY of
RWANDA

COLLEGE OF SCIENCE
AND TECHNOLOGY



AFRICAN CENTER OF
EXCELLENCE IN ENERGY FOR
SUSTAINABLE DEVELOPMENT

MASTER OF SCIENCE IN ELECTRICAL POWER SYSTEM COHORT 5

“POWER LOSS ASSESSMENT AND REDUCTION IN TRANSMISSION LINE:
Case Study of “RULINDO-GABIRO”

DONE AND SUBMITTED BY
UWIZERAMARIYA Monique (222000244)

SUPERVISOR: Dr.-Ing. Getachew Biru, Assoc. Prof.

DATE:,, 2025

DECLARATION

I, the undersigned, declare that this project is my original work and has not been submitted for a degree at the University of Rwanda or any other University. All sources of material used in this thesis work have been fully acknowledged.

Signature: _____ Date: _____

UWIZERAMARIYA Monique

(REG. NO: 222000244)

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

Signature: _____ Date: _____

Assoc. Prof. Getachew Biru

ACKNOWLEDGEMENT

I would like to appreciate for the guidance and contributions offered by my supervisor, Assoc. Professor Biru Getachew this research current.

I am deeply grateful to the outstanding lecturers who guided us through the two semesters of coursework, enabling us to successfully complete this research.

I sincerely thank the African Center of Excellence in Energy Studies for Sustainable Development (ACE-ESD), College of Science and Technology, for offering us valuable opportunities through their education and mentorship. I am deeply grateful to my family for their prayers and support and especially thankful to my friends and colleagues for their valuable ideas and insights sharing, as well as their contributions to this research. Finally, I thank you for taking your precious time to ready this work; I hope it will be relevant, educative and useful to you all.

ABSTRACT

This research focuses on analyzing and minimizing power loss in high-voltage transmission networks, specifically on the 64 km, 110 kV Rulindo-Gabiro line from the Rwanda Energy Group (REG). A comprehensive literature review examines the methods for assessing bulk transmission capacity and quantifying energy losses. Key issues include calculating the energy lost during electrical transmission across the grid and identifying technological measures to reduce these losses.

The study analyse the energy losses in the transmission line based on actual data collected from the site. Using ETAP-PowerStation for system modeling, a single-line diagram of the existing network was developed, followed by load flow analysis, incorporating peak loads from REG. This analysis calculates total peak capacity loss across various voltage levels and identifies loss contributions from line and transformer components. The impact of load and line length variations on transmission losses is also examined. The "Loss Factor " is used to estimate annual average power loss, translating peak loss values from load flow analysis into annual energy loss figures. This approach is detailed in the literature section, with analyses by employing this methodology.

Efficiency improvements for REG's grid are explored, applying industry-standard loss-reduction methods, including line double circuiting, nominal voltage uprating, and reactive power compensation. Lines identified for potential upgrades were evaluated based on power dissipation. For double circuiting, high-loss lines at 110 kV were prioritized, while voltage uprating targets included select levels. Reactive power compensation was applied selectively to enhance voltage profiles across the grid.

The study quantifies the annual energy savings from each loss-reduction approach, presenting these in terms of financial gains. Conclusions and recommendations for optimizing the Rulindo-Gabiro line are provided. The study found initial power losses of 195.8 kW (1.23%).

The introduction of a double-circuit transmission line significantly reduced active power losses from 195.8 kW to 129 kW, representing an improvement of 34.11%. Similarly, reconductoring the transmission line using twin conductors decreased losses to 137.8 kW, marking a 29.62%

enhancement in efficiency from actuary values. Additionally, reactive power compensation through the installation of capacitor banks improved the power factor from 0.78 to 0.92 and reduced active power losses from 186.22 kW to 139.78 kW, marking a 24.93%, which subsequently reduced reactive power losses and improved overall power quality. These upgrades also improved voltage stability, reducing the voltage drop from 1.63% to 1.27%.

Key Words: Power Loss, Energy Loss, Transmission Line, Load Flow, Loss Reduction, Double Circuiting, Voltage Uprating, Reactive Power Compensation.

TABLE OF CONTENTS

<i>DECLARATION</i>	<i>ii</i>
<i>ACKNOWLEDGEMENT</i>	<i>iii</i>
<i>ABSTRACT</i>	<i>iv</i>
<i>TABLE OF CONTENTS</i>	<i>vi</i>
<i>LIST OF TABLES</i>	<i>ix</i>
<i>ABBREVIATION LIST</i>	<i>x</i>
CHAPTER I. INTRODUCTION	11
1.1. Background	11
1.1. Problem Statement	12
1.2. Main Objective	12
1.3. Specific Objectives	13
1.4. Research Questions	13
1.5. Hypothesis	13
1.6. Scope of the Study	13
1.7. Expected Outcomes and Significance of the Study	14
1.7.1. Expected Outcomes	14
1.7.2. Significance of the Study.....	14
CHAPTER II. LITERATURE REVIEW	16
2.1. Theoretical Background	16
2.1. Current Research Paper Review	18
2.2.1. The Comparative Analysis of the Different Relevant Research Findings	19
2.2.2. Contribution of this Thesis Research.....	22
2.3. Overview of Rwanda’s Electricity System	22
2.3.1. Evolution of the generation capacity	22
2.3.2. Share of installed capacity by generation source.....	23
2.3.3. Future Demand Forecast.....	24
CHAPTER III. METHODOLOGY	26
3.1. Data Correction	27
3.1. Data Correction from Rulindo to Gabiro Substation	27

3.3.2. The rating of the Line	30
3.2.3. Energy Transmission Efficiency and Loss Analysis of Rulindo-Gabiro 110kV Transmission Lines	33
3.3.2. Benchmark with other regional utilities	35
3.2.4. Active and Reactive Energy Over Time at Rulindo Substation	35
3.2.5. Daily load demand from 2021 up to 2024 for Rulindo-Gabiro transmission line	36
3.2.6. Active Energy (Kwh) and Reactive Energy (Kvarh) over Time	37
3.3. Loss Calculation.....	38
3.3.1 Transformer loading at Gabiro substation	38
3.3.2 Transmission Line Loss Calculation	39
Parameter.....	39
3.3. Load Flow Analysis	40
3.4. Power Loss Reduction Methods Evaluated.....	42
CHAPTER IV. MODELLING AND SIMULATION	43
4.1. Introduction	43
4.2. Power Flow Simulation and Analysis of Rulindo to Gabiro.....	43
4.2.1. Active and Reactive Power Flows.....	47
4.2.2. Transformer Losses at Gabiro Substation	48
4.2.3. Loading Status of Gabiro Substation Feeder.....	50
4.2.4. Potential Methods for Power Loss Reduction.....	50
4.2.5. Sizing power factor corrector at Gabiro Substation	50
Reason that the PF is Low for T8 and High for T10	51
4.3. Double circuit.....	53
4.4. Twin conductor-single circuit Transmission Line	57
4.4.1. Transformer Losses for Single Circuit (Twin Conductor).....	57
CHAPTER V. RESULTS AND DISCUSSION.....	59
5.1. Overview of Simulation Result.....	59
5.2. Power Losses in Transmission Line	60
5.3. Summary of the power loss assessment and reduction result	60
5.3. Conclusion from Simulation.....	61
CHAPTER VI. CONCLUSION AND RECOMMENDATION	62
6.1. Conclusion	62
6.2. Recommendations.....	62
REFERENCES	64
Appendices	66

LIST OF FIGURES

Figure 1: Classification of losses	18
Figure 2: Capacity increase of the installed generation capacity in MW in Rwanda	23
Figure 3: Current Energy Mix.....	24
Figure 4: Total Generation Capacity Forecast (MW) in the longer term 2028 – 2050.....	25
Figure 5. Methodology chart flow.....	26
Figure 6: Gabiro substation.....	27
Figure 7: single line diagram from Rulindo to Gabiro substation.....	32
Figure 8: Active and reactive energy index	36
Figure 9: Daily load demand profile	37
Figure 10: Load demand increase pattern	38
Figure 11: Rulindo to Gabiro single line diagram overview.....	42
Figure 12: Power flow simulation of Actual line parameter.....	45
Figure 13: Transformer losses at Gabiro substation.....	49
Figure 14: Improved Rulindo to Gabiro line-single circuit.....	55

LIST OF TABLES

Table 1: The comparative analysis of the research findings	20
Table 3: R/X ratio for some common conductors	29
Table 4: Transmission line resistance and reactance	30
Table 5: Feeder at Rulindo substation (It can only be incoming or outgoing feeder	30
Table 6: Feeder at Gabiro substation.....	31
Table 7:Energy Transmission for Rulindo-Gabiro 110kV Line (2021-2024)	34
Table 8:Simulation Line losses	47
Table 9: Transformer losses at Gabiro substation.....	49
Table 10:Loading Status of Gabiro Substation Feeder	50
Table 11: Transformer losses for double circuit	56
Table 12: Simulation result for improve of transmission line losses between Rulindo to Gabiro.	56
Table 13: Transmission Line losses in single circuit (Twin conductor)	57
Table 14: Transformer losses for single circuit (Twin conductor).....	58

ABBREVIATION LIST

ACSR: Aluminum Conductor Steel Reinforced

ETAP: Electrical Transient Analyzer Program

FACTS: Flexible AC Transmission Systems

kV: Kilovolt

kW: Kilowatt

kWh: Kilowatt-hour

kVAr: Kilovolt-ampere reactive

PMU: Phasor Measurement Unit

REG: Rwanda Energy Group

SS: Substation

μ F: Microfarad

CHAPTER I. INTRODUCTION

1.1. Background

In today's world, electric power systems have become essential, with countless utilities supplying electricity to billions of consumers globally. The reliability of electric power is indispensable, with vast amounts of equipment and devices depending entirely on electricity. This high dependency underscores the need for efficient power systems, especially as fuel costs and the expenses for building new power generation and transmission infrastructure have risen significantly in recent decades. This situation has prompted power system planners and operators to place greater emphasis on reducing transmission losses, as these losses represent lost revenue for electric utilities.

A critical challenge for the global power industry is to meet the growing demand for electrical energy efficiently and sustainably. Often, power generation sites are located far from urban centers and industrial zones, necessitating long transmission distances, which can lead to significant energy losses. With the pressing concerns around CO₂ emissions and environmental sustainability, energy efficiency has become a widely supported pillar of a secure energy future.

In Rwanda, the Rulindo-Gabiro transmission line, managed by Rwanda Energy Group (REG), represents an important link in the country's power grid. Like many bulk transmission systems, it experiences power losses that contribute to an approximate 4% of total electrical energy lost in transmission on a global scale, with losses at peak load reaching around 5% of system capacity. Utility companies continually invest in transmission line upgrades, transformer improvements, and capacitor installations to minimize these losses and enhance efficiency. In planning system expansions, the cost-benefit analysis of loss reduction measures often informs the design choices, as efficient transmission reduces the need for additional generation capacity.

Efficient transmission is crucial to ensure that electrical energy reaches end-users reliably and cost-effectively. However, the transmission of electricity inevitably leads to power losses, which can be categorized into technical and non-technical losses. Technical losses are caused by physical electrical effects such as Joule losses, corona losses, and leakage losses, while non-technical losses

are due to unregistered and illegal connections, inaccurate measurements, and poor records of measurements [1].

Traditionally, energy-efficiency measures have targeted end-use consumption. However, the electric power industry itself is one of the largest consumers of electricity through transmission and distribution losses. Addressing these losses requires a thorough understanding of both technical and non-technical factors influencing power loss [2].

Among the technical losses, Joule losses, which are proportional to the square of the current flowing through the conductor, are the dominant component. However, at higher voltage levels such as 110 kV, the influence of the electrical corona discharge effect and current leakage can have a significant impact on power loss, especially in poor weather conditions like fog, rain, and snow.

Quantifying and minimizing these losses can significantly enhance the economic operation of a power system. Identifying the causes of transmission losses enables targeted interventions, thereby making existing power generation and transmission assets more effective without needing additional infrastructure. Consequently, reducing losses in the transmission and distribution network, such as in the Rulindo-Gabiro line, offers societal benefits, including improved energy availability, increased capacity, and reduced carbon emissions.

1.1. Problem Statement

The power transmission network faces several critical issues, including frequent voltage drops due to the small size of network conductors, system overloading, and long distances. Additionally, high voltage in transmission lines arises from light loading and limited reactive power control capability. It is imperative to design a plan for upgrading or maintaining the existing network without causing any interference or interruption in the power supply.

1.2. Main Objective

To assess and reduce power losses in the Rulindo-Gabiro transmission line by identifying the primary causes of technical and non-technical losses for proposing effective mitigation strategies, and implementing solutions to enhance system reliability and energy efficiency.

1.3. Specific Objectives

In the assessment and reduction of power losses in the Rulindo to Gabiro transmission line, the specific objectives focus on identifying the key factors contributing to power losses and implementing effective strategies to minimize them. This study aims to analyze the technical loss in the transmission system, evaluate the impact of line parameters on power dissipation, and propose optimization techniques using ETAP simulation.

- To identify the level of the power losses due to line resistance.
- To analyze technical losses and identify the primary causes of voltage drops and system inefficiencies.
- To propose and model practical solutions for reducing power losses and improving the transmission system's reliability.

1.4. Research Questions

1. What is the magnitude of power losses attributed to line resistance and transformer inefficiencies in the Rulindo-Gabiro transmission line?
2. How do reactive power and voltage instability contribute to power losses, and what methods can mitigate these issues?
3. What are the most cost-effective strategies to enhance transmission efficiency and reduce power losses, including conductor upgrades and load distribution improvements?

1.5. Hypothesis

By upgrading conductors, improving load balancing, and installing reactive power control devices (e.g., capacitors), the technical power losses in the Rulindo-Gabiro transmission line can be significantly reduced, leading to enhanced voltage stability and increased transmission efficiency. This structure aligns well with the problem statement and the existing objectives of the study, providing a clear pathway for addressing the key challenges in the transmission network.

1.6. Scope of the Study

Assessing and minimizing power losses on the 110kV transmission line between the Rulindo and Gabiro substations is the main objective of this study. Technical losses brought on by imbalances

in load flow will be examined in the study. Information about load profiles and the line's operational parameters will be gathered and examined. To model the transmission line, simulate power flows, and compute energy losses under various operating situations, the study will use Electrical Transient Program (ETAP) software. Potential methods for reducing power losses, such as maximizing conductor size and putting in place compensatory devices like capacitors, will be suggested based on the analysis. These alternatives' potential will be assessed from a technical and financial standpoint, guaranteeing useful suggestions for increased transmission line efficiency.

1.7. Expected Outcomes and Significance of the Study

1.7.1. Expected Outcomes

The expected outcomes of this study include a detailed quantification of power losses along the Rulindo-Gabiro 110 kV transmission line, identifying the magnitude and types of losses, with a focus on technical losses such as resistive and corona losses. Using the Electrical Transient Program (ETAP) software, an optimized transmission line model will be developed to simulate load flow and analyze inefficiencies. The study aims to identify the primary causes of these losses and propose practical reduction measures, such as upgrading line conductors, implementing compensation devices, or optimizing operational parameters. Additionally, a cost-benefit analysis will be conducted to evaluate the technical and economic feasibility of the proposed solutions, ensuring actionable and sustainable recommendations. Ultimately, the study will provide a roadmap for improving the efficiency, reliability, and sustainability of the Rulindo-Gabiro 110 kV transmission line.

1.7.2. Significance of the Study

The significance of this study lies in its potential to address critical issues in power transmission efficiency and sustainability. By focusing on the Rulindo-Gabiro 110kV transmission line, the research aims to identify and quantify power losses, which directly impact the reliability of power supply and increase operational costs. Understanding the underlying causes of these losses and proposing effective reduction strategies can lead to improved energy efficiency, reduced system downtime, and lower energy costs for both utility providers and consumers. Furthermore, the study's findings can contribute to enhancing the overall performance of Rwanda's transmission

network, supporting the country's efforts to achieve sustainable development and meet growing energy demands. By utilizing advanced tools like ETAP software, this research also provides a methodological framework that can be replicated for loss analysis and reduction in other transmission systems, fostering innovation in the power sector.

CHAPTER II. LITERATURE REVIEW

2.1. Theoretical Background

Generating electricity and transmitting power to load centers is quite challenging and requires a lot of human and material resources. For efficient performance of transmission lines, transmission losses should be minimized. This minimization of losses entails taking into account the equipment or material responsible for the losses, which is accounted for Ohms loss, whereas the environmental factors (air density, disruptive voltage) leading to loss of power in the transmission line is accounted by Corona loss. Power losses whether reactive or active could be curtailed at the design and testing stages [3]. However, Ohms loss could be attributed to increased transmission current, the resistivity of the conducting materials, and the length of transmission lines [4]. Also decreasing the cross-section area of the conducting materials could also boost power losses in the transmission line.

Transmission line losses significantly impact the efficiency of power delivery systems and can be categorized into two main types: copper losses and corona losses. Copper losses occur due to the resistance of conductors carrying electrical current. These losses depend on the resistivity of the conductor material, the current flowing through the line, and the length of the transmission line. As current passes through the conductor, part of the energy is dissipated as heat, proportional to the square of the current. To reduce copper losses, conductors with lower resistivity, such as copper or high-grade aluminum, are often used. Optimizing the conductor size and material also plays a significant role in minimizing these losses.

Corona losses, on the other hand, are caused by the ionization of air surrounding conductors when the voltage exceeds the breakdown threshold of air. This phenomenon is more pronounced in high-voltage transmission systems and is influenced by factors such as air density, conductor diameter, surface condition, and environmental factors like humidity and altitude. Corona losses not only lead to power dissipation but can also generate noise and interference in the system. Effective mitigation measures include using bundled conductors, increasing the spacing between conductors, and improving conductor surface design to minimize the ionization effect. Transmission [5].

In addition to copper and corona losses, other forms of losses can occur in transmission systems.

Dielectric losses result from energy dissipation in the insulating materials used for cables. Eddy current and hysteresis losses occur in magnetic components, such as transformers and inductors, when subjected to alternating currents. Atmospheric factors, such as thunderstorms and environmental disturbances, can also cause power losses, particularly when transmission lines are exposed to surges and dielectric breakdown.

To address transmission losses, several mitigation strategies can be implemented. Using high-conductivity materials like copper or advanced aluminum grades helps to minimize copper losses. Thunder arresters can be installed to protect the lines from atmospheric surges, reducing potential disruptions. Further, designing inductors with laminated cores suppresses eddy currents, while optimizing line design through proper spacing and conductor bundling helps to control corona losses. Together, these measures ensure more efficient power delivery and improve the overall reliability of the transmission system [6].

As represented in Fig. 1, losses that occur in power system networks are classifiable into technical and nontechnical losses. Technical losses are natural being due to the material properties of the components that make up the system. These losses are due to the heat generated in transformers windings and iron cores, overhead lines and distribution lines. The non-technical losses, on the other hand, are a result of factors external to the power system, for example, electricity theft arising from non-payment of electricity bills, billing errors, improper reading of meters, poor record-keeping, transformer overloading and defective meters, etc. [7].

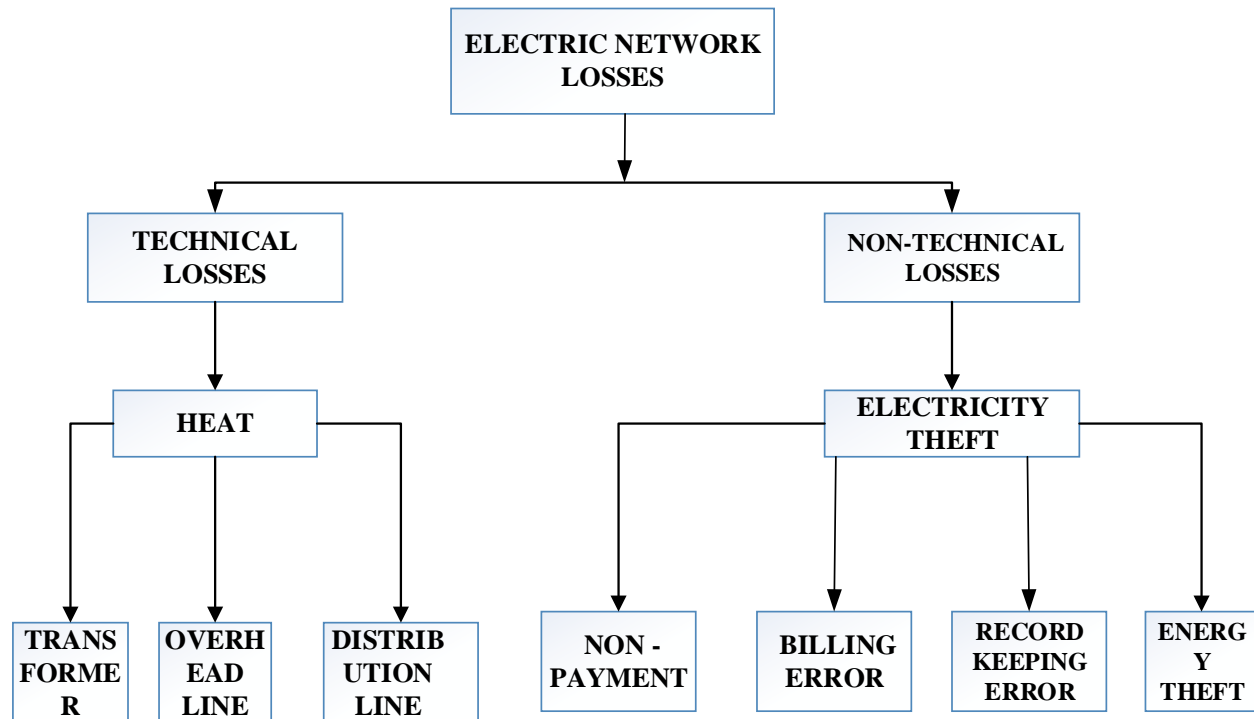


Figure 1: Classification of losses

2.1. Current Research Paper Review

The exploration of power loss reduction in transmission lines has been a crucial area of research, particularly in the context of enhancing the efficiency and reliability of electrical power systems. Several studies have contributed to understanding the mechanisms behind power losses and proposing methods to mitigate these losses. The technical literature often distinguishes between two main types of losses: technical losses, which include factors like Joule effect, corona discharge, and leakage currents; and non-technical losses, such as those arising from theft, metering inaccuracies, and unregistered connections [7].

A recent study by Aneke (2021) emphasized the importance of optimizing transmission networks to reduce power losses. The research introduced various optimization methods designed to address technical losses, particularly those arising from the resistivity of conductors and the operating conditions of transmission lines. Similarly, Nnamchi et al. (2023) conducted a comprehensive analysis of power losses in Uganda's high-voltage transmission lines, focusing on the impact of environmental factors like weather conditions and their contribution to corona losses[8]. The study

highlighted the necessity of continuous monitoring and advanced modeling techniques to predict and manage these losses effectively.

Another significant contribution to this field comes from the work of Komolafe and Udofia (2020), who reviewed the state of electrical energy losses in Nigeria. Their research identified key areas where improvements could be made, such as enhancing the quality of conductors and upgrading transmission infrastructure[9]. They also discussed the role of regulatory frameworks in ensuring that power loss reduction strategies are effectively implemented.

In the Rwandan context, Bizimungu et al. (2023) provided an analysis of grid stability, which is closely related to the issue of power losses. Their work underscored the challenges faced by Rwanda's power grid, particularly in maintaining voltage stability and minimizing losses under varying load conditions. This study forms a critical reference point for ongoing research in Rwanda, including the current proposal focused on the Rulindo-Gabiro transmission line[10].

Moreover, the importance of integrating modern technologies, such as Phasor Measurement Units (PMUs) and real-time monitoring systems, has been highlighted across multiple studies. These technologies are essential for accurately assessing real-time losses and implementing dynamic strategies to reduce them. The integration of such technologies is central to the current research proposal, which aims to model and validate loss reduction techniques on Rwanda's 110 kV transmission line between Rulindo and Gabiro.

2.2.1. The Comparative Analysis of the Different Relevant Research Findings

Table 1. Table 1 Presents findings of significant contributions and gaps across various studies. Tekabe Anbessie Setegn's study on Addis West Distribution Substation highlights methods like Monte Carlo simulations for reliability improvement but faces gaps in addressing the causes of reliability issues and voltage profile enhancements [11]. Wubante Getachew focuses on high-voltage network losses and financial impacts, yet lacks consideration of FACTS controllers and renewable energy integration [12]. Bamigbola et al.'s mathematical modeling offers a theoretical approach to power loss but needs practical validation and deeper exploration of conductor temperature effects [13]. Carlos Moreira Rodrigues' methodology for technical loss calculation advances precision in loss quantification but struggles with non-technical losses and limited data

for low voltage networks, showing the need for refined models and detection techniques [14]. Together, these studies contribute valuable methodologies but leave room for further investigation into practical applications and comprehensive loss reduction strategies.

Table 1: The comparative analysis of the research findings

Title	Authors	Contributions	Research Gap
Power Loss Reduction, Voltage Profile and Reliability Improvement Using Distributed Generation (Case Study of Addis West Distribution Substation) [11]	Tekabe Anbessie Setegn	<ul style="list-style-type: none"> ▪ The mutation operator generates random changes in chromosomes. ▪ Monte Carlo methods simulate random events in computer models. ▪ Arithmetical genetic operators produce offspring from parent chromosomes. 	<ul style="list-style-type: none"> ☞ Reliability indices are below national and international standards. ☞ Voltage profile and power loss need significant improvement. ☞ Main causes of reliability problems require investigation. ☞ Load flow analysis to determine network losses is necessary.
Analysis and minimization of power loss in EEPCo's [12].	Wubante Getachew	<ul style="list-style-type: none"> ▪ Analysis of bulk power transmission loss in high voltage networks. ▪ Development of a one-line diagram using ETAP-PowerStation. ▪ Evaluation of transmission losses across various voltage levels. ▪ Implementation of loss reduction methods for EEPCo's grid. ▪ Financial profit estimation from energy loss reductions. ▪ Recommendations for using FACTS controllers for further loss minimization. 	<ul style="list-style-type: none"> ☞ The study lacks exploration of FACTS controllers for loss reduction. ☞ Limited focus on reactive power management techniques. ☞ Insufficient analysis of long-term impacts of proposed methods. ☞ No consideration of renewable energy integration effects on losses. ☞ Absence of comparative studies with other utility companies.
Mathematical modeling of electric power flow and the minimization of	O. Bamigbola M Ali M Oke	<ul style="list-style-type: none"> ▪ Development of a mathematical model for power loss determination. ▪ Consideration of current and voltage flow in transmission 	<ul style="list-style-type: none"> ☞ Limited focus on practical implementation of mathematical models. ☞ Lack of consideration for varying voltage along

Title	Authors	Contributions	Research Gap
power losses on transmission lines. [13]		<p>lines.</p> <ul style="list-style-type: none"> ▪ Application of classical optimization technique for loss minimization. ▪ Focus on ohmic and corona losses in transmission lines. 	<p>transmission lines.</p> <ul style="list-style-type: none"> ☞ Insufficient exploration of alternative loss reduction methods. ☞ Need for real-world validation of mathematical predictions. ☞ Absence of comprehensive analysis on conductor temperature effects.
Technical Loss Calculation in Distribution Grids [14].	Carlos Moreira Rodrigues etc.	<ul style="list-style-type: none"> ▪ Introduces a modified methodology for technical losses calculation. ▪ Utilizes reduced equivalent networks for loss calculations. ▪ Incorporates customer energy billing data for accuracy. ▪ Disaggregates energy injections into various loss categories. ▪ Employs measurement campaigns to characterize load consumption profiles. 	<ul style="list-style-type: none"> ☞ Non-technical losses are not routinely addressed in power flow studies. ☞ Existing methodologies lack precision in technical losses calculation. ☞ Limited data availability for low voltage networks affects accuracy. ☞ Need for improved detection of irregular energy consumption patterns. ☞ Current models require adjustments for each electric network.

2.2.2. Contribution of this Thesis Research

This research makes an attempt to investigate the impact of double line circuiting and conductor cross-sectional area increase on power loss reduction in the RULINDO-GABIRO transmission lines. Analyze the effectiveness of this technique in minimizing losses and improving the overall efficiency of the network. Understanding the specific parameters and conditions of the RULINDO-GABIRO lines will be crucial in determining the feasibility and potential benefits of implementing this upgrade.

Evaluate the potential of reactive power compensation as a strategy for reducing power losses in the transmission lines of RULINDO-GABIRO. Assess how reactive power support can optimize voltage profiles, minimize losses, and enhance the reliability of the network. By studying the impact of reactive power compensation on the system, you can provide valuable insights into the effectiveness of this technique in mitigating losses and improving the overall performance of the transmission lines.

2.3. Overview of Rwanda's Electricity System

2.3.1. Evolution of the generation capacity

The figure 2 illustrates the steady growth of installed capacity from 100.4 MW in 2010 to 406.4 MW in 2024, with notable surges between 2013-2015 (119.6-186) and 2022-2023 (276-386.9), suggesting significant infrastructure investments or project completions during these periods. This consistent increase reflects efforts to address rising energy demands, support economic development, and possibly enhance electrification and renewable energy integration. The sharp growth in recent years indicates a strategic push toward expanding energy production, aligning with national development goals or sustainability initiatives [15]. Key milestones include surpassing 150 MW in 2014 and reaching over 400 MW in 2024.

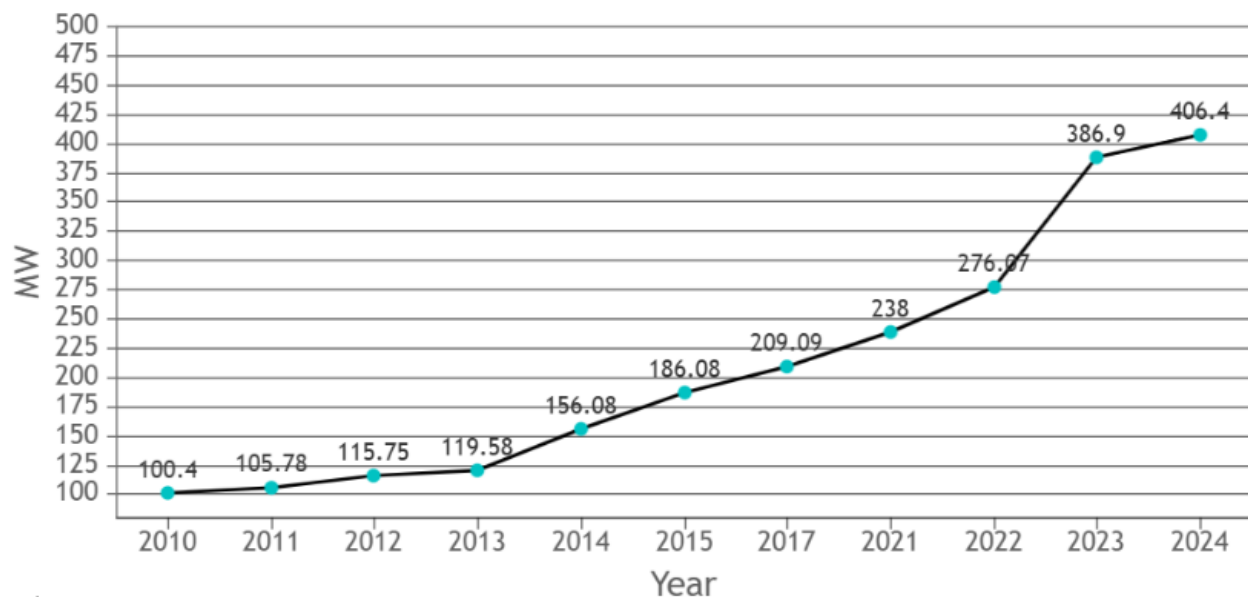


Figure 2: Capacity increase of the installed generation capacity in MW in Rwanda

2.3.2. Share of installed capacity by generation source

The figure below illustrates the energy mix composition, highlighting the proportional contributions of various energy sources. Hydro power is the largest contributor at 34%, reflecting its significant role in the energy supply. Peat follows with 27%, underlining its substantial usage, possibly due to local availability or cost factors. Thermal energy contributes 19%, indicating its role in complementing renewable sources. Methane accounts for 10%, showcasing efforts to utilize alternative resources, while solar energy represents a modest 4%, suggesting potential for growth in renewable deployment. Imports at 6% demonstrate reliance on external energy sources, likely to balance domestic generation shortfalls. This distribution underscores the importance of optimizing the energy mix for sustainability, reliability, and cost-effectiveness.

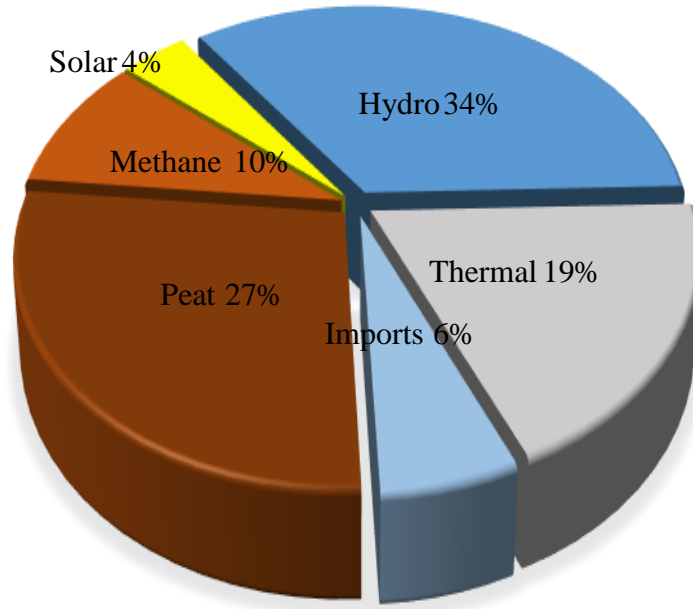


Figure 3: Current Energy Mix

2.3.3. Future Demand Forecast

Rwanda, like other emerging nations is experiencing rapid expansion, with energy growth reaching 8.9 and 10 percent per year, respectively [16]. The figure depicts the load prediction and energy demand from 2028 to 2050, indicating the need for an urgent increase in generation as current economic trends suggest a growth in industries investment, as well as other new industrial facilities, which are gradually realizing this forecast. As a result, if the country's producing capacity is not boosted, it will soon be outpaced, and its reliance on hydropower puts the country at danger during droughts, necessitating the development of alternative sources of energy. Figure below shows a projection in an increase in energy and maximum demand.

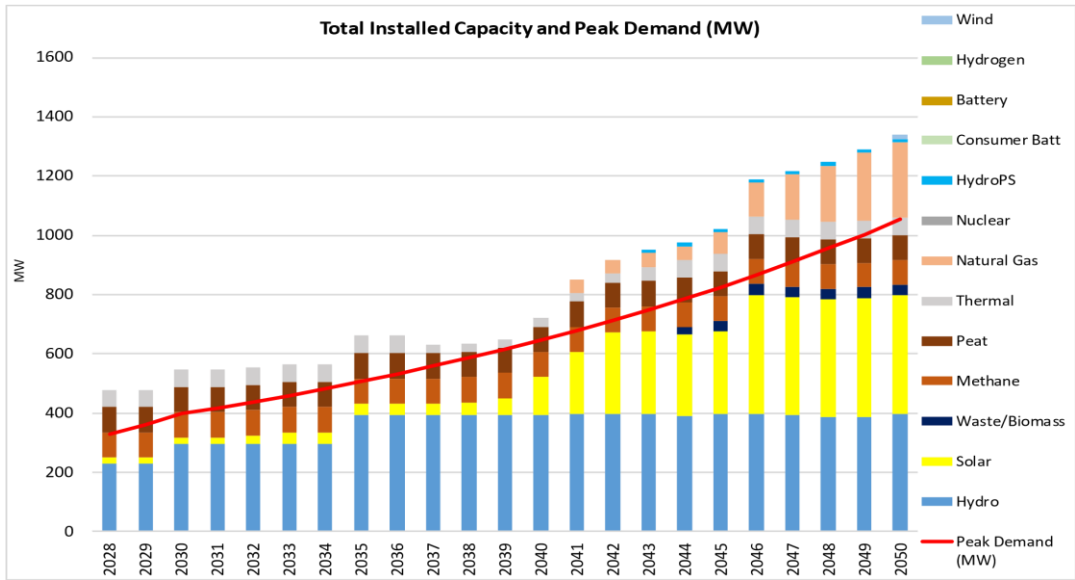


Figure 4: Total Generation Capacity Forecast (MW) in the longer term 2028 – 2050.

CHAPTER III. METHODOLOGY

The methodology for assessing and reducing power losses in transmission lines using ETAP involves three main phases: data collection, modeling and simulation, and result analysis. First, transmission line parameters such as conductor type, length, loading conditions, and system configuration are gathered. In the simulation phase, load flow analysis and other assessments are performed to quantify power losses under different operating conditions. The study evaluates losses in terms of active and reactive power dissipation, considering power factor, and network. Finally, loss reduction strategies, including reactive power compensation, conductor upgrading, and network reconfiguration, are analyzed based on their effectiveness. ETAP simulations help identify optimal solutions for improving transmission efficiency and minimizing losses.

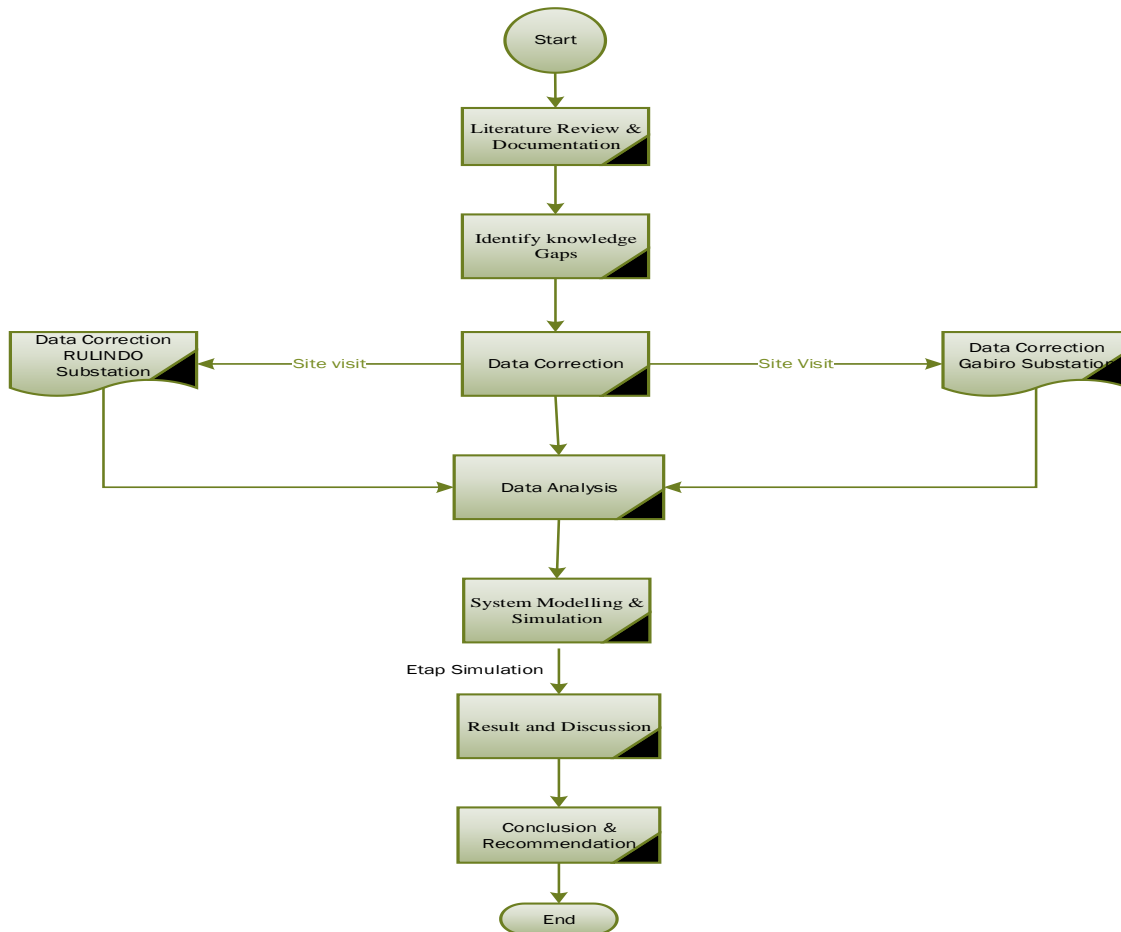


Figure 5. Methodology chart flow

3.1. Data Correction

The research methodology in this thesis focuses on analyzing power losses within the transmission line connecting Rulindo and Gabiro substations, as seen in figure 5, with the goal of identifying factors contributing to power losses and evaluating strategies for reduction. Data collection involved gathering critical transmission line specifications, such as line length, conductor type, voltage levels, and load data at each bus, from existing records and measurements within the Rwanda Energy Group (REG) network. Using this data, Load Flow Analysis was conducted with ETAP 19 software, a sophisticated tool for simulating and analyzing electrical power systems. This approach enabled a detailed examination of voltage profiles, active and reactive power flows, and losses across transmission lines and transformers. By integrating parameters like resistance, current, and voltage, ETAP 19 provided insights into the system's efficiency and potential areas for improvement. This comprehensive methodology supports the development of targeted solutions to enhance the reliability and efficiency of power transmission between Rulindo and Gabiro.



Figure 6: Gabiro substation

3.1. Data Correction from Rulindo to Gabiro Substation

3.3.1. Line parameter

The transmission line analysis between Rulindo and Gabiro provides valuable insights into the factors affecting power losses and system efficiency. The line operates at a voltage level of 110 kV spans a total length of 64 km and has a line resistance of 7.872 Ω . The higher voltage level effectively minimizes losses associated with current flow, making it a crucial factor in long-distance transmission. The transmission line is an Aluminum Conductor Steel Reinforced (ACSR) with a cross-sectional area of 240/40 mm².

The table 1 shows the transmission line data between Rulindo and Gabiro provides valuable insights into the factors affecting power losses and system efficiency.

Table 2: Transmission Line data from Rulindo to Gabiro substation

Section	Parameter	Description/Details	Units/Notes
Line Characteristics	Length of Line	Total length of the line	64 km
	Voltage Level	Voltage level of the line	110 kV
	Type of Conductors	Material type (e.g., ACSR, Copper)	ACSR
	Size of Conductors	Cross-sectional area of conductors	240/40 mm ²
	Type of Line Circuit	Single, Double, or Bundled	Single
	Frequency	Operational frequency	50 Hz
Transmission Line Parameters	Power Flow Direction	Rulindo to Gabiro or vice versa	Rulindo to Gabiro
	Resistance	Total or per km resistance	0.123 Ω /km or Total
	Inductance/Reactance	Total or per km inductance	0.427 Ω /km or Total
	Capacitance	Total or per km capacitance	0.009 μ F/km or Total
Substation Transformer Data	Transformer Rating (Rulindo s/s)	Transformer capacity	2x10 MVA (Star/Delta)
	Transformer Rating (Gabiro s/s)	Transformer capacity	2x10 MVA (Star/Delta)

To thoroughly understand and simulate these dynamics, we employed **ETAP 19**, a sophisticated software tool designed for modeling and analyzing electrical power systems. ETAP 19 enables us to explore various scenarios and optimize the design of the transmission line, providing insights

into potential improvements in power transmission efficiency. By incorporating critical parameters such as resistance, current, and voltage levels, the software allows for a comprehensive analysis of power losses and their implications on system performance. This approach not only aids in identifying strategies for reducing losses but also enhances the overall reliability and effectiveness of the transmission system between Rulindo and Gabiro.

In distribution system R/X ratio is high compared with transmission line, Table 2 depicts example of R/X ratio of some conductors [19]. The ac resistance of the cables is approximated from DC resistance value of cable manufacturers data sheet. The ac resistance of a conductor is always larger than the dc resistance. The primary reasons for this are skin effect and proximity effect.

Table 2: R/X ratio for some common conductors

Cable type	R (Ω/km)	X(Ω/km)	(R/X)
587mm ² Al	0.00344	0.01784	0.192
506mm ² Al	0.004	0.01812	0.220
431mm ² Al	0.00461	0.01844	0.25
356mm ² Al	0.00597	0.01874	0.318
307mm ² Al	0.00689	0.01902	0.362
262mm ² Al	0.00812	0.01934	0.419
182mm ² Al	0.01162	0.02004	0.579
95mm ² Al	0.206	0.079	2.61
50mm ² Al	0.320	0.082	3.90
16mm ² Al	0.641	0.085	7.54
35mm ² Al	1.910	0.096	19.90
35mm ² Al	0.532	0.074	7.19
50mm ² Al	0.387	0.072	5.38
10mm ² Al	1.837	0.088	20.88
6mm ² Al	3.061	0.100	30.61

Both table 4 and table 5 depict the resistance and reactance values and voltage drop for the transmission line, along with other characteristics such as length and conductor details. The data

includes Line1, with a length of 64,000 meters (64 km) and a specified conductor size from the library. The Table lists the resistance R, reactance X, and admittance Y per conductor at a temperature of 75°C. For Line1, the resistance R is 0.123 ohm/km, and the reactance X is 0.157245 ohm/km. This data is crucial for calculating the impedance of the line, which impacts power losses and voltage regulation in the transmission system. The resistances are specified at the given temperature, as conductor resistance changes with temperature, affecting the overall performance of the line.

Table 3: Transmission line resistance and reactance

ID	Size	Length	T (°C)	R/ ohm/km	X/ ohm/km	Y/ ohm/km
Line	262	64000 (m)	75	0.123	0.416504	0.157245

3.3.2. The rating of the Line

The below table provide an overview of the feeder load distribution at the Rulindo and Gabiro substations, highlighting the power demand and transformer connections. At Rulindo substation, the 110/30 kV transformer supplies a maximum of 8.85 MW to Gabiro, with smaller loads distributed to nearby areas like Gasiza (0.5 MW), Base (0.77 MW), Musasa (0.69 MW), and Gatuna (1.7 MW). Another transformer feeds 3.54 MW to Byumba. At Gabiro substation, power flows back from Rulindo with a load of 8.11 MW, while loads serve Nyagatare (9.6 MW), Kiziguro (2 MW), and Ngarama (1.5 MW). These tables reflect the power distribution and regional demands along the feeder lines between the two substations.

Table 4: Feeder at Rulindo substation (It can only be incoming or outgoing feeder)

Substation	Incoming feeder (kV)	Outgoing feeder (kV)	Feeder name	Active Power
T2-GBMG T4-BYUMBA	110	110	Gabiro	8.85MW
	110	30	Gasiza	0.6MW
	110	30	Base	1MW
	110	30	Musasa	0.9 MW

	110	30	Gatuna	2.4 MW
	110	30	Byumba	5 MW

Table 5: Feeder at Gabiro substation

Substation	Incoming feeder (kV)	Outgoing feeder (kV)	Feeder name	Active Power
T8-GABIRO T10-GABIRO	110	110	Rulindo	8.11MW
	110	30	Nyagatare	9.6MW
	110	30	Kiziguro	2MW
	110	30	Ngarama	0.6 MW

This Figure below represents a single-line diagram of the transmission and distribution network between Rulindo and Gabiro substations, highlighting the power flow and connection points between various substations and buses. The Rulindo substation (110 kV) feeds into multiple distribution transformers, including T2 and T4, each with a capacity of 10 MVA and connected to Bus1 and Rulindo feeder at 30 kV. These transformers serve various regions, including Gasiza (0.6 MVA), Musasa (0.976 MVA), Base (1.089 MVA), Gatuna (2.204 MVA), and Byumba (5.06 MVA), distributing power efficiently to these areas.

The power is also transmitted to the Gabiro substation (110 kV), connected to Gabiro substation, with further connections to distribution transformers T1 and T2, each rated at 10 MVA. The substations then distribute power to regions like Nyagatare (9.749 MVA), Kiziguro (2.332 MVA), and Ngarama (0.666 MVA), maintaining effective regional distribution. The diagram also shows circuit breakers (CB) and load disconnections (LD) for operational safety and control, ensuring proper isolation and protection during maintenance or faults. Overall, the figure 6 outlines a structured transmission and distribution system that ensures power is effectively transmitted between the substations while supplying various local loads across the network.

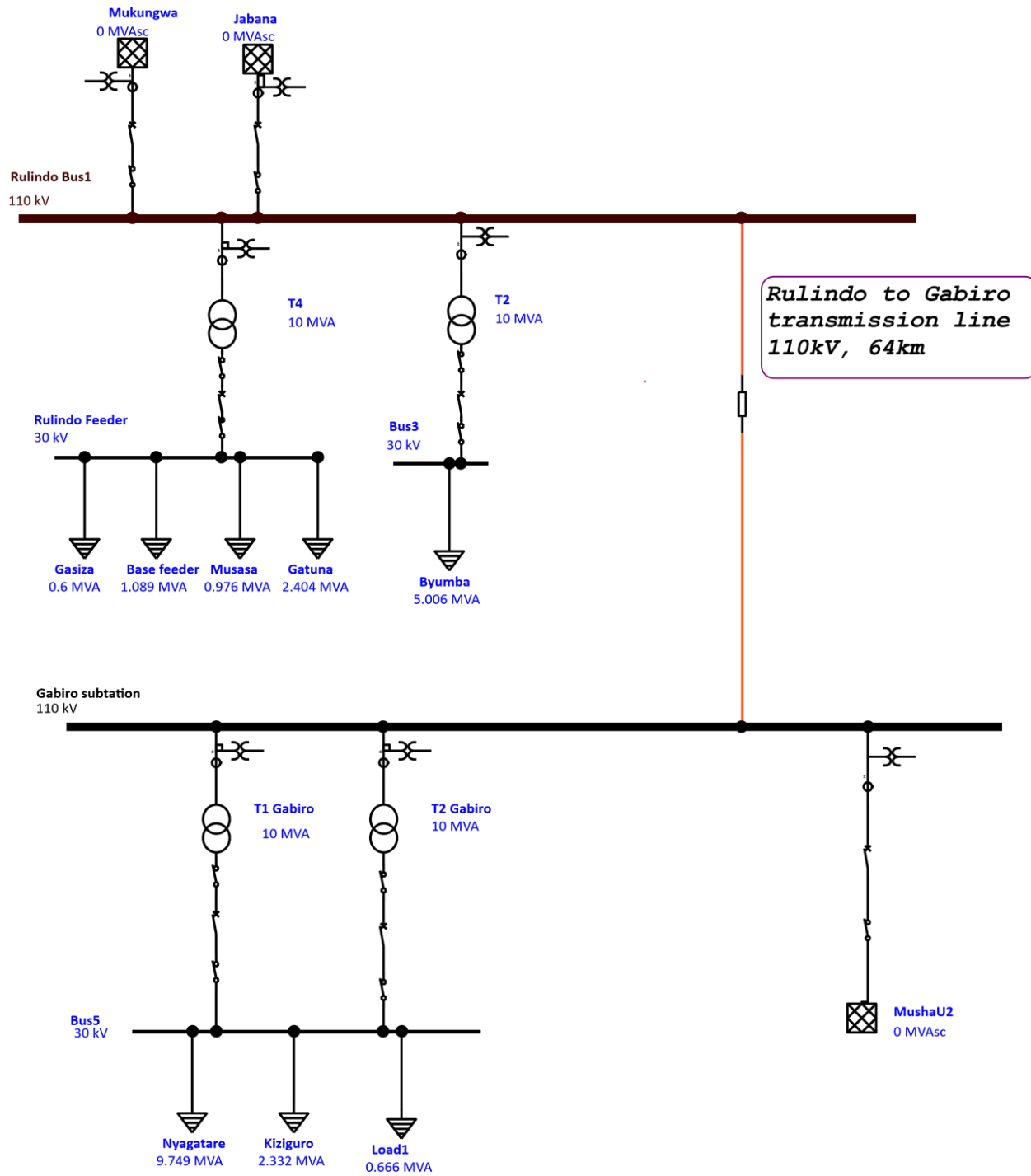


Figure 7: single line diagram from Rulindo to Gabiro substation

3.2.3. Energy Transmission Efficiency and Loss Analysis of Rulindo-Gabiro 110kV

Transmission Lines

Energy losses and efficiency of Rulindo to Gabiro transmission line (110kV) are calculated and shown over several years, from 2021 to 2024 and summarized in Table 38.

To analyze the energy transmission efficiency and losses of the Rulindo-Gabiro 110kV transmission line, the following key formulas and inputs are typically used:

Key formulas:

$$\text{Power loss } (P_{loss}) = I^2R \dots \dots \dots \text{eq. 1}$$

$$\text{Energy loss } (E_{loss}) = P_{loss} \times t \dots \dots \dots \text{eq. 2}$$

$$\text{Efficiency } (\eta) = \left(\frac{P_{Received}}{P_{Sent}} \right) \times 100\% \dots \dots \dots \text{eq. 3}$$

Energy Loss Trends

Starting **2022**, energy losses are calculated each month by subtracting the energy received at the Gabiro substation from the energy transmitted at Rulindo. Monthly losses remain relatively constant, ranging between approximately **32,784 kWh to 36,467 kWh**. Despite the steady monthly losses, total energy transmitted increased yearly, indicating growth in demand or transmission needs on this line.

Efficiency Improvement

The **efficiency** of the transmission line has steadily improved over time: In **2022**, efficiency ranged from **73% to 82%**. In **2023**, it rose to **83% to 86%**. By **2024**, efficiency values reached **87% to 89%**. This trend shows that efficiency improvements were made over the years due to increasing the number of consumption.

Potential Implications

The increase in efficiency implies that the line's operational improvements could be due to better load management.

Tracking these losses and efficiencies can aid in identifying periods of high losses and root causes to further reduce operational losses and costs.

Overall, this data helps monitor transmission efficiency and provides insight for developing strategies to further enhance performance between the Rulindo and Gabiro substations.

Table 6: Energy Transmission for Rulindo-Gabiro 110kV Line (2021-2024)

		Rulindo to Gabiro transmission line 110kV			
Year	Month	Energy transmitted at Rulindo substation [kWh]	Energy received at Gabiro substation [kWh]	Loss [kWh]	Efficiency %
2021	January				
	February				
	March	76,683,200			
	April	81,980,800	48,385,170	33,595,630	59%
	May	87,560,000	52,702,600	34,857,400	60%
	June	93,451,600	56,020,030	37,431,570	60%
	July	98,969,500	59,337,460	39,632,040	60%
	August	104,957,600	64,682,140	40,275,460	62%
	September	110,475,500	70,341,490	40,134,010	64%
	October	115,993,400	76,881,640	39,111,760	66%
	November	121,426,800	81,199,070	40,227,730	67%
	December	127,828,800	86,758,960	41,069,840	68%
2022	January	132,963,600	97,267,510	35,696,090	73%
	February	137,992,800	102,939,090	35,053,710	75%
	March	143,893,200	109,018,340	34,874,860	76%
	April	149,586,800	114,503,110	35,083,690	77%
	May	155,496,000	120,572,120	34,923,880	78%
	June	162,272,000	125,804,610	36,467,390	78%
	July	167,301,200	131,538,660	35,762,540	79%
	August	172,994,800	140,210,760	32,784,040	81%
	September	172,330,400	144,422,980	27,907,420	84%
	October	184,382,000	150,774,730	33,607,270	82%
	November	191,941,200	156,836,350	35,104,850	82%
	December	197,758,000	162,507,930	35,250,070	82%
2023	January	203,482,400	168,249,770	35,232,630	83%
	February	208,432,400	173,227,800	35,204,600	83%
	March	214,082,000	178,715,140	35,366,860	83%
	April	219,533,600	183,985,690	35,547,910	84%
	May	225,306,400	190,050,490	35,255,910	84%
	June	230,370,800	194,783,960	35,586,840	85%
	July	234,696,000	199,414,530	35,281,470	85%
	August	239,421,600	204,148,000	35,273,600	85%
	September	243,777,600	208,375,190	35,402,410	85%

	October	248,520,800	213,108,660	35,412,140	86%
	November	253,176,000	217,850,920	35,325,080	86%
	December	258,099,600	222,860,330	35,239,270	86%
2024	January	264,836,000	229,357,280	35,478,720	87%
	February	274,832,800	239,375,160	35,457,640	87%
	March	279,818,000	244,600,960	35,217,040	87%
	April	284,785,600	249,276,680	35,508,920	88%
	May	290,074,400	254,528,820	35,545,580	88%
	June	296,507,200	260,655,780	35,851,420	88%
	July	301,646,400	266,050,840	35,595,560	88%
	August	306,746,000	271,029,630	35,716,370	88%
	September	311,401,200	275,829,090	35,572,110	89%
	October	316,707,600	280,628,550	36,079,050	89%
	November				
	December				

In order to improve efficiency and reduce losses on the 110kV Rulindo-Gabiro transmission line, key mitigation measures include upgrading conductors to low-resistance, optimizing operating voltage, and installing reactive power compensation equipment can be selected. Regular maintenance and monitoring of insulation and phase balancing can also further minimize losses, while advanced solutions like FACTS devices enhance power flow control. Additionally, distributed generation near load centers and smart grid analytics for load forecasting can reduce transmission distances and peak loads, contributing to a more efficient and reliable transmission system.

3.3.2. Benchmark with other regional utilities

IEC document, “Efficient electrical energy transmission and distribution”, 2007*[1], gives ranges of power losses for parts of Transmission & Distribution network as follows:

- 1-2% Step up transformer from generator to transmission line
- 2-4% Transmission line
- 1-2% Step down transformer from transmission line to distribution network
- 4-6% Distribution network transformers to cables

The overall losses between the power plant and consumers is then in the range between 8 and 15%.

3.2.4. Active and Reactive Energy Over Time at Rulindo Substation

The figure illustrates the Active and Reactive Energy Index for both import and export over time. The most prominent trend is the steady increase in Import Active Energy (blue line), indicating a continuous rise in imported energy consumption. In contrast, Export Active Energy (cyan line) remains relatively low and stable, suggesting minimal energy being sent out. Similarly, Import Reactive Energy (orange dotted line) shows a gradual increase, while Export Reactive Energy (red dotted line) stays at consistently low levels. The presence of gaps in the data, particularly around mid-2022, may indicate missing records or reporting inconsistencies. Overall, the trends suggest a growing dependence on imported energy, with significantly lower levels of energy export and reactive energy exchange.

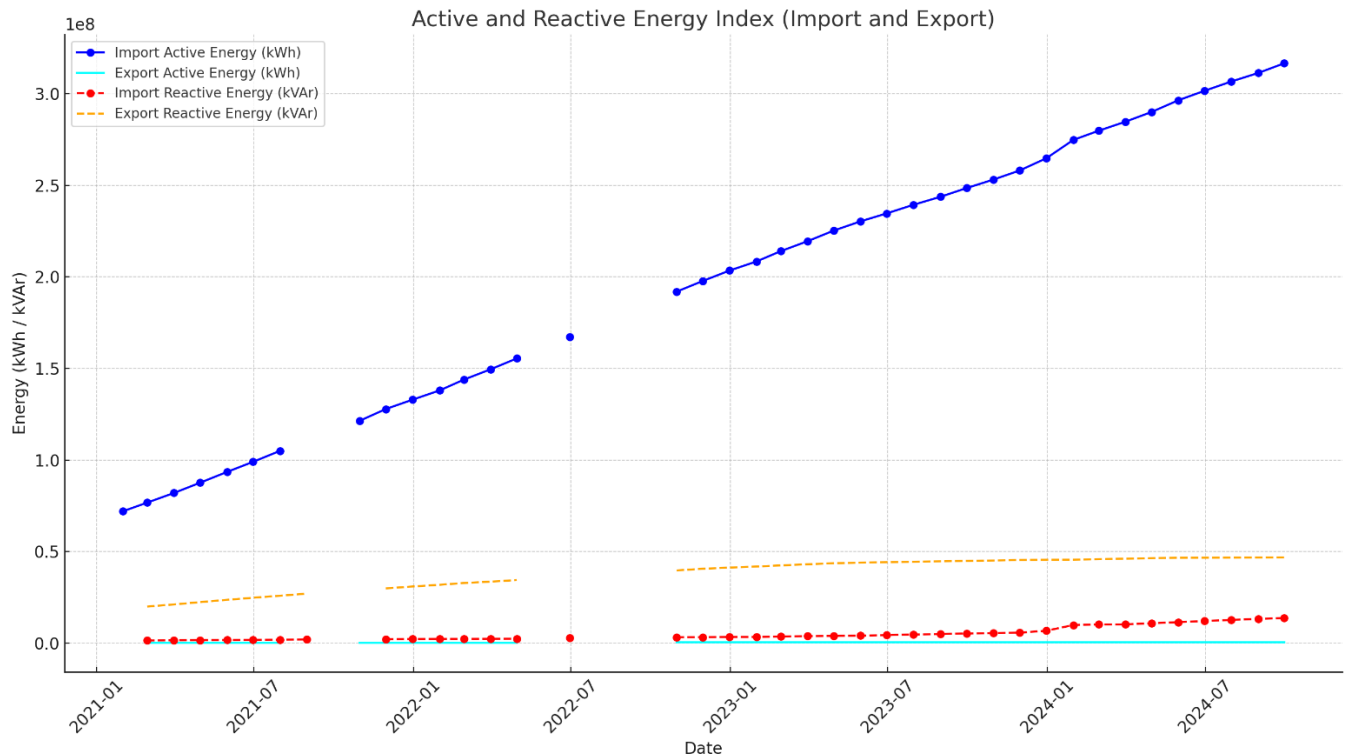


Figure 8: Active and reactive energy index

3.2.5. Daily load demand from 2021 up to 2024 for Rulindo-Gabiro transmission line

The graph represents the load variation (in MW) over a 24-hour period for the years 2021, 2022, 2023, and 2024. Each year is represented by a different color: red for 2021, yellow for 2022, purple for 2023, and green for 2024. The load fluctuates throughout the day, showing a general

increasing trend from early morning to evening, with peaks observed between 17:00 and 22:00. The curves for different years follow a similar pattern but with variations in specific hours, indicating year-on-year changes in demand. Notably, 2023 (purple) and 2024 (green) show higher peaks in the evening compared to previous years, suggesting an increase in power consumption. The variations could be due to factors such as economic growth, weather conditions, or changes in electricity usage patterns.

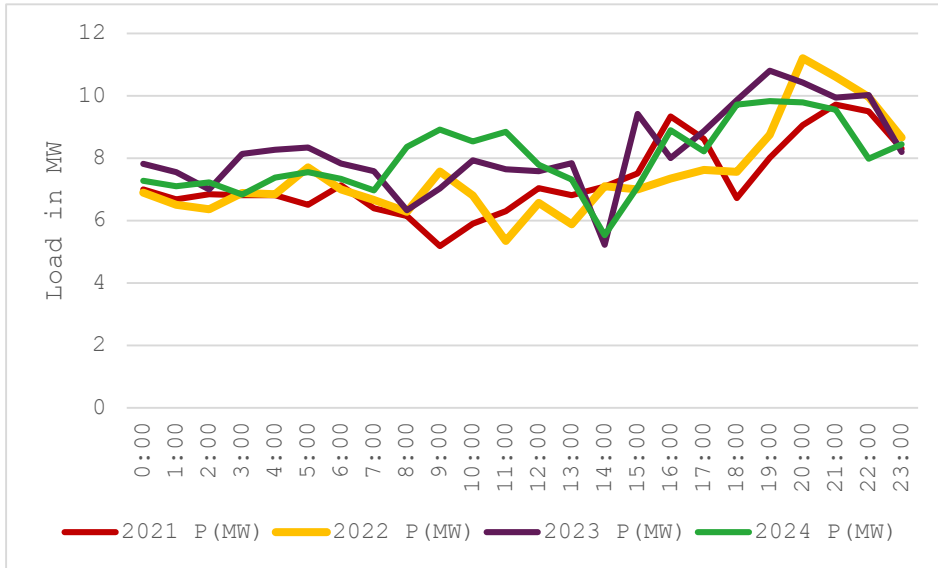


Figure 9: Daily load demand profile

3.2.6. Active Energy (Kwh) and Reactive Energy (Kvarh) over Time

The figure presents the trends of **Active Energy (kWh)** and **Reactive Energy (kVArh)** over time, from 2021 to 2024. The **Active Energy (blue bars)** shows a clear increasing trend, with periodic peaks indicating a cyclical pattern, possibly due to seasonal or operational variations.

On the other hand, **Reactive Energy (orange line)** remains relatively stable over time, exhibiting a repeating oscillatory pattern. This suggests that while reactive energy demand fluctuates, it does not show significant long-term growth compared to active energy.

Overall, the figure highlights the growing consumption of active energy over the years, with fluctuations in reactive energy but no significant increase. The presence of gaps in the data may indicate missing records or interruptions in measurement.

The increasing trend in **Active Energy (kWh)** suggests a steady rise in electricity consumption over time, which could be attributed to factors such as **higher demand, industrial expansion, or population growth**. The periodic spikes in active energy could indicate **seasonal variations**, possibly due to changing energy needs across different months or operational cycles.

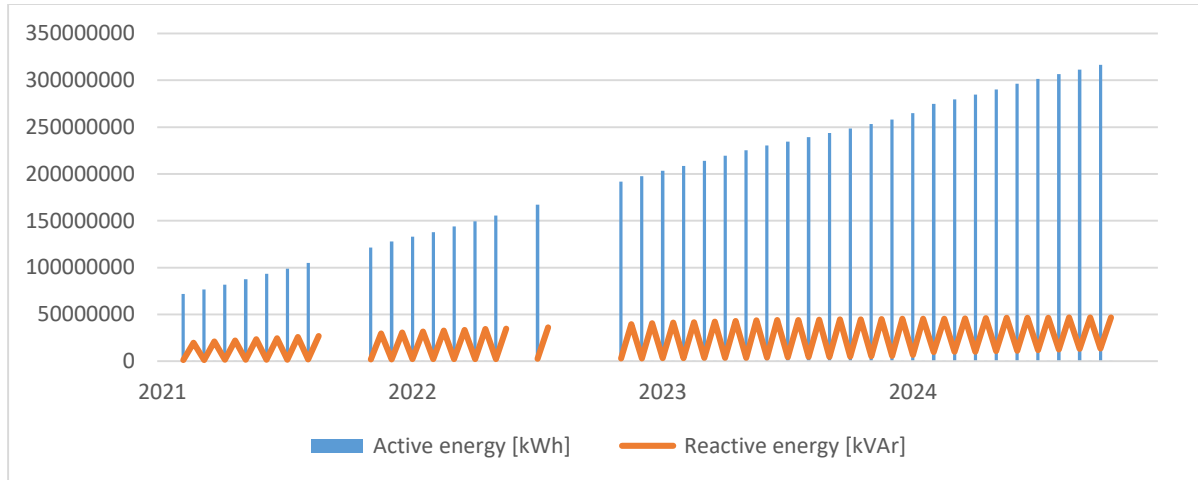


Figure 10: Load demand increase pattern

3.3. Loss Calculation

3.3.1 Transformer loading at Gabiro substation

$$\text{Transformer one} = 8400kW + j5340kvar \dots \dots \dots \text{eq. 4a}$$

$$\text{Transformer two} = 6058kW + j1036kvar \dots \dots \dots \text{eq. 4b}$$

Transformer losses calculation:

No-load losses (core losses) $\approx 0.1\%$ of rated power

Load losses (copper losses) $\approx 1\%$ of operating power

Transformer 1:

$$\text{Apparent power } S = \sqrt{8400^2 + 5340^2} = 9943.77KVA \dots \dots \dots \text{eq. 5}$$

Transformer 1: Total Power Loss

$$\mathbf{Total} = \text{Load losses (99.44kW)} + \text{No-load losses (11kW)} = 110.44 \text{ kW} \dots \dots \dots \text{eq. 6a}$$

Transformer 2: Total power loss

$$\mathbf{Total} = \text{Load losses (61.48kW)} + \text{No-load losses (11kW)} = 72.48 \text{ kW} \dots \dots \dots \text{eq. 6b}$$

3.3.2 Transmission Line Loss Calculation

Parameter

Resistance ($R = 0.123\Omega/\text{km}$).

Reactance ($X = \frac{0.427\Omega}{\text{km}}$).

Length = 64km .

$$R_{total} = R_{per\ km} \times \text{line length} = \frac{0.123\Omega}{\text{km}} \times 64\text{km} = 7.872\Omega$$

$$X_{total} = X_{per\ km} \times \text{line length} = \frac{0.427\Omega}{\text{km}} \times 64\text{km} = 27.328\Omega$$

$$\text{Line Capacitance: } C = \frac{0.009\mu\text{F}}{\text{km}} = C_{total} = 0.009\mu\text{F} \times 64\text{km} = 0.576\mu\text{F}$$

Voltage at sending End: $V_S = 110\text{kV}$

Active Power at Receiving End: $P_r = 15,804\text{MW}$

Power Factor: $PF_{initial} = 0.78$

Current corrected $I = 88.8\text{A}$

Real power losses (P_{loss}) for three phase system ($P_{loss} = 3 \cdot I^2 \cdot R_{total} \dots \dots \dots \text{eq. 7}$)

$$P_{loss} = 3 \cdot (88.8)^2 \cdot 7.872 = 186.22\text{kW}.$$

3.3.3. Corona Loss

For 110 kV lines, corona loss can be using empirical formula:

$$P_{Corona\ loss} = 242.2 \times f \times \delta \left(\frac{V_{eff}}{E_{critical}} - 1 \right)^2 = 292.73\text{kW} \dots \dots \dots \text{eq. 8}$$

Where $f = 50\text{Hz}$.

$\delta = 1.0$ (air density factor).

$E_{critical} = 21.1 \cdot \delta \cdot \log_{10} \left(\frac{d}{r} \right)$ (critical disruptive in $\frac{kV}{CM}$).

$d = 2.5m$ (spacing between conductor).

$r = 0.015m$ (conductor radius).

Total efficiency of the transmission line

The total power losses include:

- Transformer losses = 182.92kW
- Transmission line losses = 186.22kW
- Corona loss = 292.73kW

Total losses = 182.92kW + 186.22kW + 292.73kW = 661.87kW eq.9

Percentage loss with respect input power $Total\ efficiency = \left(\frac{15804}{15804+661.87} \right) \times 100 = 95.98\%$

3.3. Load Flow Analysis

In this research thesis, the load flow analysis was used to determine the bus voltages profiles, active power flows, reactive power flows and losses on all lines and transformers of REG high voltage transmission network. The software used in carrying out this analysis was Electrical Transient Analyzer Program (ETAP) Power Station. To thoroughly understand and simulate these dynamics, we employed ETAP 19, a sophisticated software tool designed for modeling and analyzing electrical power systems. ETAP 19 enables us to explore various scenarios and optimize the design of the transmission line, providing insights into potential improvements in power transmission efficiency. By incorporating critical parameters such as resistance, current, and voltage levels, the software allows for a comprehensive analysis of power losses and their implications on system performance. This approach not only aids in identifying strategies for reducing losses but also enhances the overall reliability and effectiveness of the transmission system between Rulindo and Gabiro.

The figure represents a high-voltage power transmission and distribution network, highlighting the connections between substations, transmission lines, and end consumers. The system receives power from two sources, Mukungwa and Jabana, both feeding into a 110 kV transmission line. Circuit breakers (CB) are installed at these entry points to provide protection and control over the power flow.

The 110 kV transmission line extends through different substations, such as Rulindo SS, where it splits into multiple paths. One path continues as a 64 km transmission line (TL) to another 110 kV substation, which further steps down the voltage to serve different loads, including industrial, commercial, and residential consumers.

Additionally, 30 kV distribution lines branch out from the main grid to supply electricity to industries and local communities. Transformers at various points step down the voltage levels to meet the specific demands of different consumers. The presence of isolators, circuit breakers, and transformers ensures safe and efficient power distribution, protecting the system from faults and overloads.

Overall, this diagram provides an overview of a regional power distribution network, demonstrating how electricity is transmitted over long distances at high voltage before being stepped down and distributed to various end users.

CHAPTER IV. MODELLING AND SIMULATION

4.1. Introduction

The efficient transmission of electrical energy is crucial for the overall performance of power systems. However, power losses in transmission lines are an inevitable phenomenon, primarily caused by technical factors, operational inefficiencies, and environmental conditions. This chapter discusses the analysis of power losses in transmission lines, focusing on identifying their causes and exploring effective reduction strategies. The objective is to provide a comprehensive understanding of the mechanisms behind power losses and outline methods to enhance the efficiency and reliability of the transmission network.

4.2. Power Flow Simulation and Analysis of Rulindo to Gabiro

This single-line diagram, illustrating a portion of an electrical power transmission and distribution system in Rwanda, was likely generated using ETAP software, a widely used tool for power system analysis and simulation. The diagram depicts the flow of power from two initial sources, Mukungwa-U1 and Jabana-U3, both operating at an implied 110kV level. These sources feed into a central "BusDuct2" which acts as a common connection point. From BusDuct2, the power is transmitted via a 64km line (Line 9, labeled AL) to the Gabiro Substation. This line, as simulated in ETAP, exhibits significant losses, noted as 195.8 kW and 5469 kvar.

The Gabiro Substation, through ETAP's modeling, demonstrates the step-down of voltage from 110kV to approximately 30kV using two transformers, T8-GABIRO and T10-GABIRO, both rated at 10 MVA. The diagram, a result of the ETAP simulation, shows the power flow through these transformers and the resulting voltage at the 30kV side. From the Gabiro Substation, the 30kV power, as analyzed by ETAP, is distributed to three locations: Nyagatare, Kiziguro, and Ngarama. The voltage at these locations, as calculated by ETAP, is shown to be slightly below 30kV, with specific voltage drops indicated. These voltage drops, along with the power and reactive power values at various points, as determined through the ETAP simulation, provide insight into the efficiency and performance of the transmission and distribution network. The diagram, generated by ETAP, also includes the power and reactive power values at various buses

and connection points, offering a snapshot of the system's loading and power flow characteristics as simulated within the software. Overall, this ETAP-generated diagram offers a simplified yet informative overview of the electrical network's configuration and operation in this region, as modeled and analyzed by the ETAP software.

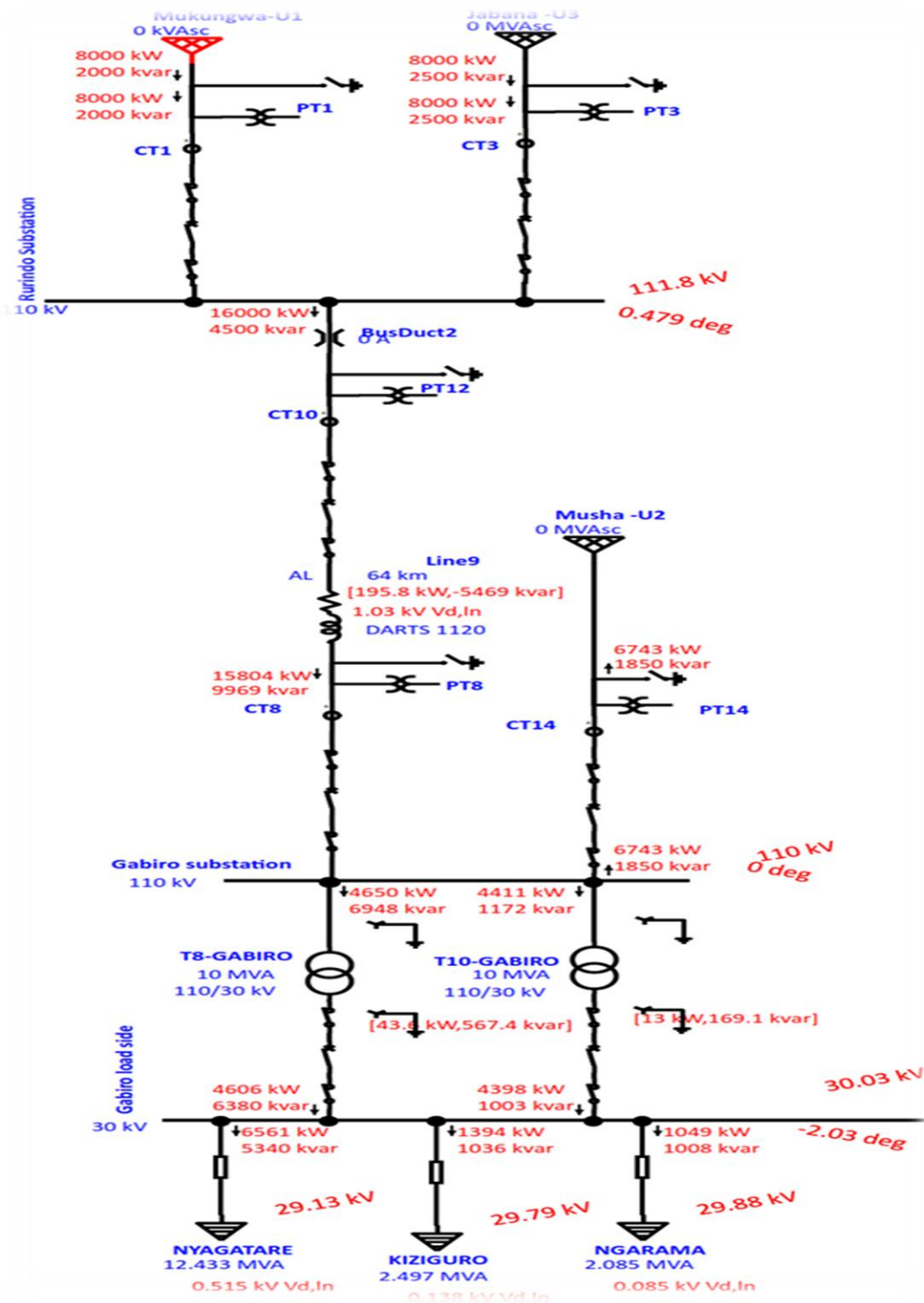


Figure 12: Power flow simulation of Actual line parameter

Table form show the bus voltage, power, reactive power and losses on the lines and buses.

Bus name	Voltage (kV)	Active power (kW)	Reactive power (kvar)	losses
Mukungwa-U1	110kV	8000	2000	
Habana –U3	110kV	8000	2500	
BusDuct2	110kV	16000	4500	
Musha-U2	110kV	6743	1850	
Gabiro SS 110kV	110kV	15804	9969	
Gabiro SS 30kV	30.03			
Nyagatare	29.13	4606	6380	0.515kV
Kiziguro	29.79	4398	1003	0.138kV
Ngarama	29.88	1049	1008	0.085kV
Line 9				195.8kW + 5469kvar

This single-line diagram, likely generated from an ETAP simulation, represents a segment of an electrical power transmission and distribution network in Rwanda, featuring the Rulindo Substation and the Gabiro load side. It begins with two power sources, Mukungwa-U1 and Jabana-U3, both operating at an implied 110kV level. Mukungwa-U1 delivers 8000 kW of active power and 2000 kvar of reactive power, while Jabana-U3 provides 8000 kW and 2500 kvar. These sources feed into a common bus, BusDuct2, resulting in a combined power of 16000 kW and 4500 kvar.

From BusDuct2, the power is transmitted through a 64 km line, Line 9 (AL), which experiences losses of 195.8 kW and 5469 kvar, as indicated within brackets. The voltage drop along this line is 1.03 kV, calculated by DARTS 1120. The line terminates at the Gabiro Substation, where the power is 15804 kW and 9969 kvar.

At Gabiro Substation, two 10 MVA transformers, T8-GABIRO and T10-GABIRO, step down the voltage from 110kV to approximately 30kV. T8-GABIRO delivers 4606 kW and 6380 kvar

on the 30kV side, while T10-GABIRO provides 4398 kW and 1003 kvar. Losses within the transformers are indicated in brackets as 43 kW and 567.4 kvar for T8-GABIRO and 1394 kW and 1036 kvar for T10-GABIRO.

From the Gabiro load side, the 30kV power is distributed to three locations: Nyagatare, Kiziguro, and Ngarama. The voltages at these locations are 29.13 kV, 29.79 kV, and 29.88 kV, respectively, with corresponding voltage drops of 0.515 kV, 0.138 kV, and 0.085 kV. The diagram also provides the power and reactive power values at these locations, along with the MVA ratings, offering a comprehensive overview of the network's operation and performance. The voltage at the Gabiro substation is at 30.03 kV with an angle of -2.03 degrees. The voltage at BusDuct2 is 111.8 kV with an angle of 0.479 degrees. The voltage at the 110 kV side of Gabiro substation is 110 kV with an angle of 0 degrees.

Table 7: Simulation Line losses

ID	Rating 1	Rating 2	kW Flow	kvar Flow	Amp Flow	% PF	% Voltage Drop	kW Losses	kvar Losses
Line9	64000 m	262	15804.2	9969.5	98.08	84.58	1.63	195.8	-2164.2

$$\text{Percentage power loss} = \frac{195.8}{15804.2} \times 100 = 1.23\%$$

4.2.1. Active and Reactive Power Flows

The active and reactive power flow values at major points in the transmission system are as follows:

Location	Active Power (kW)	Reactive Power (kVAr)	Power Factor
Rulindo Substation (Sending End)	15,819 kW	12691.12 kVAr	0.78
Gabiro Substation (Receiving End)	15,804.2 kW	9,969.5 kVAr	0.84
T8-GABIRO Transformer	4,649.7 kW	6,947.5 kVAr	0.55

(83.6% Loaded)			
T10-GABIRO Transformer (45.6% Loaded)	4,411.2 kW	1,172.4 kVAr	0.96
Nyagatare Feeder Load	6,337.2 kW	5,216.0 kVAr	0.77
Kiziguro Feeder Load	1,380.1 kW	1,031.8 kVAr	0.80
Ngarama Feeder Load	1,041.6 kW	1,005.4 kVAr	0.71

The **T8-GABIRO transformer** had a lower power factor (**0.55**), indicating poor efficiency due to high reactive power demand.

The **T10-GABIRO transformer** performed better with a power factor of **0.96** due to lower reactive power consumption.

4.2.2. Transformer Losses at Gabiro Substation

The power flow diagram shown in the figure below represent the electrical parameters of Gabiro Substation simulated using ETAP software. This analysis provides insights into transformer performance power losses, voltage profiles and loading condition.

The transformer losses at Gabiro substation as presented in below table and specifically T8-GABIRO and T10-GABIRO, highlight efficiency and performance under varying load conditions. For T8-GABIRO (10 MVA, 110/30 kV), the in-flow power is 4649.7 kW with 6947.5 kVAr, and the outflow is 4411.2kW with 1172.4kVAr, resulting in real power losses of 143.65 kW and reactive power losses of 567.4kVAr. The transformer operates at a power factor of 0.55 indicating poor efficiency due to high reactive power consumption and it is loaded at 83.6% of its capacity. In contrast, T10-GABIRO shows negligible real power loss (13.01 kW) and minimal reactive power loss. The transformer is loaded at 45.6% with a power factor of 0.9664 indicating that it may be operating or lightly loaded condition, which contributes to its lower loss figures. The data underscores the importance of load balancing and reactive power management for optimal transformer efficiency.

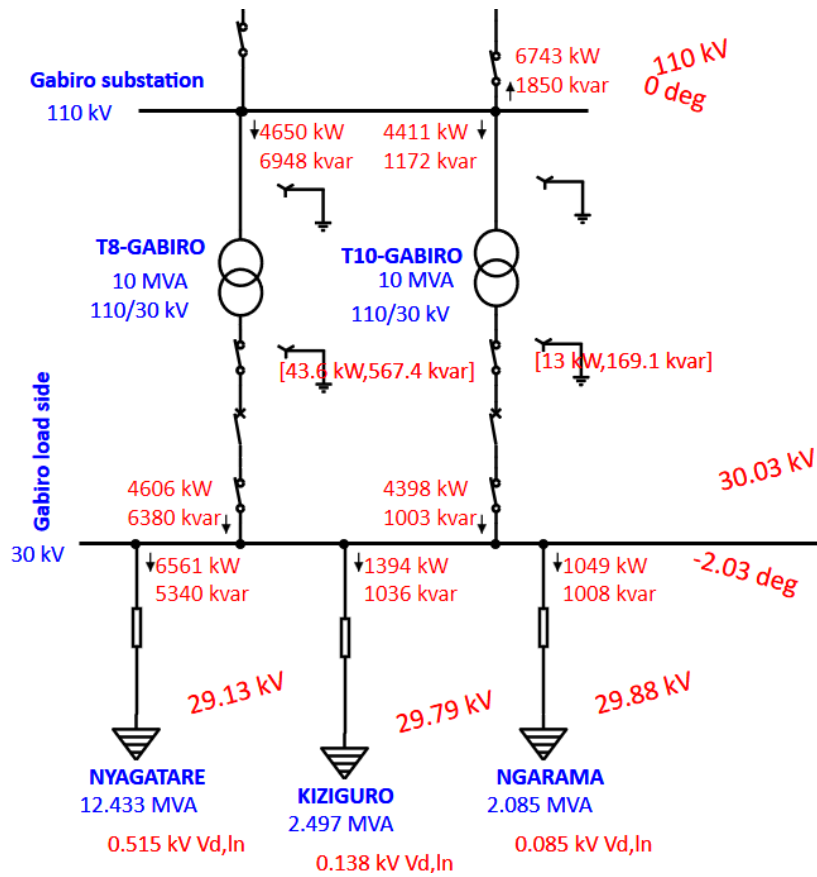


Figure 13: Transformer losses at Gabiro substation

Table 8: Transformer losses at Gabiro substation

ID	Rating 1	kW Flow	kVAr Flow	kW Losses	kVAr Losses	Amp Flow	PF	% Loading	% Voltage drop
T8-GABIRO	10MVA 110/30 kV	4649.7	6947.5	143.65	567.4	43.88	0.55	83.6	0.09
T10-GABIRO	10MVA 110/30 kV	4411.2	1172.4	13.01	169.1	23.96	0.96	45.6	0.09

4.2.3. Loading Status of Gabiro Substation Feeder

The data represents the loading conditions of three feeders: Kiziguro, Ngarama, and Nyagatare from Gabiro Substation. Each feeder operates at a rated voltage of 30 kV with slight variations in operational voltage. Kiziguro, with a capacity of 2497 kVA, operates at 69.5% loading and a power factor of 0.80. Ngarama, rated at 2085 kVA, runs at 69.7% loading with a lower power factor of 0.71. Nyagatare, the largest at 12,433 kVA, operates at 68% loading and a power factor of 0.77. The feeders are running below their maximum capacity, ensuring system reliability, though power factor improvements could enhance efficiency as shown in Table 9.

Table 9: Loading Status of Gabiro Substation Feeder

ID	Rating/Limit	Rated kV	Op. kV	kW	kvar	Amp	PF	% Loading
KIZIGURO	2497kVA	30	29.13	1380.1	1031.8	33.4	0.80	69.5
NGARAMA	2085kVA	30	29.79	1041.6	1005.4	27.97	0.71	69.7
NYAGATARE	12433 kVA	30	29.88	6337.2	5216	162.7	0.77	68

4.2.4. Potential Methods for Power Loss Reduction

Based on the analysis of the existing system, an improved transmission line design is recommended to address the identified issues and enhance performance. To improve the performance of the Gabiro Substation and its associated transmission line losses, the researcher recommends several key upgrades. First, reactive power compensation should be implemented by installing capacitor banks along Line 9.

Moreover, Line 9, which experiences significant losses over its 64 km span, should be upgraded by reconductoring with a twin conductor-line or applying a double circuit higher capacity, lower-resistance conductors to reduce I^2R losses. These improvements will collectively reduce transmission losses, optimize efficiency, and ensure the long-term reliability of the system.

4.2.5. Sizing power factor corrector at Gabiro Substation

Properly sizing a power factor corrector at Gabiro Substation involves the following steps:

Step1. Assess Current Power Factor

Let's calculate the current power factor for each transformer based on the active and reactive power flows.

✓ For **T8-GABIRO**:

$$\text{Power Factor (PF)} = \frac{\text{Active Power (kW)}}{\sqrt{\text{Active Power}^2 + \text{Reactive Power}^2}} = \frac{4,649.7}{\sqrt{4,649.7^2 + 6,947.5^2}} = 0.556$$

✓ For **T10-GABIRO**:

$$\text{Power Factor (PF)} = \frac{4,411.2}{\sqrt{4,411.2^2 + (1172.4)^2}} = 0.9664.$$

Reason that the PF is Low for T8 and High for T10

a) Reasons for Low PF in T8

High Reactive Power Demand: A low PF indicates a higher proportion of reactive power (kvar) compared to real power (kW). This could be due to a high presence of inductive loads such as:

- Large motors with poor or no power factor correction
- Welding machines
- Inductive lighting (e.g., fluorescent lights with magnetic ballasts)

Long Feeder Length & Voltage Drop: If T8 has long distribution lines with high impedance, voltage drops can occur, increasing reactive power demand and lowering the power factor.

Uncompensated Loads: If there are fewer capacitors or power factor correction equipment on T8, the reactive power remains high, keeping the power factor low.

b) Reasons for High PF in T10

- **More Resistive Loads:** A higher PF means the feeder has more loads that primarily consume active power (kW) with minimal reactive power (kvar). This includes:
 - Electric heating systems
 - Incandescent or LED lighting
 - Electronic equipment with built-in power factor correction
- **Power Factor Correction:** If T10 has capacitor banks installed or automatic power factor correction (PFC) units, the reactive power is minimized, leading to a higher PF.

- **Shorter Feeder Length:** If T10 has a shorter distribution length, there may be less line reactance, leading to lower kvar losses and a higher PF.

Step2. Determine the Target Power Factor

The targeted power factor, is typically **0.98**, as recommended by utility standards.

Step3. Calculate Reactive Power Compensation Needed

Let's calculate the reactive power to correct to the target power factor using the following formula:

$$Q_c = P(\text{tancos}^{-1}(\text{current PF}) - \text{tancos}^{-1}(\text{target PF})).$$

For **T8-GABIRO**:

$$Q_c = 4,649.7(\text{tancos}^{-1}(0.556) - \text{tancos}^{-1}(0.98)) = 6006.82 \text{ kvar.}$$

For **T10-GABIRO**:

$$Q_c = 4411.2(\text{tancos}^{-1}(0.9664) - \text{tancos}^{-1}(0.98)) = 322.42 \text{ kvar.}$$

Step 4. Select Power Factor Correction Equipment

Now, combine the calculated reactive power requirements:

$$Q_{\text{total}} = Q_c(T8) + Q_c(T10) = 6006.82 + 322.42 = 6329.24 \text{ kvar}$$

A capacitor banks with a total capacity of approximately 2965 kvar or slightly higher is selected to ensure improved PF and flexibility.

Efficiency improvement obtained by the method:

1. Power factor before compensation

The total apparent power before compensation can be found using

$$P_{\text{loss}} = 3 \times (88.8)^2 \times 0.123 \times 64 = 186.22kW \dots\dots\dots \text{eq.1}$$

$$S_{\text{before}} = \sqrt{P_{\text{total}}^2 + Q_{\text{total}}^2}$$

Where:

$$P_{\text{total}} = 6337.2 + 1380.1 + 1041.6 = 8758.9kW.$$

$$Q_{\text{total}} = 6329.24kvar.$$

$$S_{\text{before}} = \sqrt{(8758.9)^2 + (6329.24)^2} = 10850.86kVA.$$

The initial power factor is:

$$PF_{before} = \frac{P_{total}}{S_{before}} = \frac{8758.9}{10850.86} = 0.807.$$

2. Power factor after compensation

The new reactive power installing capacitor banks is:

$$Q_{new} = Q_{total} - Q_c = 6329.24 - 2965 = 3364.24 \text{ kvar}.$$

$$I_{new} = I \frac{PF_{before}}{PF_{after}} = 88.8 \times \frac{0.807}{0.931} = 76.97 \text{ A}.$$

$$P_{loss \text{ after}} = 3 \times (76.97)^2 \times 0.123 \times 64 = 139.78 \text{ kW}.$$

The new apparent power is:

$$S_{after} = \sqrt{(8758.9)^2 + (3364.24)^2} = 9412.74 \text{ kVA}.$$

The improved power factor is

$$PF_{after} = \frac{P_{total}}{S_{after}} = \frac{8758.9}{9412.74} = 0.931.$$

$$\text{percentage power loss} = \frac{186.22 - 139.78}{186.22} \times 100 = 24.93\%.$$

2. Efficiency improvement

Efficient is generally improved by reducing power losses. The reduction in apparent power helps decrease losses in transmission lines and transformers.

The percentage improvement in power factor is

$$PF \text{ Improvement} = \left(\frac{PF_{after} - PF_{before}}{PF_{before}} \right) = \left(\frac{0.931 - 0.807}{0.807} \right) \times 100 = 15.37\%.$$

This means that the power factor correction resulted in a 15.37% improvement, leading to better efficiency, reduced power losses and improved voltage regulation.

4.3. Double circuit

A **double circuit** is a transmission line configuration where two independent electrical circuits share the same transmission tower or structure. Each circuit consists of three phases, making a total of six conductors in an AC system. Double circuits enhance power transfer capacity, reliability,

and redundancy in electrical transmission networks. A double circuit can be identified by looking for parallel transmission lines that run between substations or generating units, often operating at the same voltage level and sharing a common transmission path.

Double line parameter line parameters

- *Line length = 64km*
- *Cable type Aluminium cable = 262mm²*
- *Resistance = 0.123 Ohm/km*
- *Reactance = 0.416504 Ohm/km*
- *Voltage Line = 110kV*
- *Admittance = 0.157245 Ohm/km*

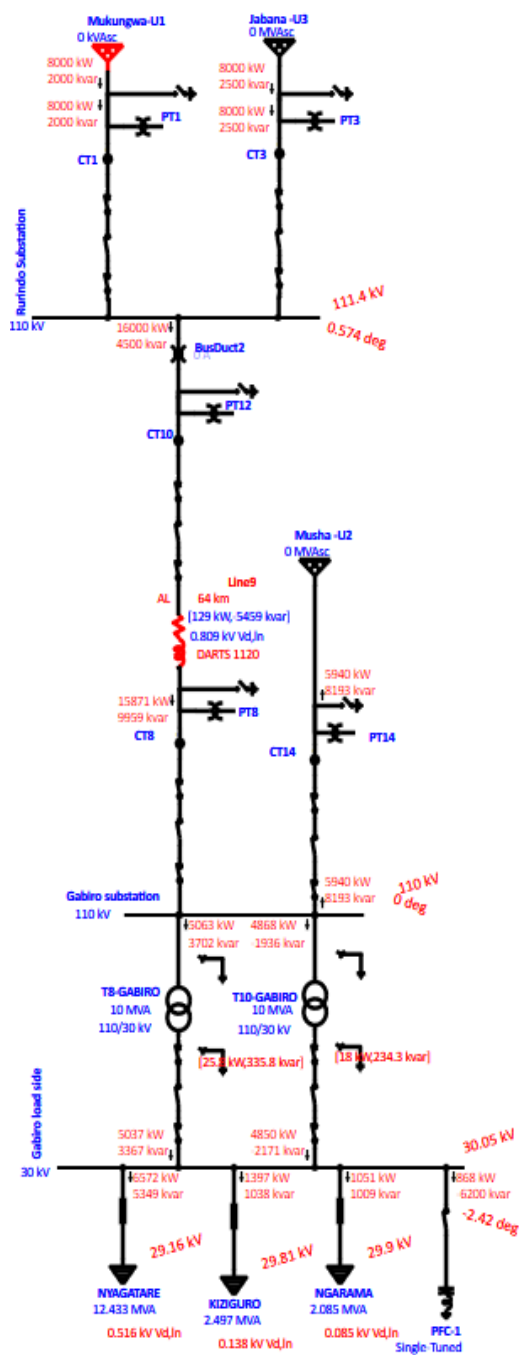


Figure 13: Improved transmission line - Double circuit type

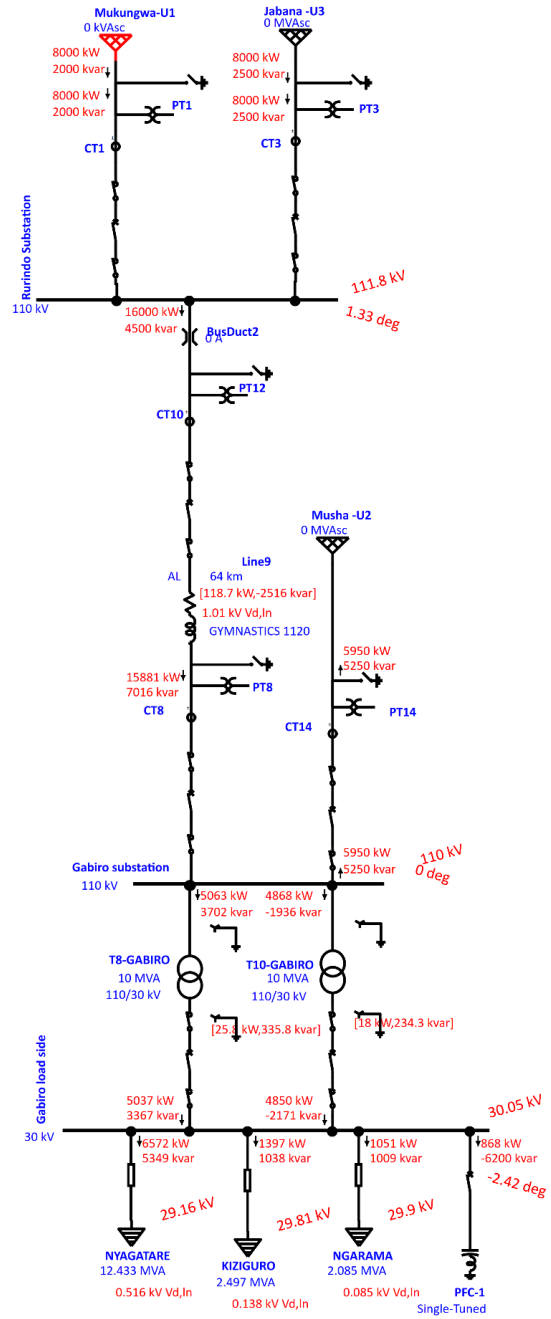


Figure 14: Improved Rurindo to Gabiro line - single circuit

As shown in Figure 13 and Figure 14, the upgrade of Line 9 to a double circuit significantly improves its performance by reducing active and reactive power losses. The active power losses decrease from 195.8 kW to 129 kW, ie that The active power losses decreased by 34.11% from the base case, representing a notable improvement in efficiency. Reactive power losses also improve, reducing to -5447.9 kvar, indicating a better balance in reactive power flow along the line. Additionally, the power factor improves to 84.73%, and the current flow remains manageable at 98.34 A, while the voltage drop reduces to 1.27%, enhancing voltage stability across the line. These improvements highlight the benefits of the double-circuit upgrade, including reduced losses, improved power delivery efficiency, and enhanced system stability. In addition, the capacitor banks optimized the system by reducing kvar demand and boosting operational efficiency.

Table 10: Transformer losses for double circuit

ID	Rating 1	Rating 2	kW Flow	kvar Flow	Amp Flow	% PF	% Loading	% Voltage Drop	kW Losses	kvar Losses
T8-GABIRO	110 / 30 kV	10000 kVA	5063.2	3702.4	16.44	32.92	62.7	0.17	25.83	335.8
T10-GABIRO	110 / 30 kV	10000 kVA	4850.3	-2170.7	68.28	102.1	53.1	0.17	18.02	234.3

Table 11: Simulation result for improve of transmission line losses between Rulindo to Gabiro

ID	Rating 1	Rating 2	kW Flow	kvar Flow	Amp Flow	% PF	% Voltage Drop	kW Losses	kvar Losses
Line 9	64000 m	262	15871.1	9947.9	98.34	84.7	1.27	129	-5459.1

By addressing both conductor inefficiencies and reactive power challenges, these measures will not only reduce energy wastage but also enhance voltage stability along the transmission line. This ensures a more reliable and efficient system capable of meeting current and future load demands.

$$\text{Percentage reduction in power losses } \Delta P_{loss} = \frac{P_{loss,initial} - P_{loss,new}}{P_{loss}} \times 100$$

$$\text{Loss Reduction percentage} = \frac{195.8-129}{195.8} \times 100 = 34.11\%.$$

4.4. Twin conductor-single circuit Transmission Line

To mitigate these losses, reconductoring the line with twin conductor of higher-capacity, low-resistance conductors of Aluminum cable type of 431mm² Al and resistance of 0.00461 ohm per km and reactance 0.01844 ohm per km. This upgrade will reduce I²R losses and improve overall transmission efficiency [21]. Additionally, integrating reactive power compensation devices like capacitor banks along the line will help manage reactive power flows, further minimizing losses and improving the power factor.

Table 12: Transmission Line losses in single circuit (Twin conductor)

ID	Rating 1	Rating 2	kW Flow	kvar Flow	Amp Flow	% PF	% Voltage Drop	kW Losses	kvar Losses
Line 9	64000 m	431/506	15862.2	6960.6	90.92	91.57	1.72	137.8	-2460.6

$$\text{Percentage reduction in power losses } \Delta P_{\text{loss}} = \frac{P_{\text{loss,initial}} - P_{\text{loss,new}}}{P_{\text{loss}}} \times 100$$

$$\text{Loss Reduction percentage} = \frac{195.8-137.8}{195.8} \times 100 = 29.62\%.$$

4.4.1. Transformer Losses for Single Circuit (Twin Conductor)

The analysis of Line 9 with a single circuit and twin conductor of low resistance highlights moderate improvements in performance compared to the original installation. The line carries an active power flow of 15,862.2 kW and a reactive power flow of 6960.6 kvar. The active power losses are reduced to 137.8 kW from the original 195.8 kW, while reactive power losses decrease to -2460.6 kvar. The power factor improves slightly to 90.92%, and the voltage drop is minimized to 1.72%, enhancing the line's voltage stability.

While the use of low-resistance conductors reduces power losses and improves voltage regulation, the active power losses (137.8 kW) remain higher than those achieved with a double circuit (128.9 kW). This indicates that, although this solution is less costly, additional measures such as reactive power compensation and further conductor upgrades may be required to achieve optimal efficiency and minimize energy losses.

Table 13: Transformer losses for single circuit (Twin conductor)

ID	Rating	Rating	kW	kvar	Amp	%	%	%	kW	kvar
	1	2	Flow	Flow	Flow	PF	Loading	Voltage Drop	Losses	Losses
T8- GABIRO	110 / 30 kV	10000 kVA	4,800.1	3,805.7	68.94	0.76	76.4%	0.15%	121.4	389.8
T10- GABIRO	110 / 30 kV	10000 kVA	4,600.4	1,812.3	43.21	0.93	45.8%	0.08%	10.8	124.2

4.4.1. Impact of the Twin Conductor Upgrade on SS Transformers

The simulation provided the voltage magnitudes at different buses along the transmission line:

Table 0-8: Voltage magnitude at different buses

Bus name	Voltage (kV)	Voltage Drop (%)
Rulindo Substation (Sending End)	110.00 kV	0
Gabiro Substation (Receiving End)	108.21 kV	1.63% (before optimization)
After Twin Conductor Upgrade	108.72 kV	1.72%
After Double-Circuit Upgrade	109.30 kV	1.27%

- The voltage drop from Rulindo to Gabiro was 1.63%.
- The double-circuit upgrade improved voltage profile, reducing the drop to **1.27%**.

CHAPTER V. RESULTS AND DISCUSSION

5.1. Overview of Simulation Result

The analysis of power losses on the Rulindo-Gabiro transmission line revealed significant inefficiencies primarily attributed to conductor resistance, reactive power imbalances, corona discharge, and transformer losses. Before optimization, the system experienced an active power loss of 195.8 kW, with a substantial voltage drop of 1.63%. The initial transmission efficiency was recorded at 59% in 2021, indicating high energy dissipation. The power factor of 0.78 further contributed to inefficient energy flow, increasing reactive power demand and amplifying system losses. These inefficiencies underscored the urgent need for strategic interventions to enhance energy transmission efficiency.

To mitigate these losses, several loss reduction techniques were implemented. The introduction of a double-circuit transmission line significantly reduced active power losses from 195.8 kW to 129 kW, representing an improvement of 34.11%. Similarly, reconductoring the transmission line using twin conductors decreased losses to 137.8 kW, marking a 29.62% enhancement in efficiency. Additionally, reactive power compensation through the installation of capacitor banks improved the power factor from 0.78 to 0.92, which subsequently reduced reactive power losses and improved overall power quality. These upgrades also improved voltage stability, reducing the voltage drop from 1.63% to 1.27%. A closer examination of transformer losses at the Gabiro substation highlighted the disparity in loading conditions. The T8-GABIRO transformer, operating at 83.6% capacity, exhibited substantial losses of 143.65 kW due to high reactive power demand. In contrast, the T10-GABIRO transformer, which was underutilized at 45.6%, experienced significantly lower losses of 13.01 kW. This imbalance in transformer loading emphasized the need for improved load distribution to enhance operational efficiency.

5.2. Power Losses in Transmission Line

- The double-circuit upgrade reduced active power losses by 34.11%, from 195.8 kW to 129 kW.
- The reactive power compensation improved the power factor from 0.78 to 0.92, leading to better transmission efficiency, reduced **active power losses by 34.11%**, from **186.22 kW to 139.78kW**.
- The Twin conductor upgrade reduced **active power losses by 29.62%**, from **195.8 kW to 137.8 kW**.

5.3. Summary of the power loss assessment and reduction result

Table 5.2: Impact of power loss reduction measures

Parameter	Base Line data	After Integration of different Techniques		
	Actual Loss	Capacitor Integration	Double Line	Twin conductor
P_{Loss} (kW)	195.8	139.78	129	137.8
% P_{Loss}	1.23	24.93	34.11	29.62
pf	0.78	0.92	0.84	0.91
%Voltage Drop	1.63	1.53	1.27	1.72

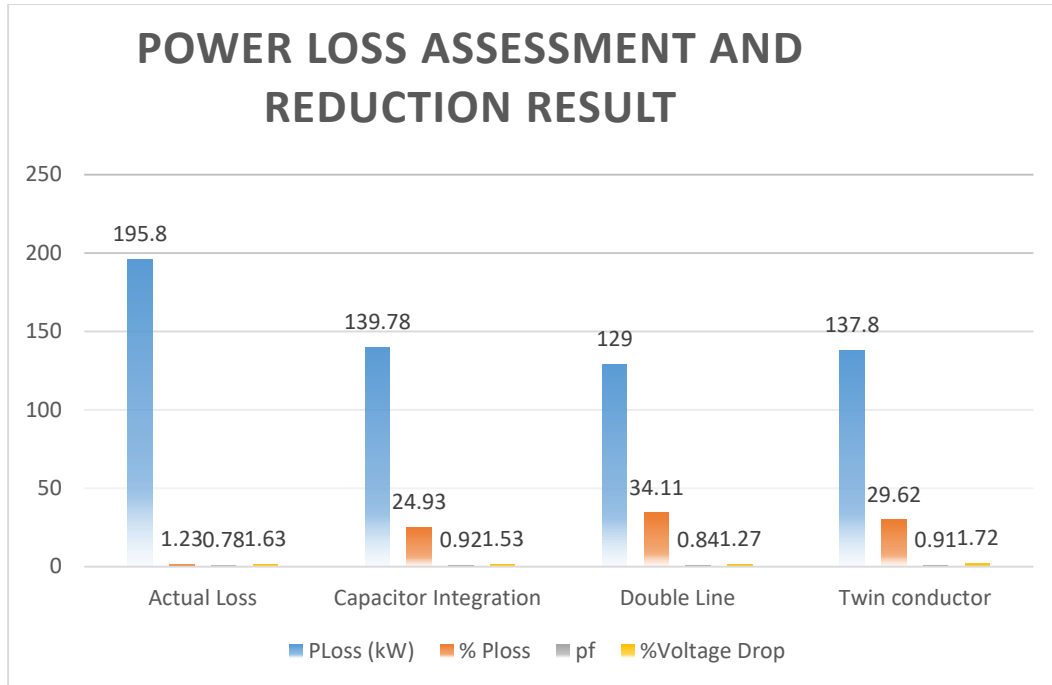


Figure 15. Graph of the Power loss assessment and reduction result

5.3. Conclusion from Simulation

- The highest loss reduction was achieved through the double-circuit upgrade, bringing active power losses down to 129 kW.
- Voltage stability improved significantly, with voltage drop reduced to 1.27% after the upgrades.
- Power factor improvement through reactive power compensation it has increased from 0.78 to 0.92, resulting in lower reactive losses and better transmission efficiency.

CHAPTER VI. CONCLUSION AND RECOMMENDATION

6.1. Conclusion

The study on power loss assessment and reduction for the Rulindo-Gabiro transmission line has demonstrated that power losses significantly impact the efficiency and reliability of electricity transmission. The analysis identified that resistive losses in conductors, transformer inefficiencies, and reactive power imbalances were the primary contributors to transmission losses. Through systematic load flow analysis using ETAP software, it was established that losses could be mitigated through targeted interventions such as reconductoring, double circuit expansion, and reactive power compensation.

Quantitative Results Obtained on this Research:

- Twin Conductor Upgrade: loss is reduced from 195.8 to 137.8 kW (29.62%)
- Double-Circuit Upgrade: loss is reduced from 195.8 to 129 kW (34.11%)
- Reactive Power Compensation: Power factor improved from 0.78 to 0.92 this gives loss is reduced from 186.22 to 139.78kW (24.93%)

Furthermore, the study highlighted the importance of voltage regulation, with improvements in the voltage profile reducing transmission losses and enhancing power quality at the receiving end. Load balancing among transformers at the Gabiro substation was also identified as a critical factor in reducing energy wastage and optimizing overall system efficiency. The research underscores the necessity for continuous monitoring, infrastructure upgrades, and the integration of smart grid technologies to sustain and further improve transmission efficiency. Ultimately, the study concludes that adopting a combination of technical improvements, strategic planning, and modernized infrastructure can significantly enhance the performance of Rwanda's transmission network, ensuring a more stable and reliable electricity supply.

6.2. Recommendations

To further optimize the efficiency of the Rulindo-Gabiro transmission line, several key

recommendations are proposed. Firstly, upgrading the transmission line conductors to low-resistance materials such as Aluminum Conductor Steel Reinforced (ACSR) or High-Temperature Low-Sag (HTLS) cables should be prioritized to minimize resistive power losses. Additionally, implementing a double-circuit transmission line can significantly enhance power transfer capacity, reducing line losses and improving overall network reliability. To mitigate reactive power losses, the installation of capacitor banks at strategic locations along the transmission line should be carried out to improve the power factor and reduce the burden on transformers.

Another crucial recommendation is the optimization of transformer loading at the Gabiro substation. Balancing the load between T8-GABIRO and T10-GABIRO transformers will enhance operational efficiency and minimize power dissipation. Regular maintenance and real-time monitoring using advanced metering and smart grid technology should also be implemented to ensure early detection of power losses and system inefficiencies. To further enhance the security of the transmission system, energy theft prevention measures should be strengthened by deploying advanced metering infrastructure (AMI) and improving surveillance along transmission lines.

Lastly, investing in continuous research and development is essential to keep pace with emerging energy-efficient technologies and ensure that Rwanda's power transmission network remains resilient and sustainable. By integrating these recommendations, Rwanda Energy Group (REG) can further improve the reliability, efficiency, and sustainability of the Rulindo-Gabiro transmission line, ultimately reducing operational costs and enhancing energy delivery to end-users.

REFERENCES

- [1] O. Method and N. E. Aneke, "Reduction of Power System Losses in Transmission Network Using Reduction of Power System Losses in Transmission Network Using Optimization Method," no. April, 2021, doi: 10.35629/6734-1004015866.
- [2] M. H. Weik, *Transmission System*. 2000. doi: 10.1007/1-4020-0613-6_20021.
- [3] O. Living, S. N. Nnamchi, K. J. Ukagwu, A. Abdulkarim, and Z. O. Jagun, "Minimization of Electric Power Losses on 132 kV and 220 kV Uganda Electricity Transmission Lines," *Energy Power Eng*, vol. 15, no. 02, pp. 127–150, 2023, doi: 10.4236/epe.2023.152006.
- [4] O. M. Komolafe and K. M. Udofia, "Review of electrical energy losses in Nigeria," *Nigerian Journal of Technology*, vol. 39, no. 1, pp. 246–254, 2020, doi: 10.4314/njt.v39i1.28.
- [5] S. Bizimungu, F. Njoka, C. Saoke, and C. Siame, "Analysis of Rwanda'S Grid Point of Stability Loss," *ASEAN Engineering Journal*, vol. 13, no. 3, pp. 1–14, 2023, doi: 10.11113/aej.V13.18556.
- [6] P. Losses, E. Improvements, and R. P. Grid, "College of Science and Technology Title of the Research : Study of Power Losses and Efficiency Improvements on Rwandan Power Grid," pp. 1–17, 2023.
- [7] P. Thirupathaiah, P. A. B., K. Ravikumar, and P. K. R. D. O.-10. 22214/ijraset. 2024. 62588 E. R. -, "No Title."
- [8] S. Reconfiguration and D. G. Sizing, "Power Loss Minimization and Voltage Profile Improvement by," no. July, 2022.
- [9] B. A. Abdulmumin, G. Uzuner, O. A. Seyingbo, and L. A. D. O.-10. 1186/s40008-023-00325-8 E. R. -, "No Title."
- [10] S. Peer, R. Journals, B. Publishing, and P. Management, "Electricity Access Project Services and Community Development in Rwanda; A Case of EPC Project in Burera District," *Journal of Entrepreneurship & Project Management*, vol. 7, no. 8, pp. 23–40, 2023, doi: 10.53819/81018102t2172.
- [11] T. A. Setegn, "Msc thesis on: Power Loss Reduction, Voltage Profile and Reliability Improvement Using Distributed Generation (Case Study of Addis West Distribution Substation)," 2022.
- [12] Wubante Getachew, "ANALYSIS AND MINIMIZATION OF POWER LOSS IN EEPCo's TRANSMISSION GRID NETWORK DEPARTMENT OF ELECTRICAL ENGINEERING," 2011.

- [13] O. M. Bamigbola, M. M. Ali, and M. O. Oke, “Mathematical modeling of electric power flow and the minimization of power losses on transmission lines,” *Appl Math Comput*, vol. 241, pp. 214–221, Aug. 2014, doi: 10.1016/j.amc.2014.05.039.
- [14] C. E. Moreira Rodrigues *et al.*, “Technical loss calculation in distribution grids using equivalent minimum order networks and an iterative power factor correction procedure,” *Energies (Basel)*, vol. 14, no. 3, Feb. 2021, doi: 10.3390/en14030646.
- [15] REG, “Evolution of installed capacity in Rwanda.” Accessed: Dec. 11, 2024. [Online]. Available: <https://www.reg.rw/index.php?id=2>
- [16] “Updated_Rwanda_LCPDP_Plan_2023-2050_-_June_2023”.
- [17] “Updated_Rwanda_Electricity_Distribution_Development_Plan_-_June_2023”.
- [18] I. Bosu, H. Mahmoud, and H. Hassan, “Energy audit and management of an industrial site based on energy efficiency, economic, and environmental analysis,” *Appl Energy*, vol. 333, p. 120619, Mar. 2023, doi: 10.1016/J.APENERGY.2022.120619.
- [19] A. N. M. M. Haque, P. H. Nguyen, T. H. Vo, and F. W. Blik, “Agent-based unified approach for thermal and voltage constraint management in LV distribution network,” *Electric Power Systems Research*, vol. 143, pp. 462–473, Feb. 2017, doi: 10.1016/J.EPSR.2016.11.007.
- [20] T. A. Setegn, “Msc thesis on: Power Loss Reduction, Voltage Profile and Reliability Improvement Using Distributed Generation (Case Study of Addis West Distribution Substation),” 2022.
- [21] IEC, “IEC 61089:1991 | IEC.” Accessed: Dec. 02, 2024. [Online]. Available: <https://webstore.iec.ch/en/publication/4484>

APPENDICES

Monthly Peak Power Load (01 – 28 February 2022)

DATE	NYGATARE FEEDER				KIZIGURO FEEDER				NGARAMA FEEDER				TOTAL PEAK POWER LOAD	
	Hours	P(Mw)	Hours	Q(Mvar)	Hours	P(Mw)	Hours	Q(Mvar)	Hours	P(Mw)	Hours	Q(Mvar)	P (MW)	Q(Mvar)
2/1/2022													0.00	0.00
2/2/2022	17:00	2.50	17:00	0.10	17:00	0.90	17:00	-0.20	17:00	0.80	17:00	-0.30	4.20	-0.40
2/3/2022	16:00	2.40	16:00	0.20	15:00	0.90	16:00	-0.10	17:00	0.70	15:00	0.00	4.00	0.10
2/4/2022	11:00	2.70	11:00	0.00	15:00	0.80	15:00	-0.10	17:00	0.80	17:00	-0.30	4.30	-0.40
2/5/2022													0.00	0.00
2/6/2022													0.00	0.00
2/7/2022	17:00	2.60	17:00	0.00	17:00	0.70	17:00	-0.10	17:00	0.70	17:00	-0.30	4.00	-0.40
2/8/2022	10:00	2.70	10:00	0.00	17:00	0.80	17:00	-0.20	17:00	0.60	17:00	-0.30	4.10	-0.50
2/9/2022	17:00	2.80	17:00	0.10	17:00	0.90	17:00	-0.10	17:00	0.50	17:00	-0.70	4.00	-0.70
2/10/2022	17:00	2.50	17:00	0.10	17:00	0.80	17:00	-0.20	17:00	0.70	17:00	-0.30	4.00	-0.40
2/11/2022	17:00	2.80	17:00	0.30	16:00	1.10	16:00	0.00	17:00	0.70	17:00	-0.20	4.60	0.10
2/12/2022													0.00	0.00
2/13/2022													0.00	0.00
2/14/2022	16:00	2.40	16:00	0.20	17:00	1.20	17:00	0.00	17:00	0.80	17:00	-0.20	4.40	0.00
2/15/2022	16:00	2.60	16:00	0.10	17:00	1.00	17:00	-0.10	17:00	0.80	17:00	-0.40	4.40	-0.40
2/16/2022	11:00	2.70	17:00	0.10	17:00	0.90	17:00	-0.10	17:00	0.80	17:00	-0.20	4.40	-0.20
2/17/2022	17:00	2.70	17:00	0.10	17:00	1.00	17:00	0.00	17:00	0.90	17:00	-0.10	4.60	0.00
2/18/2022	16:00	2.40	12:00	0.00	16:00	0.90	16:00	-0.20	10:00	0.60	14:00	-0.30	3.90	-0.50
2/19/2022													0.00	0.00
2/20/2022													0.00	0.00
2/21/2022	9:00	2.30	17:00	-0.10	16:00	0.80	16:00	-0.10	17:00	0.60	17:00	-0.30	3.70	-0.50
2/22/2022	10:00	2.70	16:00	0.10	15:00	0.70	17:00	-0.10	11:00	0.80	17:00	-0.20	4.20	-0.20
2/23/2022	12:00	2.60	12:00	0.00	17:00	1.00	17:00	0.00	17:00	0.60	17:00	-0.40	4.20	-0.40
2/24/2022	16:00	3.10	14:00	0.10	16:00	1.00	16:00	0.00	16:00	0.80	17:00	-0.30	4.90	-0.20
2/25/2022	17:00	2.80	17:00	0.30	16:00	1.10	16:00	0.00	16:00	0.70	17:00	0.00	4.60	0.30
2/26/2022													0.00	0.00
2/27/2022													0.00	0.00
2/28/2022	16:00	2.80	16:00	0.30	17:00	1.10	16:00	0.00	17:00	0.80	17:00	-0.30	4.70	0.00
													0.00	0.00
													0.00	0.00
													0.00	0.00

PEAK HOURS for AUGUST 2024															
DATE	NYAGATARE FEEDER				KIZIGURO FEEDER				NGARAMA FEEDER				TOTAL PEAK POWER LOAD		
	Hours	P(Mw)	Hours	Q(Mvar)	Hours	P(Mw)	Hours	Q(Mvar)	Hours	P(Mw)	Hours	Q(Mvar)	P (MW)	Q(Mvar)	
8/1/2022	9:00	5.40	9:00	1.10	17:00	1.40	17:00	0.00	17:00	1.20	17:00	-0.10	8.00	1.00	
8/2/2022													0.00	0.00	
8/3/2022													0.00	0.00	
8/4/2022													0.00	0.00	
8/5/2022	17:00	4.70	17:00	1.20	10:00	1.10	17:00	0.00	9:00	1.20	17:00	-0.30	7.00	0.90	
8/6/2022	10:00	4.00	10:00	0.80	17:00	1.20	17:00	0.00	10:00	1.10	17:00	-0.30	6.30	0.50	
8/7/2022	17:00	4.60	17:00	1.10	15:00	1.20	17:00	0.00	11:00	1.00	16:00	-0.30	6.80	0.80	
8/8/2022	16:00	4.70	16:00	0.90	10:00	1.30	17:00	0.00	17:00	1.20	17:00	-0.20	7.20	0.70	
8/9/2022	11:00	3.70	11:00	0.50	15:00	1.00	12:00	-0.10	10:00	1.10	11:00	-0.30	5.80	0.10	
8/10/2022													0.00	0.00	
8/11/2022													0.00	0.00	
8/12/2022													0.00	0.00	
8/13/2022	17:00	4.10	17:00	0.70	17:00	1.30	17:00	0.10	11:00	1.10	11:00	-0.40	6.50	0.40	
8/14/2022	17:00	4.50	17:00	0.90	17:00	1.30	17:00	0.10	10:00	1.10	16:00	-0.30	6.90	0.70	
8/15/2022													0.00	0.00	
8/16/2022	9:00	3.30	9:00	0.30	11:00	1.20	10:00	-0.10	9:00	0.90	9:00	-0.40	5.40	-0.20	
8/17/2022													0.00	0.00	
8/18/2022													0.00	0.00	
8/19/2022	16:00	4.30	16:00	0.90	17:00	1.30	17:00	0.00	17:00	1.10	17:00	-0.20	6.70	0.70	
8/20/2022	17:00	3.90	17:00	0.60	16:00	1.00	17:00	-0.10	11:00	1.00	11:00	-0.20	5.90	0.30	
8/21/2022	10:00	4.00	17:00	0.80	17:00	1.40	17:00	0.00	14:00	1.10	17:00	-0.30	6.50	0.50	
8/22/2022	17:00	4.40	17:00	0.90	17:00	1.30	17:00	0.00	17:00	1.20	17:00	-0.20	6.90	0.70	
8/23/2022	11:00	4.20	11:00	0.70	14:00	1.30	14:00	-0.10	12:00	1.10	14:00	-0.30	6.60	0.30	
8/24/2022													0.00	0.00	
8/25/2022													0.00	0.00	
8/26/2022	11:00	4.50	17:00	1.00	17:00	1.20	17:00	0.00	9:00	1.10	9:00	-0.40	6.80	0.60	
8/27/2022	9:00	4.10	16:00	0.60	17:00	1.40	17:00	0.00	9:00	1.00	16:00	-0.30	6.50	0.30	
8/28/2022	16:00	4.20	16:00	1.10	16:00	1.30	16:00	0.00	15:00	0.90	16:00	-0.30	6.40	0.80	
8/29/2022	15:00	3.70	11:00	0.20	17:00	1.40	17:00	0.20	11:00	1.00	17:00	0.10	6.10	0.50	
8/30/2022	11:00	4.10	17:00	0.50	17:00	1.30	17:00	0.00	17:00	1.10	17:00	-0.20	6.50	0.30	
8/31/2022													0.00	0.00	

ACTIVE AND REACTIVE ENERGY EXPORT For February 2022										
	MUSHA BAY (Kwh)	RULINDO BAY (Kwh)	I/P TX E02 (Kwh)	O/P TX E02 (Kwh)	I/P TX E04 (Kwh)	O/P TX E04 (Kwh)	NYAGATARE (Kwh)	KIZIGURO (Kwh)	NGARAMA (Kwh)	S.A
ACTIVE										
Current	51701240.00	100110.00	43245180.00	45153640.00	37617650.00	39737600.00	50229960.00	26783580.00	8822770.00	313500.00
Previous	49178490.00	100110.00	42089420.00	44027760.00	36455420.00	38623490.00	48818790.00	26292690.00	8478210.00	299601.60
Difference	2,522,750.00	-	1,155,760.00	1,125,880.00	1,162,230.00	1,114,110.00	1,411,170.00	490,890.00	344,560.00	13,898.40

	MUSHA BAY (Kvarh)	RULINDO BAY (Kvarh)	I/P TX E02 (Kvarh)	O/P TX E02 (Kvarh)	I/P TX E04 (Kvarh)	O/P TX E04 (Kvarh)	NYAGATARE (Kvarh)	KIZIGURO (kvarh)	NGARAMA (kvarh)	S.A
REACTIVE										
Current	64119550.00	3482980.00	553780.00	27805470.00	287230.00	26378380.00	1533940.00	17090.00	36200.00	371.00
Previous	62342060.00	3417000.00	550520.00	27105160.00	283340.00	25716640.00	1520380.00	16720.00	36030.00	370.00
Difference	1,777,490.00	65,980.00	3,260.00	700,310.00	3,890.00	661,740.00	13,560.00	370.00	170.00	40.00

ACTIVE AND REACTIVE ENERGY IMPORT FOR February 2022										
	MUSHA BAY (Kwh)	RULINDO BAY (Kwh)	I/P TX E02 (Kwh)	O/P TX E02 (Kwh)	I/P TX E04 (Kwh)	O/P TX E04 (Kwh)	NYAGATARE (Kwh)	KIZIGURO (Kwh)	NGARAMA (Kwh)	S.A
ACTIVE										
Current	30029030	102939090	0.00	3880.00	0.00	240.00	10.00	0.00	0.00	0.00
Previous	30028020	98092640	0.00	3880.00	0.00	240.00	10.00	0.00	0.00	0.00
Difference	1,010.00	4,846,450.00	-	-	-	-	-	-	-	-

	MUSHA BAY (Kvarh)	RULINDO BAY (Kvarh)	I/P TX E02 (Kvarh)	O/P TX E02 (Kvarh)	I/P TX E04 (Kvarh)	O/P TX E04 (Kvarh)	NYAGATARE (Kvarh)	KIZIGURO (kvarh)	NGARAMA (kvarh)	S.A
REACTIVE										
Current	727310	17993940	25210130	164160	24348920	151980	18614360	19346870	15094260	0.00
Previous	727050	17442360	24530720	163900	23702190	151480	18189400	18998060	14550790	0.00
Difference	260.00	551,580.00	679,410.00	260.00	646,730.00	500.00	424,960.00	348,810.00	543,470.00	-

ACTIVE AND REACTIVE ENERGY EXPORT FOR AUGUST 2024

	MUSHA BAY (Kwh)	RULINDO BAY (Kwh)	I/P TX E02 (Kwh)	O/P TX E02 (Kwh)	I/P TX E04 (Kwh)	O/P TX E04 (Kwh)	NYAGATARE (Kwh)	KIZIGURO (Kwh)	NGARAMA (Kwh)	K.INTAKE (Kwh)	K.IRRIGAT ON (Kwh)	S.A
ACTIVE												
Current	127553120.00	444250.00	91312760.00	91857190.00	83592630.00	84202740.00	107380170.00	46824320.00	23223890.00			8688.59
Previous	126445350.00	444250.00	89318750.00	89897210.00	81590700.00	82238640.00	104921350.00	46009900.00	22576360.00			8491.79
Difference	1,107,770.00	0.00	1,994,010.00	1,959,980.00	2,001,930.00	1,964,100.00	2,458,820.00	814,420.00	647,530.00	0.00	0.00	7,872.00

	MUSHA BAY (Kvarh)	RULINDO BAY (Kvarh)	I/P TX E02 (Kvarh)	O/P TX E02 (Kvarh)	I/P TX E04 (Kvarh)	O/P TX E04 (Kvarh)	NYAGATARE (Kvarh)	KIZIGURO (kvarh)	NGARAMA (kvarh)	K.INTAKE (Kwh)	K.IRRIGAT ON (Kwh)	S.A
REACTIVE												
Current	148,082,610.00	5,169,350.00	1,203,040.00	50,180,890.00	931,400.00	47,421,960.00	2,698,310.00	208,290.00	60,740.00			4.64
Previous	144,964,670.00	5,169,340.00	1,168,080.00	49,544,210.00	890,740.00	46,824,560.00	2,583,700.00	202,850.00	60,700.00			4.64
Difference	3,117,940.00	10.00	34,960.00	636,680.00	40,660.00	597,400.00	114,610.00	5,440.00	40.00	0.00	0.00	0.00