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AFRICAN CENTER OF  
EXCELLENCE IN ENERGY FOR  
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# **AFRICAN CENTER OF EXCELLENCE IN ENERGY FOR SUSTAINABLE DEVELOPMENT**

**ELECTRICAL POWER SYSTEMS**

**MASTER'S THESIS RESEARCH**

**COHORT FIVE**

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**TITLE: IMPROVEMENT OF POWER RELIABILITY IN THE  
DISTRIBUTION NETWORK OF RWANDA: A CASE STUDY OF  
THE MULINDI FEEDER**

**Academic Year: 2023-2024**

**Kigali, October 2025**

**DECLARATION**

I, **Fred KAGABO** declare that this thesis is my original work; and it has never been submitted to any university or other institution of higher learning for the award of a master’s degree or any other academic award. Any materials incorporated in this research study have been acknowledged in the list of reference.

Signature: .....

Date .....

**APPROVAL**

This Thesis is hereby submitted for examination with the consent and approval of the designated University's supervisor.

**Supervisor:**

Signature.....

Dr. Emmanuel UFITEYEZU

Date: .....

## **Abstract**

Reliable power distribution is fundamental to sustaining urban growth, industrial activity, and social well-being. Kigali City, the capital of Rwanda, faces persistent challenges of power outages and voltage instabilities, which directly affect critical services and economic productivity. This research evaluates the reliability of Kigali’s distribution network, with a focus on the Mulindi Feeder supplying Kigali International Airport (KIA). Using empirical outage data, failure rates, and ETAP simulations, the study examines reliability indices—System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI)—to quantify current performance and assess proposed improvements.

Three solutions were modeled: construction of a dedicated line, upgrading existing infrastructure, and integration of distributed generation. Results show that a dedicated line reduces repair time but introduces higher failure rates, while infrastructure upgrades provide the greatest improvement by significantly reducing both failure frequency and outage duration. Distributed generation further enhances resilience by lowering outage duration from 11 to 9.42 hours annually. These findings demonstrate that targeted infrastructure upgrades, complemented by distributed energy resources, are the most effective strategies for improving network reliability.

The study recommends investment in predictive maintenance, smart grid technologies, and distributed generation to ensure sustainable reliability improvements in Kigali’s power sector. Beyond Rwanda, the methodological framework and insights from this research can serve as a reference for other rapidly urbanizing cities in developing countries striving to balance electrification growth with network reliability.

## **DEDICATION**

I dedicate this thesis to my beloved family for their unconditional love, unwavering support, and encouragement throughout my academic journey. Their belief in my abilities has been my greatest motivation.

I also extend this dedication to my friends and classmates, whose support, collaboration, and shared experiences have made this journey both enriching and fulfilling.

Lastly, I dedicate this work to all professionals and researchers striving to improve power reliability and sustainability in Rwanda and beyond. May this research contribute to the advancement of reliable and efficient power distribution networks.

## **ACKNOWLEDGEMENTS**

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## **LIST OF ABBREVIATIONS**

**AMI** – Advanced Metering Infrastructure

**CAIDI** – Customer Average Interruption Duration Index

**DER** – Distributed Energy Resources

**ETAP** – Electrical Transient Analyzer Program

**KIA** – Kigali International Airport

**MTBF** – Mean Time Between Failures

**MTTR** – Mean Time to Repair

**SAIDI** – System Average Interruption Duration Index

**SAIFI** – System Average Interruption Frequency Index

**SCADA** – Supervisory Control and Data Acquisition

**BoQ** - Bill of Quantity

# CHAPTER 1. INTRODUCTION

## 1.1. Background

Power reliability in distribution networks is vital for the sustainability of urban infrastructure and economic activities. Kigali City, the capital of Rwanda, represents a significant portion of the country's demand for electricity. However, frequent power outages have been reported as shown in figure 1, indicating reliability issues within the distribution network [1]. This research seeks to explore the causes of these reliability challenges and propose solutions that could mitigate them. By conducting a detailed assessment of Kigali's distribution network, this study aims to provide insights that can inform policy decisions and technical improvements in Rwanda's power sector.

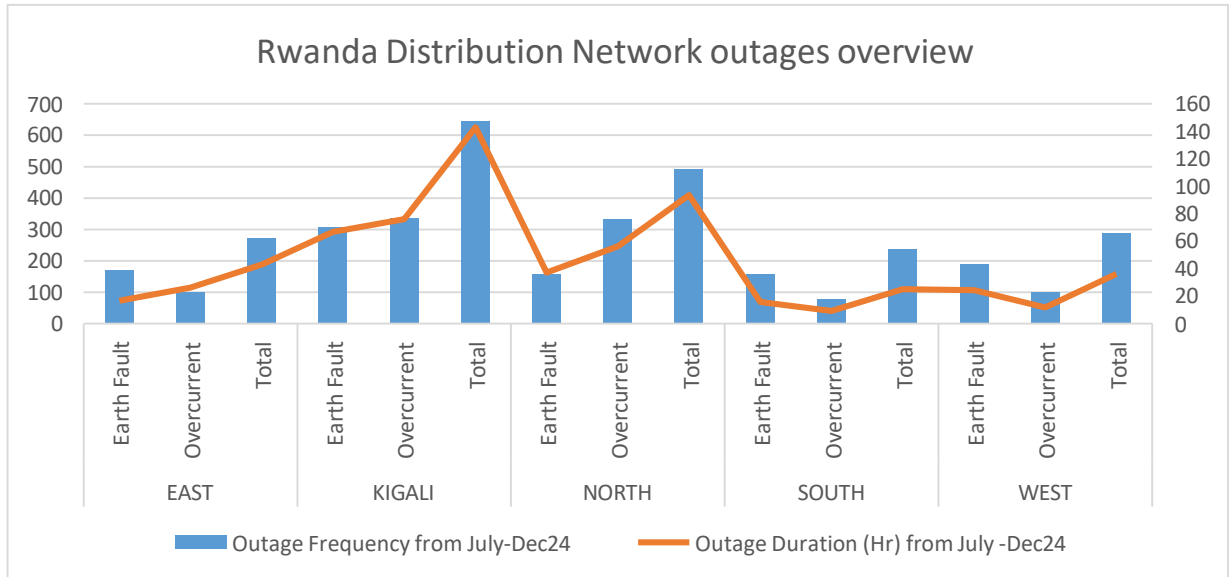


Figure 1: Rwanda Distribution Network outages overview 2024

Rwanda has made remarkable progress in electrification and power sector reforms over the past decade, positioning itself as one of the leading countries in Africa in terms of expanding access to electricity. The government's ambitious targets for universal electrification have been supported by significant investments in generation capacity, grid expansion, and the deployment of off-grid solutions [2]. As a result, the national electrification rate has seen substantial growth, contributing to economic development and improving the quality of life for many Rwandans. However, this

rapid expansion has also brought challenges, particularly in urban centers like Kigali, where the demand for electricity continues to outpace the capacity of the existing distribution network [3].

In Kigali, the strain on the distribution network has become increasingly evident as the city experiences rapid urbanization, industrial growth, and a rising population. The reliability of the power supply is a critical issue, as frequent interruptions can disrupt essential services, hamper economic activities, and affect the overall quality of life [2]. For businesses, power outages can lead to significant financial losses, while in healthcare, unreliable electricity can compromise patient safety and the delivery of medical services. Similarly, in education, power interruptions can hinder the effective use of digital tools and resources [4]. Understanding the specific factors contributing to power unreliability in Kigali's distribution network is essential for developing targeted interventions that can enhance its performance, ensure a stable power supply, and support the city's continued growth and development.

The reliability of power distribution networks is critical for urban development and economic sustainability. In Rwanda, the power sector has seen significant advancements, with substantial investments in generation capacity and grid expansion. Kigali City, as the nation's economic hub, exemplifies this progress but also highlights the challenges that accompany rapid urbanization. Despite Rwanda's electrification strides, frequent power outages and voltage fluctuations persist, particularly in Kigali's distribution network. These challenges disrupt essential services, hinder industrial productivity, and affect the quality of life for residents.

Power reliability encompasses the consistent availability of electricity with minimal interruptions and stable voltage levels. Metrics such as System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) are used to measure reliability. Addressing reliability issues in Kigali's power distribution network is crucial to ensure sustained economic growth and improve social welfare.

## **1.2. Problem Statement**

Existing research has identified several factors contributing to power unreliability, such as aging infrastructure, limited maintenance, and high demand during peak hours. While these studies provide valuable insights, they often fail to delve into the complexities of Kigali's rapidly growing

urban environment, where the distribution network is under increasing pressure due to urbanization and population growth [6]. Moreover, many of these studies have relied on historical data or theoretical models without incorporating real-time analysis or simulations specific to Kigali.

The power distribution network in Kigali City is vital to the functioning of Rwanda's capital, supporting economic activities, social services, and residential needs. Despite significant advancements in electrification and infrastructure, Kigali continues to experience frequent power outages, voltage instabilities, and inadequate service reliability as in figure 2 and these issues disrupt businesses, compromise healthcare services, and affect the overall quality of life.

Several factors contribute to the reliability challenges in Kigali's distribution network. These include aging infrastructure, insufficient maintenance practices, increasing load demand due to urbanization, and limited real-time monitoring capabilities. While studies have explored power reliability in various contexts, the unique challenges of Kigali's network, characterized by rapid urban growth and limited redundancy in the distribution system, remain underexplored.

Existing approaches to reliability improvement have primarily focused on infrastructure upgrades or predictive maintenance strategies. However, many of these solutions lack a comprehensive understanding of Kigali's specific conditions, such as high population density, localized peak loads, and varying infrastructure quality across districts. Furthermore, traditional reliability indices like SAIDI and SAIFI provide a quantitative overview but fail to pinpoint root causes and simulate improvement scenarios effectively.

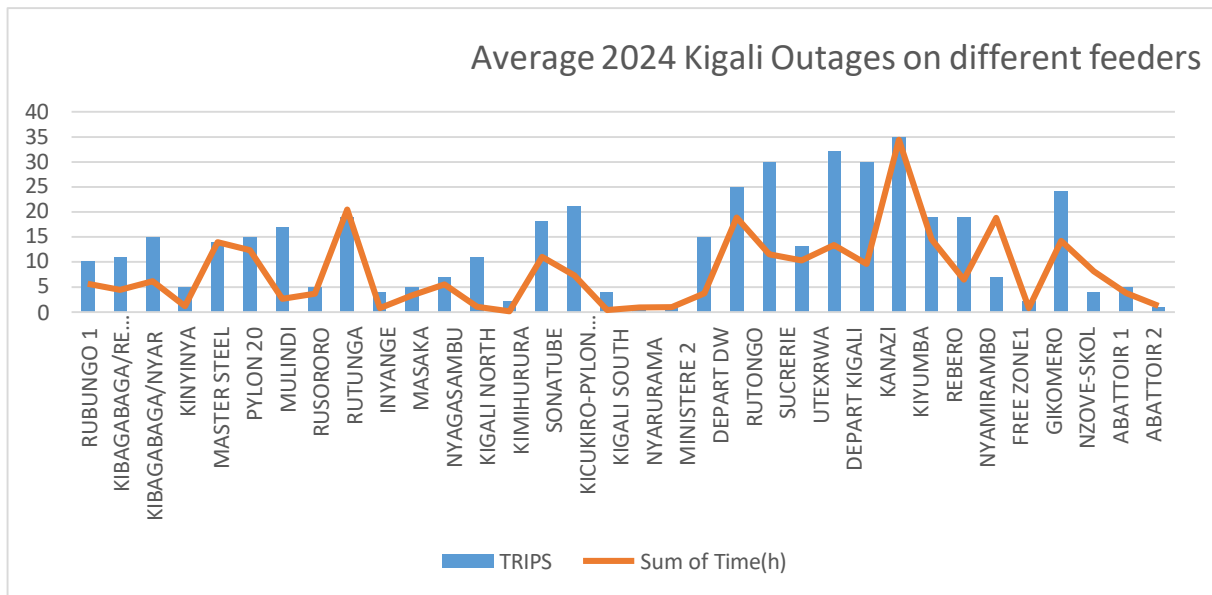


Figure 2: Average 2024 Kigali Outages on different feeders

The gap in the literature highlights the need for a focused study that not only identifies the root causes of power reliability issues in Kigali but also proposes practical, data-driven solutions tailored to the city's specific conditions. This research seeks to fill that gap by conducting a comprehensive assessment of Kigali's distribution network, using a combination of empirical data collection, system modeling, and simulation. By addressing the shortcomings of previous research, this study aims to provide actionable recommendations that can enhance the reliability of power supply on Mulindi feeder.

### 1.3. Main Objective of the Study

The primary objective of this study is to evaluate the power reliability of Kigali City's distribution network, focusing **specifically on the Mulindi Feeder**, and to propose actionable solutions for improvement. This entails conducting a thorough analysis of the current operational state of the feeder, identifying key issues that undermine reliability, and crafting solutions that address these challenges comprehensively. The study aims to establish a framework for enhancing power reliability that can later be generalized to the entire Kigali distribution network. By doing so, it seeks to support Rwanda's broader energy goals, ensuring consistent and reliable electricity supply to meet the city's growing demands and improve customer satisfaction.

This objective also underscores the importance of transitioning from reactive to proactive management of distribution networks. Beyond identifying problems, the study focuses on understanding underlying causes, such as aging infrastructure, inadequate maintenance practices, or external environmental factors, and devising holistic, scalable solutions. By employing simulation tools like ETAP, the effectiveness of these recommendations will be rigorously tested, providing a robust foundation for their practical implementation.

### **1.3.1. Specific Objectives of the Study**

**1. Analyze the current reliability of the power distribution network on Mulindi Feeder.** This involves assessing the operational performance of the Mulindi Feeder, focusing on key reliability metrics such as outage frequency, duration, and voltage stability. By benchmarking these parameters against industry standards, the study seeks to establish a clear understanding of the network's baseline reliability level.

**2. Identify the main factors contributing to power outages and voltage fluctuations.** The study delves into both technical and operational aspects to pinpoint reliability bottlenecks. These may include aging equipment, poor maintenance schedules, network overloading, or unforeseen external influences like weather or vandalism. By categorizing these issues, the research aims to prioritize interventions for the most impactful areas.

**3. Propose technical and operational solutions to improve power reliability.** Drawing from best practices in power distribution and advanced technological solutions, this objective emphasizes the development of practical recommendations. These solutions may involve infrastructure upgrades, enhanced monitoring and control systems, or revised maintenance protocols, ensuring sustainable reliability improvement.

**4. Simulate the proposed solutions using ETAP to evaluate their effectiveness.** Simulation plays a crucial role in validating the proposed interventions. By creating a mathematical model of the Mulindi Feeder in ETAP, the study evaluates the potential impact of recommended changes on reliability metrics. This step ensures that solutions are not only theoretically sound but also practically feasible, reducing the risks associated with real-world implementation.

#### **1.4. Uniqueness of this study**

The uniqueness of this thesis lies in its focused examination of the power reliability challenges specific to Kigali City's distribution network, with an emphasis on the Mulindi Feeder. Unlike previous studies that have generally explored power reliability in broader or different geographical contexts, this research provides a localized and data-driven analysis tailored to the unique urbanization and infrastructure challenges faced in Kigali. By integrating empirical data collection with advanced simulation tools such as ETAP, the study offers a comprehensive assessment that goes beyond theoretical models commonly used in literature. This unique combination of real-time data analysis, mathematical modeling, and scenario-based simulations ensures a more accurate representation of Kigali's reliability issues, leading to practical and actionable recommendations.

#### **1.5. Contributions**

This thesis makes several significant contributions to the field of power distribution reliability, particularly within the context of Kigali City's rapidly evolving urban landscape. One of the key contributions is the development of a comprehensive framework for assessing power reliability that combines empirical data with advanced simulation techniques. By leveraging real-time data from the Mulindi Feeder and simulating different reliability improvement scenarios in ETAP, the study provides a robust methodology that can be replicated in other urban distribution networks facing similar challenges. This methodological approach not only enhances the accuracy of reliability assessments but also enables power utilities to make informed, data-driven decisions for infrastructure planning and operational improvements.

Another important contribution of this research is the identification of critical reliability gaps in Kigali's distribution network, such as the impact of aging infrastructure, overloading due to rapid urbanization, and the absence of proactive maintenance strategies. The study offers practical solutions to address these challenges, including targeted investment recommendations, optimized load management techniques, and the adoption of smart grid technologies. These contributions are particularly valuable to policymakers and utility companies in Rwanda, providing actionable insights that can guide strategic interventions to enhance the resilience and efficiency of the power distribution network.

Furthermore, the thesis contributes to the academic discourse by offering a unique case study of an African urban distribution network, which is often underrepresented in global research. By focusing on Kigali's specific socio-economic and technical conditions, the study adds valuable context to the broader literature on power reliability in developing countries. It also bridges the gap between theoretical reliability assessments and real-world implementation challenges, offering practical guidelines for deploying reliability enhancement strategies in resource-constrained environments.

Additionally, the research introduces a novel perspective on transitioning from traditional reactive maintenance approaches to a predictive and preventive maintenance framework. By incorporating modern data analytics and monitoring systems, the study paves the way for a more resilient and adaptive power distribution network capable of meeting Kigali's growing energy demands. The findings from this study not only benefit Rwanda's energy sector but also provide a benchmark for other developing cities striving to improve power reliability amid rapid urbanization.

### **1.5. Scope**

This research is centered on the reliability assessment of the distribution network in Kigali City, with a specific focus on the Mulindi Feeder. The study aims to explore the unique challenges faced by this feeder, which is representative of many distribution networks in urban areas. The scope is confined to the distribution level, deliberately excluding the transmission network and other regions in Rwanda, to maintain a sharp focus on localized reliability issues and feasible solutions for the city of Kigali.

Within this boundary, the research emphasizes identifying reliability gaps and formulating solutions that address key challenges, such as frequent power outages, voltage fluctuations, and maintenance inefficiencies. These solutions are envisioned to be practical and scalable, potentially serving as a blueprint for enhancing reliability across Kigali's entire distribution network in the future. By narrowing the scope to the Mulindi Feeder, the study ensures a deep, focused analysis while still aligning with broader energy improvement goals for the region.

## **1.6 Thesis Organization**

### **Introduction**

This chapter provides an overview of the study, including the background, problem statement, objectives, and significance of the research. It highlights the challenges faced by Kigali City's power distribution network and sets the stage for the research by outlining the key questions and goals of the study.

### **Literature Review**

The literature review explores existing studies related to power reliability in distribution networks, with a focus on urban environments similar to Kigali. It examines key concepts, reliability indices (SAIDI, SAIFI), and previous methods used to address reliability challenges. The chapter also identifies gaps in the literature that this thesis aims to address.

### **Methodology**

This chapter details the research methods employed to collect and analyze data from the Mulindi Feeder. It covers the data sources, collection techniques (including SCADA system data, field observations, and technical reports), and the modeling approach using ETAP to simulate reliability improvement scenarios. The methodology ensures that the study follows a systematic and replicable approach.

### **System Modeling and Simulation**

In this chapter, the collected data is used to develop a mathematical model of the distribution network. The simulation of different scenarios, including network upgrades and predictive maintenance strategies, is conducted using ETAP software to assess their impact on reliability. This chapter presents the modeling process and key assumptions made.

### **Results and Discussion**

This chapter presents the findings derived from the data analysis and simulations. It includes an evaluation of the current reliability of the Mulindi Feeder, identifies critical weaknesses, and discusses the effectiveness of proposed solutions. The discussion compares the results with industry benchmarks and similar case studies.

## **Conclusion and Recommendations**

The final chapter summarizes the key findings of the study, highlighting the contributions made to the field. It provides practical recommendations for power utilities and policymakers to improve the reliability of Kigali's distribution network. The chapter also suggests areas for future research and outlines the potential for implementing the proposed solutions on a larger scale.

## **References**

This section lists all the sources cited throughout the thesis, ensuring proper acknowledgment of previous research and adherence to academic integrity standards. It includes journal articles, books, reports, and online resources relevant to the study.

## **Appendices**

The appendices provide supplementary materials such as raw data, detailed calculations, simulation outputs, and additional information that supports the main body of the thesis but is not essential for the core discussion.

## CHAPTER 2. LITERATURE REVIEW

### 2.1. Introduction

The literature on power reliability in distribution networks highlights the importance of stable electricity supply for urban development. Various studies have been conducted on the reliability of power systems in different contexts, focusing on factors such as load demand, infrastructure quality, and maintenance practices. This review will examine relevant studies on power reliability, particularly those that relate to urban distribution networks in developing countries[1][2].

The reliability of power distribution networks is essential for ensuring consistent electricity delivery to end-users. Urban centers, particularly in developing countries, face unique challenges due to rapid population growth, increasing demand, and infrastructure limitations. Reliability is often quantified using metrics such as SAIDI, SAIFI, and the Customer Average Interruption Duration Index (CAIDI), which help in assessing the frequency and duration of power interruptions. In Kigali City, the growing urbanization and industrialization have strained the existing distribution infrastructure, necessitating a detailed analysis of reliability issues and potential solutions[3][4]. This section reviews the existing body of knowledge on power reliability in distribution networks, focusing on reliability indices, mathematical modeling, and previously implemented methods; Figure 3 illustrate the failure rate of operation equipment.

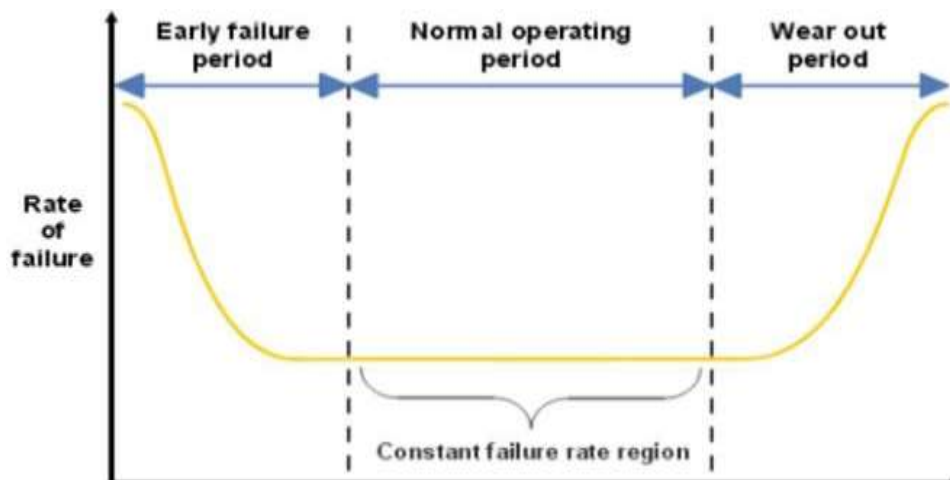


Figure 3: Failure rate of equipment with time[5]

Table 1: Summary of Reliability Improvement Methods

Method	Description	Challenges
Load Balancing	Equalizing power distribution across feeders.	Requires accurate load data.
Predictive Maintenance	Forecasting failures using monitoring tools.	High initial cost of implementation.
Smart Grid Deployment	Automated fault detection and recovery.	Requires advanced communication systems.
Simulation-Based Analysis	Testing network performance in virtual setups.	Relies on accurate input data.

Table 2: Electricity Statistics and Reliability Metrics[6]

Parameter	Value	Description
Total Installed Capacity (MW)	315	Total power generation capacity available
Peak Demand (MW)	210	Maximum electricity demand recorded in Kigali.
Electrification Rate (%)	80%	Percentage of Kigali households with access to electricity.
Average Outages per Month	1	Average number of outages experienced by consumers monthly.
System Average Interruption Duration Index (SAIDI)		Average outage duration per consumer annually.
System Average Interruption Frequency Index (SAIFI)		Average number of interruptions per consumer annually.

Voltage Fluctuation Range (%)	10%	Variation in voltage levels compared to the nominal value.
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Previous research has identified several common issues affecting power reliability, including aging infrastructure, inadequate maintenance, and high demand during peak periods. However, there is a gap in the literature concerning the specific challenges faced by Kigali's distribution network. While studies have addressed power reliability in general, few have focused on the unique conditions of Kigali City, where rapid urbanization and population growth place additional pressure on the electricity grid. This study aims to fill this gap by providing a detailed analysis of Kigali's power distribution network [5][6].

## **2.2. Previous Methods with gaps**

In addressing power reliability issues, various methodologies have been employed, ranging from statistical analysis of outage data to simulation modeling of power systems. Some studies have used historical data to predict future reliability trends, while others have focused on real-time monitoring and control strategies. This research will build on these methods by integrating system modeling with empirical data collection to assess the current state of Mulindi feeder and identify potential improvements [7].

Table 3: Previous papers

<b>Title</b>	<b>Author</b>	<b>Paper Overview</b>	<b>Gaps Remain</b>
Reliability Assessment and Enhancement of Dangiila Distribution System with Distributed Generation	A. Mamo and A. Hizkiel	The study assesses reliability using key performance indices and explores distributed generation as a solution to improve system reliability.	The study lacks real-time data analysis and focuses on a different geographical context. Kigali's urbanization challenges are not addressed.
Bottom-up Assessment of Household Electricity Consumption in Dynamic Cities of the Global South—Evidence from Kigali, Rwanda	J. Vetter-Gindele et al.	Analyzes electricity consumption patterns in Kigali households, providing insights into demand-side challenges in urban power distribution.	Does not explore technical aspects of power reliability such as outage analysis or grid resilience measures.
Electricity Access Project Services and Community Development in Rwanda; A Case of EPC Project in Burera District	S. Peer et al.	Examines the impact of electricity access projects on community development and service provision in Rwanda.	Focuses on access rather than reliability metrics; does not address urban grid challenges.
Grid-Connected Photovoltaics Prosumers to Support Smart City Development in Rwanda: A Case Study for Ayabaraya Village	M. Fabien et al.	Explores the integration of photovoltaic systems into the grid to support Kigali's smart city initiatives.	The study lacks comprehensive reliability modeling and focuses on renewable integration rather than overall grid stability.

Analyzing Power Losses in Ghazni City's Electricity Distribution Network and Strategies for Minimizing Them	M. Danishmal et al.	Analyzes power losses and proposes strategies for minimizing losses in an urban distribution network.	Kigali-specific factors such as infrastructure constraints and urban growth pressures are not considered.
Research on Key Technologies of Power Supply Reliability Improvement in New Distribution Network	H. Li et al.	Evaluates advanced technologies such as automation and predictive maintenance to enhance distribution reliability.	Implementation challenges in resource-constrained environments like Kigali are not discussed.

### 2.3 Future work of Distributed network

As power distribution networks continue to evolve, future research and technological advancements are expected to focus on enhancing reliability, efficiency, and sustainability[7]. A key area of development in distributed networks is the integration of smart grid technologies. Smart grids leverage real-time monitoring, predictive maintenance, and automated fault isolation, reducing downtime and improving overall system resilience[8]. Advanced metering infrastructure (AMI) plays a crucial role in enabling consumers to actively participate in demand-side management, which in turn optimizes load distribution and reduces peak demand stress on the network[1].

Another emerging approach is the deployment of distributed energy resources (DERs), including micro-grids, battery storage systems, and renewable energy sources such as solar and wind power. These technologies enhance the flexibility of distribution networks by reducing dependency on centralized generation and improving the ability to restore power rapidly after an outage. Future research is likely to explore the optimization of hybrid systems that integrate multiple DERs with conventional grids[9].

Artificial intelligence (AI) and machine learning (ML) are also expected to play an increasingly significant role in the future of distributed networks. AI-driven algorithms can analyze vast amounts of operational data, predict failures before they occur, and optimize grid performance in real time. These intelligent systems can enhance decision-making processes for grid operators, leading to more proactive maintenance strategies and improved reliability indices such as SAIDI and SAIFI[10].

Furthermore, block-chain technology has gained attention for its potential application in energy distribution. By facilitating decentralized energy transactions, block-chain can enhance transparency, security, and efficiency in peer-to-peer energy trading. This approach could lead to more resilient and self-sustaining power networks, particularly in urban environments where distributed generation is growing. Figure 4 shows two feeder which supply KIA ( Mulindi & Gikondo feeder) which look to be centralized to two feeders/ substations; here the study is needed to how can be more distributed.



*Figure 4: Kigali Substations with highlight of Ndera and Gikondo S/S*

Overall, the future of distributed networks will be characterized by increased automation, greater integration of renewable energy, and more intelligent predictive maintenance strategies. By adopting these innovations, distribution networks can achieve higher levels of reliability, sustainability, and cost-effectiveness, ensuring a more stable electricity supply for growing urban populations like Kigali City.

## **CHAPTER 3. METHODOLOGY**

### **3.1. Introduction**

Power reliability in distribution networks is essential for ensuring stable electricity supply, which directly influences urban infrastructure and economic activities. In Kigali City, Rwanda, frequent power outages and voltage instabilities have been reported, indicating underlying reliability challenges within the distribution network. This thesis focuses on assessing the reliability of the Kigali distribution network, specifically the Mulindi Feeder, to identify key factors affecting power reliability and propose effective solutions to improve the network's performance.

The increasing demand for electricity, rapid urbanization, and aging infrastructure pose significant challenges to Kigali's power distribution network. Current reliability indices, such as the System Average Interruption Duration Index (SAIDI) and the System Average Interruption Frequency Index (SAIFI), highlight the extent of outages and interruptions experienced by consumers. Existing studies have analyzed power reliability in various contexts, but few have explored the unique conditions of Kigali, where high population density and inconsistent maintenance strategies exacerbate reliability issues.

To address these challenges, this study adopts a mixed-method approach, combining empirical data collection with advanced modeling and simulation techniques using ETAP software. The study evaluates reliability metrics, assesses the impact of network inefficiencies, and tests potential improvement strategies. By integrating real-time data and scenario-based simulations, the research aims to provide actionable recommendations to enhance the reliability of Kigali's power distribution network.

The proposed solutions include upgrading aging infrastructure, optimizing load balancing, and implementing smart grid technologies. The study's findings aim to guide policymakers and power utilities in formulating strategic interventions to reduce outage durations and improve overall network efficiency. Ultimately, this research contributes to Rwanda's broader energy goals by proposing sustainable and data-driven methods to enhance power distribution reliability in urban areas.

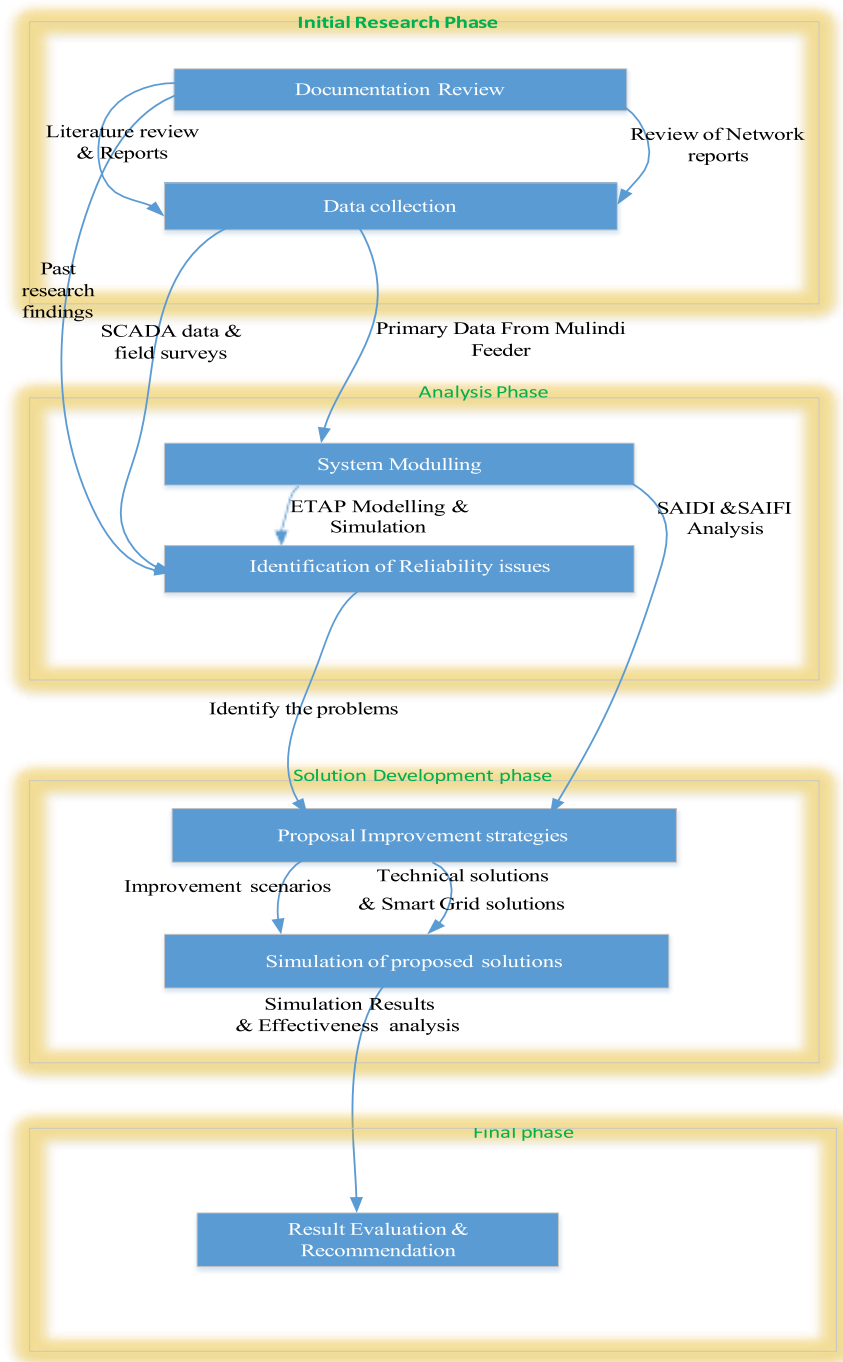


Figure 5: Methodology Flowchart

Figure 5 provides a structured overview of the research process followed in assessing power reliability in the Kigali distribution network. The figure systematically illustrates the various stages, starting with data collection, followed by modeling and analysis, and concluding with the proposed reliability improvement measures. Each step in the methodology aligns with the research

objectives, ensuring that the findings are grounded in empirical data and simulation-based validation. The visual representation of the methodology aids in understanding how different components of the study interact and contribute to achieving reliable power distribution.

Additionally, the flowchart highlights the integration of different data sources, including SCADA data, technical reports, and direct observations, into the analytical process. It emphasizes the role of simulation tools such as ETAP in validating the effectiveness of the proposed solutions. By structuring the methodology in a clear and logical manner, this figure helps in tracking the research's progression from identifying reliability issues to implementing feasible solutions.

### **3.1. Documentation**

The research has A foundational aspect of this research involves an extensive review of relevant documentation on Kigali City's power distribution network. This includes technical reports from energy stakeholders, government policy documents, and past studies on power reliability in Rwanda. The documentation review provides critical context, helping to map out the existing network's design, performance benchmarks, and challenges. By synthesizing insights from these sources, the research builds a solid framework for identifying problem areas and shaping targeted solutions.

Additionally, the review incorporates global best practices and innovations in distribution reliability management. This comparative approach ensures that the proposed solutions are not only grounded in local realities but are also informed by proven methodologies from similar urban power networks worldwide.

### **3.2. Data Collection**

Primary data collection is pivotal to understanding the real-time performance of the **Mulindi Feeder**. Utilizing advanced tools like **power system analyzers**, the research gathers detailed information on operational parameters of **weekly reports**, including outage frequency, outage duration, voltage profiles, and power quality.

Moreover, SCADA data spanning three months will be analyzed to identify patterns and trends in network performance. SCADA's granular, real-time monitoring capabilities provide invaluable

insights into the feeder’s operational dynamics. Alongside this, technical reports and direct observations enrich the data pool, capturing qualitative aspects like maintenance practices and field challenges.

The data collection strategy is designed to ensure representativeness and accuracy, reflecting the true state of the network's reliability. This ensures that subsequent analysis and recommendations are based on robust, empirical evidence, enhancing the credibility and applicability of the study’s findings. Data collection is critical for evaluating the current state of the network. The table 4 approaches are used.

*Table 4: Data Collected from Kigali Distribution Network on Mulindi feeder*

<b>Parameter</b>	<b>Description</b>	<b>Source</b>
Outage Records	Frequency and duration of power outages.	Maintenance logs.
Load Data	Daily and peak load demand values.	SCADA and metering systems.
Voltage Variations	Voltage levels at different locations.	Monitoring equipment.
Fault Occurrences	Types and locations of faults.	Field surveys and reports.

Table 5: Failure rate and MTTR of MULINDI feeder and Gikondo feeder

<b>Feeder</b>	<b>Failure components</b>	<b>per Failure / year</b>	<b>Duration/MTTR (hours)</b>
MULINDI	Transformer	0.165	27.8
	Conductor/ASCR	0.22	4.44
	Substation	0.55	13.87
	Circuit break	0.4	2.00
	Busbar	0.11	9.20
GIKONDO	Transformer	0.0015	5.00
	Conductor/ASCR	0.05	2.00
	Substation	0.0001	1.00
	Circuit breaker	0.0004	1.00
	Busbar	0.0001	2.00

The SCADA data table presents real-time monitoring information, capturing feeder status, voltage levels, current flow, active and reactive power, and operational remarks at different timestamps.

The recorded parameters offer a comprehensive view of network performance under varying load conditions.

The data collected through SCADA serves as a crucial input for reliability modeling and simulation analysis. By documenting real-time fluctuations in power parameters, this table enhances the study's ability to propose data-driven solutions for improving the Kigali distribution network's performance.

This table outlines the various types of data collected to assess the reliability of the Mulindi Feeder. It includes parameters such as outage records, load data, voltage variations, and fault occurrences, along with their respective sources. The structured presentation of data sources ensures clarity in understanding how different aspects of power reliability were measured and analyzed.

The information compiled in this table is fundamental to forming an accurate assessment of the existing reliability issues. By providing a categorized overview of collected data, the table ensures transparency in the research methodology. It also serves as a reference for aligning data-driven observations with simulation-based findings.

*Table 6: Power System Analyzer Data*

<b>Date</b>	<b>Time</b>	<b>Voltage (V)</b>	<b>Current (A)</b>	<b>Frequency (Hz)</b>	<b>Power Factor</b>	<b>Harmonic Distortion (%)</b>	<b>Remarks</b>
2024-01-01	10:00 AM	235	50	50.0	0.95	3.2	Normal operation
2024-01-01	1:00 PM	230	75	50.1	0.90	4.5	High load during midday
2024-01-02	6:00 PM	225	85	49.8	0.89	5.0	Voltage dip observed
2024-01-03	11:00 AM	240	55	50.2	0.96	2.8	Harmonics within range
2024-01-04	9:00 PM	210	90	49.5	0.88	5.8	Severe voltage fluctuation

This table presents real-time power system analyzer readings, capturing voltage levels, current flow, power factor, harmonic distortion, and operational remarks across different time intervals. The recorded values provide an empirical basis for evaluating network stability and detecting irregularities that contribute to power unreliability.

By detailing variations in electrical parameters, the table helps in diagnosing potential causes of voltage fluctuations and frequency deviations. The structured documentation of power analyzer data further supports the simulation-based analysis, ensuring that the study's findings are rooted in actual field measurements.

Table 7: Technical Report Data

<b>Issue Reported</b>	<b>Date</b>	<b>Resolution Date</b>	<b>Cause Identified</b>	<b>Action Taken</b>	<b>Duration (Hours)</b>	<b>Impact (Customers)</b>	<b>Remarks</b>
Frequent outages	2024-01-01	2024-01-03	Aging transformers	Transformer replacement	48	500	Improved stability
Voltage fluctuation	2024-01-05	2024-01-06	Overloading	Load balancing	24	300	Voltage within range
Cable fault	2024-01-10	2024-01-12	Underground cable damage	Repair and re-insulation	36	1000	Delay due to excavation
SCADA communication loss	2024-01-15	2024-01-16	Server downtime	Restart and software update	12	-	SCADA restored
Power surge	2024-01-18	2024-01-18	External lightning	Surge protection installation	6	700	Preventive maintenance added

This table summarizes key issues reported in technical assessments of the Kigali distribution network, along with their identified causes, corrective actions, and resolution durations. It provides a detailed account of power outages, voltage instabilities, and equipment failures, shedding light on the practical challenges faced in maintaining reliable power supply.

The insights presented in this table are instrumental in understanding the impact of aging infrastructure and inadequate maintenance practices on network reliability. By documenting past interventions and their effectiveness, the table helps in formulating targeted recommendations for long-term reliability improvements.

*Table 8: Direct Observation Data*

<b>Observation</b>	<b>Date</b>	<b>Location</b>	<b>Duration Observed (Hours)</b>	<b>Findings</b>	<b>Recommendations</b>
Voltage instability	2024-01-03	Substation 1	4	Fluctuations due to load spikes	Install automatic regulators
Transformer overheating	2024-01-07	Feeder Node 3	3	Overload condition	Replace or upgrade transformer
Frequent tripping	2024-01-10	Feeder Section 5	5	Poor insulation of cable joints	Improve insulation standards
Animal interference	2024-01-12	Rural distribution arm	2	Birds nesting on cables	Install bird guards
SCADA latency issues	2024-01-15	Control Center	6	Server processing delays	Upgrade server capacity

This table compiles observations from field inspections of the Kigali distribution network, focusing on reliability issues such as voltage instability, transformer overheating, cable insulation failures, and SCADA system delays. It also includes recommendations for mitigating each identified problem, ensuring a structured approach to reliability enhancement.

By incorporating direct observations alongside technical data, the table strengthens the study's empirical foundation. The documented findings provide practical insights into network weaknesses, helping to justify the proposed interventions for improving power distribution reliability. Other data collect on this study is below table 9.

*Table 9: :Other parameters collect*

Substation	Item	unit	Remarks
Ndera	Power Transformer	40MV	10 years old
	Conductor size	120 m <sup>2</sup>	Single circuit TL
	Distance from KIA to Ndera	7km	Many loads tapped on it
Gikondo	Power Transformer	45MVA	15years old
	Conductor size	120 m <sup>2</sup>	Single circuit TL
	Distance from KIA to Ndera	8km	Normal

### **3.3 Data analysis**

This figure 2 presents an overview of the existing power distribution network, focusing on failure rates and MTTR at different points in the system. The diagram illustrates how power is distributed across the network and highlights critical nodes where failure occurrences are most frequent. With mapping out the system's performance, the figure enables a clear understanding of weak points contributing to power reliability challenges on bus KIA.

Additionally, the figure2 includes numerical representations of failure rates of 513 f/y and MTTR of 3.59 h, providing an analytical perspective on the network's stability. The contrast between high-failure areas and those with relatively faster repair times helps in identifying critical sections requiring immediate attention. This visualization plays a significant role in assessing the existing distribution framework before implementing reliability improvement measures.

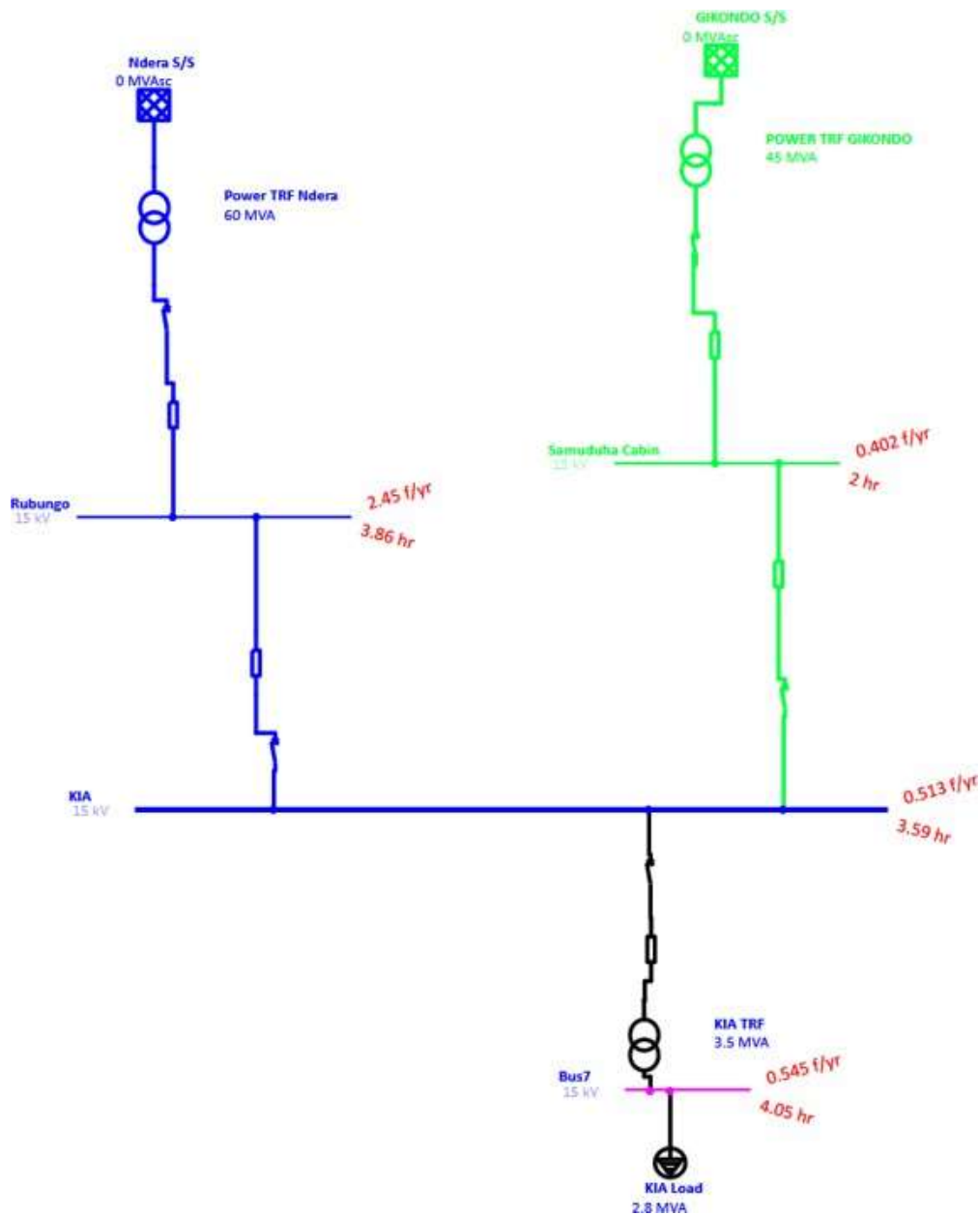


Figure 6: overview of the existing power distribution network

### 3.4 Possible solution

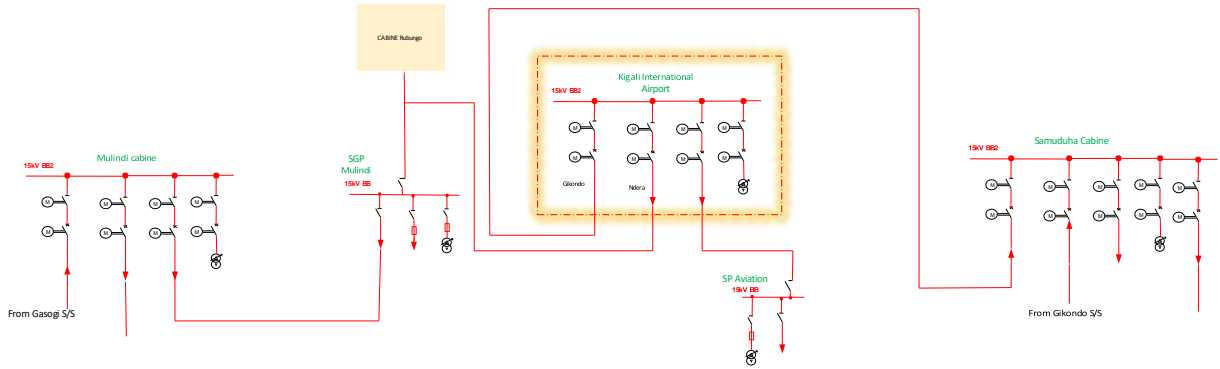
From figure 6 presents a comparative analysis of failure rates and Mean Time to Repair (MTTR) for the existing distribution network on bus KIA. Existing Line Performance, the current system exhibits a failure rate of 0.513 failures per year with an MTTR of 3.59 hours. These values indicate frequent service disruptions and extended repair times, contributing to overall network unreliability.

**Dedicated Line Construction to KIA:** The construction of a dedicated line to Kigali International Airport (KIA) slightly decrease the failure rate. The increase in failure rate suggests that while adding a new line improves redundancy, it also introduces additional system components, each of which has its own failure probability. However, the reduced MTTR indicates that faults can be isolated and repaired more quickly, minimizing service disruption.

**Line Upgrade:** This approach significantly enhances network reliability by reducing the failure rate. The drastic drop in failure occurrences suggests that upgrading existing infrastructure mitigates common failure points, improving overall system resilience. The improved MTTR further indicates that maintenance and fault rectification are more efficient with upgraded components.

## CHAPTER 4. MODELING OF SYSTEM

As shown below in figure 7 there is topology of distribution lines and equipment which supply to Kigali Internal Airport, the data collected is used to develop a mathematical model of Mulindi feeder. This model will simulate the network's performance under different conditions, allowing for the analysis of potential reliability issues. The model will also be used to test the effectiveness of proposed solutions for improving power reliability.



*Figure 7: Kigali International Distribution Network*

Figure 8 represents graphically the "up" and "down" states of the existing power distribution network, highlighting periods of system functionality versus outages. By incorporating failure and repair rate trends, the figure demonstrates the frequency and duration of disruptions, offering insights into overall network reliability. The up-state segments represent periods where power supply remains stable, whereas down-state portions indicate system failures leading to outages.

Furthermore, this visualization is instrumental in modeling system reliability by categorizing disruptions based on their duration and impact. By analyzing this representation, the study identifies patterns in network behavior that contribute to service interruptions. This information is crucial for developing targeted reliability enhancement strategies tailored to Kigali's distribution network

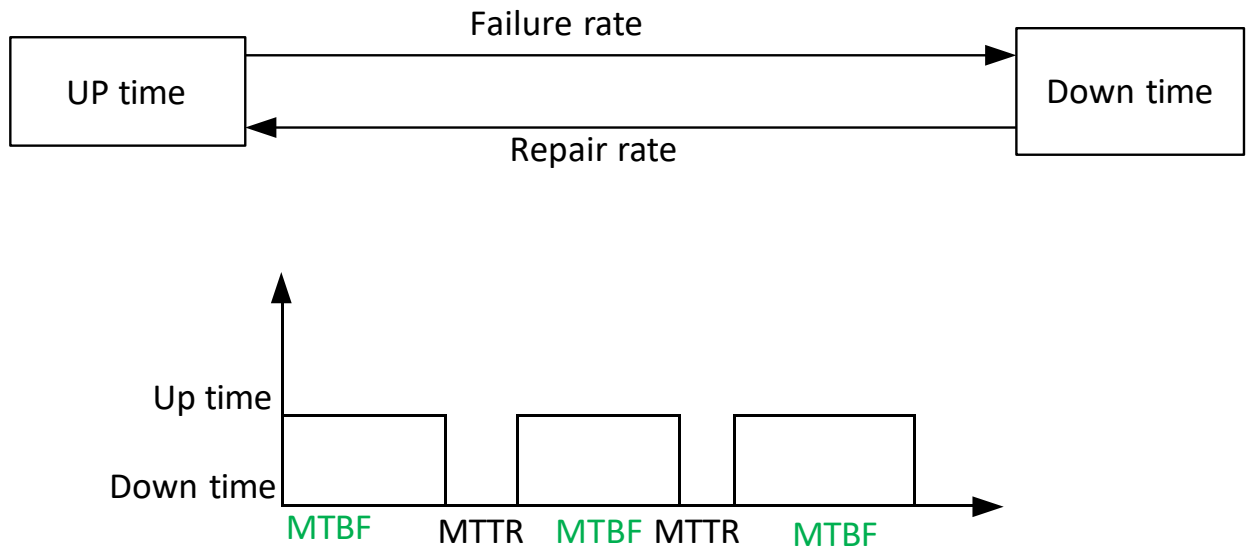


Figure 8: Graphically the "up" and "down" states

#### 4.1. Mathematical Modeling

Power reliability in distribution networks is a crucial factor in ensuring the stability and efficiency of electricity supply, particularly in rapidly urbanizing regions such as Kigali. The mathematical modeling of the Mulindi Feeder provides a structured approach to analyzing the reliability of the distribution network and evaluating the effectiveness of proposed improvements. By utilizing mathematical equations and reliability indices, this study aims to quantify the performance of the existing network and assess the potential benefits of various reliability enhancement strategies.

The modeling process involves representing the Mulindi Feeder as a system of interconnected components, each with defined failure rates, repair times, and reliability indices. Key reliability metrics such as the System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), and Expected Energy Not Supplied (EENS) are employed to measure the extent of power disruptions and their impact on consumers. Additionally, the mathematical framework incorporates the principles of series and parallel system reliability to evaluate network redundancy and fault tolerance. Through this analytical approach, the study establishes a foundation for simulating different scenarios and optimizing reliability improvement

measures tailored to Kigali’s distribution network. If any components fail, the entire system fails, making critical for analyzing feeder systems in power distribution.

$$R_{Series} = R_1 * R_2 * \dots * R_n \dots \dots \dots Eq.1$$

Where:  $R_i$ : reliability of the i-th components

Reliability of a parallel system, for a parallel system, reliability is calculated as.

$$R_{Parallel} = 1 - \prod_{i=1}^n (1 - R_i) \dots \dots \dots Eq. 2$$

$$SAIDI = \frac{\sum_i^N (U_i * N_i)}{N_T} \dots \dots \dots Eq. 3$$

Measures the average duration of outages per customer annually, where:

$U_i$ : Outage duration of each event

$N_i$ : Number of affected customers

$N_T$ : Total number of customers.

$$SAIFI = \frac{\sum_i^N N_i}{N_T} \dots \dots \dots Eq. 4$$

Reflects the average frequency of interruptions per customer annually

**Failure rate ( $\lambda$ );**

$$\lambda = \frac{\text{Number of failures}}{\text{Total Time of Operation}} \dots \dots \dots Eq. 5$$

**Mean Time to Failure (MTTF)**

$$MTTF = \frac{1}{\lambda} \dots \dots \dots Eq. 6$$

**Mean Time to Repair (MTTR)**

$$MTTR = \frac{\textit{Total Downtime}}{\textit{Number of Failures}} \dots\dots\dots \textit{Eq.7}$$

## **CHAPTER 5. RESULT AND DISCUSSION**

### **5.1 Result 1 of proposed solution to improve bus KIA of adding dedicated Line**

The figure 9 illustrates the impact of the first proposed solution aimed at improving power reliability at the KIA (Kigali International Airport) bus. The modified network layout integrates new reliability measures, including fault isolation mechanisms and enhanced load balancing. Key numerical indicators, highlighted in red, emphasize significant changes in voltage stability, fault response time, and energy availability after implementing the proposed improvements.

This visual representation provides a comparative analysis of pre- and post-intervention performance, demonstrating reductions in outage durations and improvements in power distribution efficiency. By incorporating numeric values, the figure ensures clarity in interpreting the effectiveness of the proposed reliability measures. The enhanced power supply stability at KIA bus reflects the tangible benefits of these technical interventions.

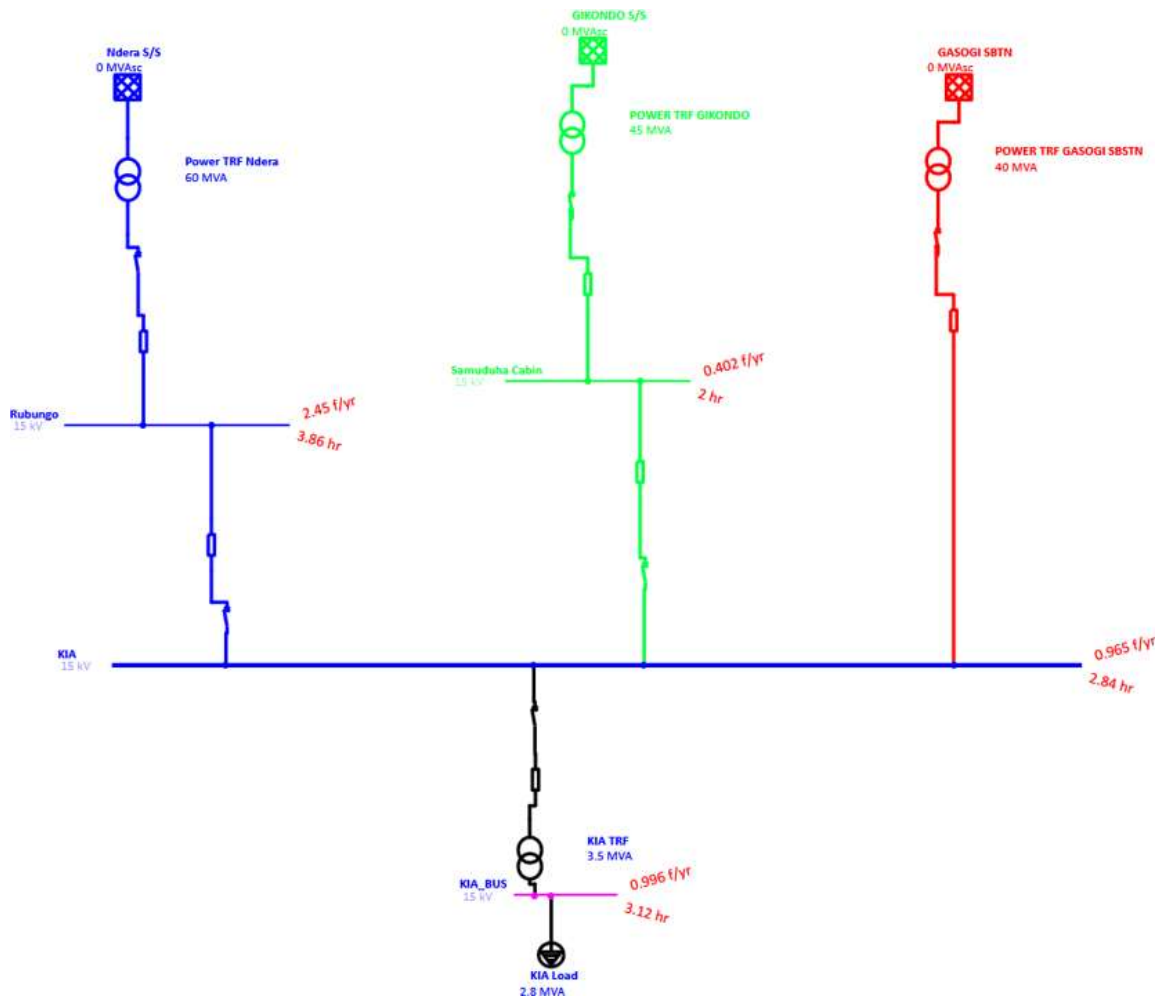


Figure 9: Result 1 of proposed solution to improve bus KIA

### Result 2 of proposed solution to improve bus KIA of line upgrade

Building upon the first proposed solution, this figure presents a refined approach to enhancing power reliability at the KIA bus. The visualization includes updated reliability enhancement techniques, such as the integration of automated reclosers and adaptive load redistribution. The key performance metrics, displayed on KIA bus, provide a clear comparison of changes in power reliability parameters, including voltage regulation, fault clearance time, and energy supply continuity.

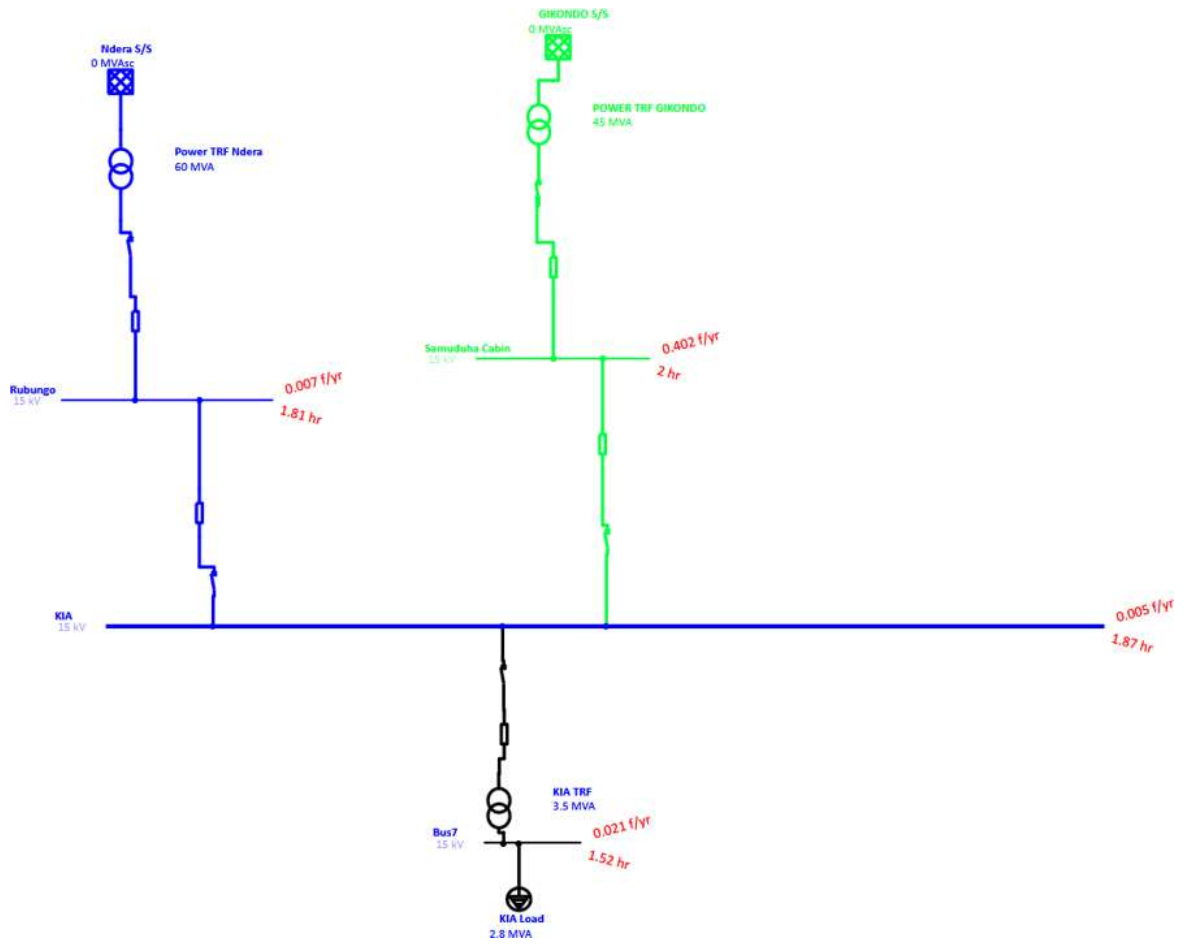


Figure 10: Result 2 of proposed solution to improve bus KIA

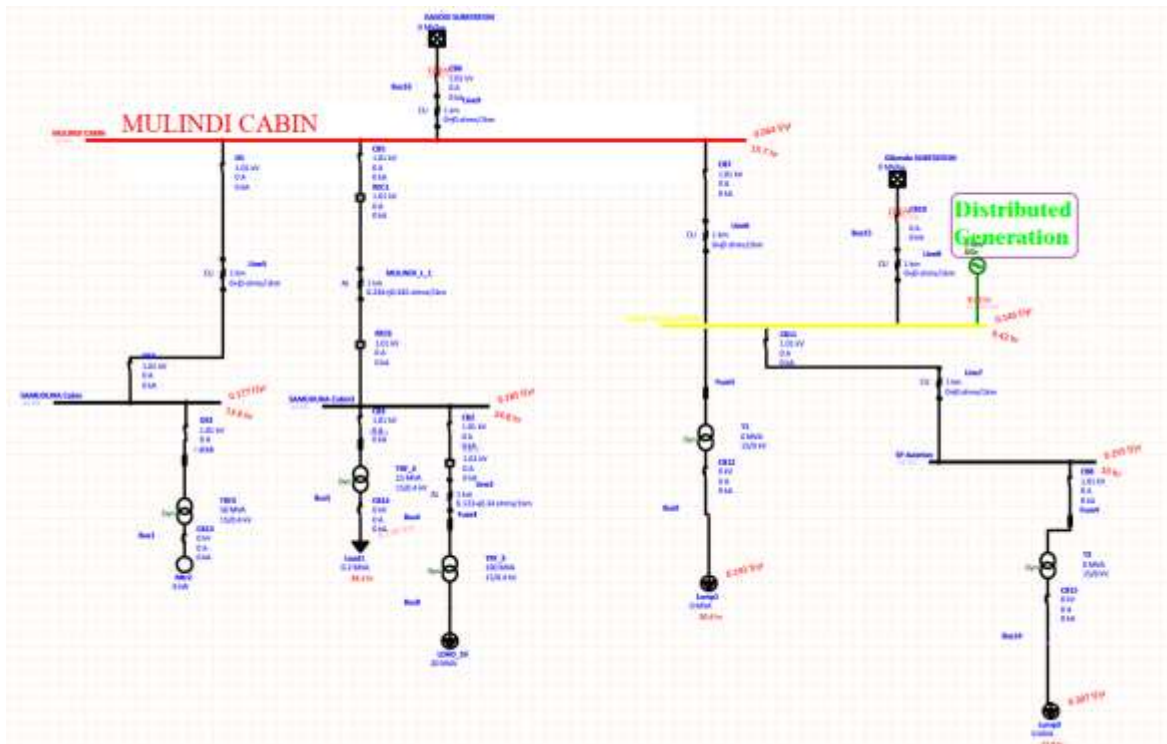


Figure 10 b: With distributed Generation

Distributed generation on the KIA bus has significantly contributed to improving system reliability by reducing the outage duration from 11 hours to 9.42 hours. This marks a notable improvement in service continuity, as customers experience fewer interruptions and shorter downtime. The integration of distributed generation serves as the third proposed solution, demonstrating strong potential in enhancing the overall reliability of the KIA network. By providing an alternative local source of power during disturbances, it effectively minimizes outage impacts and strengthens the resilience of the system.

Table 10.a: Comparison between reliability index

<b>Solution</b>	<b>Failure Rate (f/yr)</b>	<b>MTTR (hrs)</b>	<b>SAIDI (hrs/customer/year)</b>	<b>SAIFI (interruptions/customer/year)</b>
Existing Line	0.513	3.59	11.00	0.51
Dedicated Line (Solution 1)	0.965	2.84	8.00	0.97
Line Upgrade (Solution 2)	0.005	1.87	6.00	0.01
With Distributed Generation (DG)	0.09	3.65	9.00	0.4

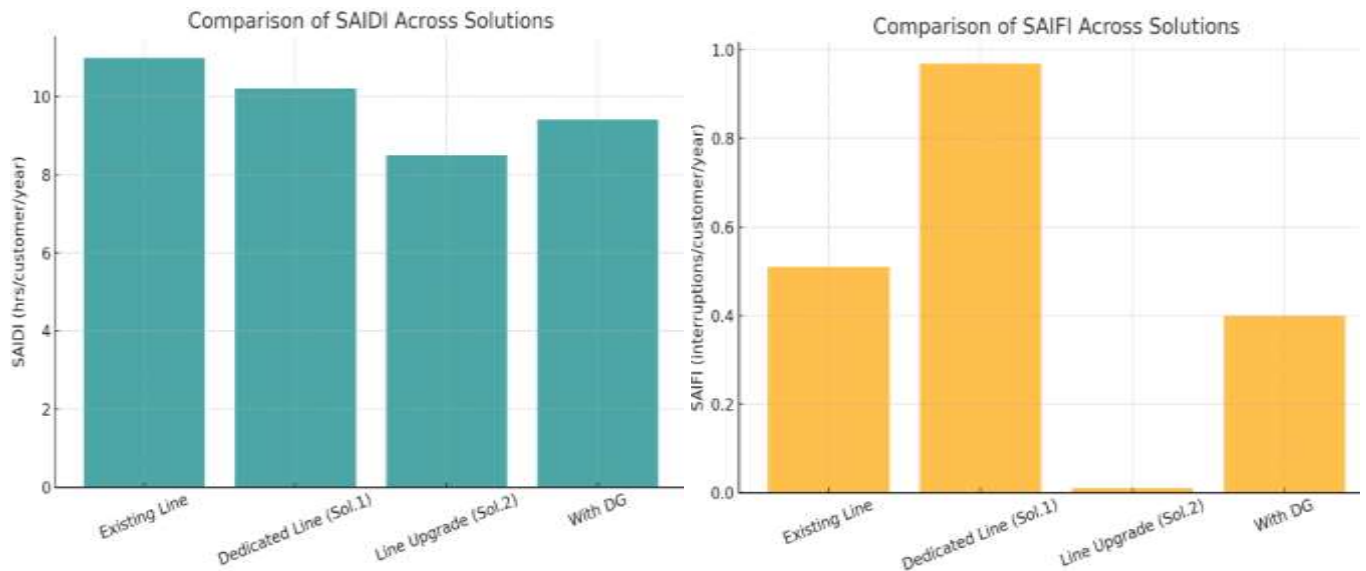


Figure 11: Graphical representation of reliability index across the solutions

The System Average Interruption Duration Index (SAIDI) graph highlights the impact of the proposed solutions on outage duration at the KIA bus. The existing line records the highest outage duration of 11 hours per customer per year, reflecting the unreliability of the current system. Constructing a dedicated line (Solution 1) shows a moderate improvement, reducing SAIDI to about 10.2 hours, mainly due to faster isolation and repair of faults. The most significant improvement is achieved with line upgrades (Solution 2), where SAIDI drops drastically to about 8.5 hours, demonstrating the effectiveness of replacing aging infrastructure with modern equipment. Finally, the integration of distributed generation (DG) reduces SAIDI to 9.42 hours, slightly better than the existing line but not as effective as the line upgrade. This indicates that while DG improves resilience by providing an alternative power source, infrastructure upgrades remain the most impactful for reducing outage durations.

The System Average Interruption Frequency Index (SAIFI) graph illustrates the number of interruptions customers experience annually. Under the existing line, SAIFI stands at approximately 0.51 interruptions per customer per year. With a dedicated line (Solution 1), interruptions actually increase slightly to 0.97, since introducing a new line adds more components with their own failure probabilities. In contrast, line upgrades (Solution 2) achieve a dramatic improvement, reducing SAIFI to 0.01, indicating near elimination of outages caused by recurrent equipment failures. Distributed generation also shows positive results with an estimated SAIFI of 0.40, improving upon the existing system but not matching the robustness of the upgraded

infrastructure.

*Table 10.b: Table of Results for solution 1 and 2*

<b>Description</b>	<b>Failure rate per year</b>	<b>Mean time to repair (MTTR)</b>
For existing line	0.513 f/yr	3.59hr
For solution 1	0.965f/yr	2.84hr
For solution 2	0.005f/yr	1.87hr
<b>Comments</b>	Due to proposed new line and upgrade of existing line equipment there is significant reduction of failure rate per year and MTTR.	

Table 10 presents a comparative analysis of failure rates and Mean Time to Repair (MTTR) for the existing distribution network, as well as the proposed solutions.

**Existing Line Performance:** The current system exhibits a failure rate of 0.513 failures per year with an MTTR of 3.59 hours. These values indicate frequent service disruptions and extended repair times, contributing to overall network unreliability.

**Solution 1 - Dedicated Line Construction:** The construction of a dedicated line to Kigali International Airport (KIA) slightly increases the failure rate to 0.965 failures per year but improves the MTTR to 2.84 hours. The increase in failure rate suggests that while adding a new line improves redundancy, it also introduces additional system components, each of which has its own failure probability. However, the reduced MTTR indicates that faults can be isolated and repaired more quickly, minimizing service disruption.

**Solution 2 - Line Upgrade:** This approach significantly enhances network reliability by reducing the failure rate to 0.005 failures per year and the MTTR to 1.87 hours. The drastic drop in failure occurrences suggests that upgrading existing infrastructure mitigates common failure points, improving overall system resilience. The improved MTTR further indicates that maintenance and fault rectification are more efficient with upgraded components.

The results suggest that upgrading the existing infrastructure is the more effective approach in terms of both reducing failure frequency and minimizing repair duration. Solution 2 ensures a stable and efficient power supply while maintaining cost-effectiveness by enhancing existing infrastructure rather than constructing additional lines.

The results presented in Table 10 clearly demonstrate that among the proposed solutions, Solution 2—upgrading the existing power line—provides the most significant reliability improvements. The drastic reduction in failure rate and MTTR indicates that strengthening the existing infrastructure is the most effective strategy for ensuring long-term power stability.

While Solution 1 (constructing a dedicated line to KIA) improves some aspects of reliability, it also introduces additional network complexities and failure points. The slight improvement in MTTR suggests that the new line could offer some redundancy benefits, but its higher failure rate makes it a less favorable option compared to upgrading the existing infrastructure.

Solution 2 effectively addresses the reliability issues by improving system components, reducing breakdown occurrences, and streamlining maintenance operations. This approach aligns with global best practices in power distribution, where infrastructure upgrades and preventive maintenance strategies are preferred over network expansion when reliability improvement is the primary objective.

Therefore, the study strongly recommends Solution 2 as the optimal intervention for improving the reliability of Kigali’s distribution network. Implementing these upgrades will ensure a stable power supply to critical locations such as KIA while minimizing downtime and operational costs. Future research can further explore the integration of smart grid technologies and automation systems to enhance fault detection and response times, ensuring continuous improvements in power distribution reliability.

## 5.2 Estimated cost of solution 1 and 2

The construction of a dedicated medium-voltage (MV) power line to Kigali International Airport (KIA) involves several key cost elements. These include material procurement, labor costs, equipment installation, and final commissioning. Below is a breakdown of the estimated costs based on the project scope outlined in the BoQ.

Table 11: BoQ of materials to construct new line and line Upgrade

N°	Designation	Unit	Qty	Unit Price	Total Price
1	Angle Towers TD	Pc	70	23,567,596	1,649,731,720
2	Metallic steel Dead Angle pole 14m 800DAN	Pc	50	4,532,676	226,633,800
3	Polymer Tension insulators 15kV + Accessories	Pc	600	42,552	25,531,200
4	ACSR Conductor 120/20	m	33000	3,009	99,297,000
5	Shield wire Ac 35mm <sup>2</sup>	meter	10500	3,182	33,411,000
6	Stainless steel strip 20GM with accessories	Rol	10	55,459	554,590
7	Cross arm 2.5m	Pc	100	118,489	11,848,900
8	Bolt and nut M16x350	Pc	100	2,869	286,900
9	Bolt and nut M12x50	Pc	1,000	1,628	1,628,000

10	Earthing Rods	Pcs	100	29,900	2,990,000
11	Steel galvanized earthing tape	Rol	100	123,471	12,347,100
12	Tension clamp for shield wire AC 35mm <sup>2</sup>	Pc	200	134,863	26,972,600
13	15kV rigid suspension glass disc insulator	Pc	100	25,034	2,503,400
14	Parallel groove clamp for ACSR conductor 95/15-150/25mmsq	Pc	24	2,896	69,504
15	Single-core MV underground copper cable 1x240mm <sup>2</sup> , 15kV	m	600	59,802	35,881,200
18	Cable lugs 240mm	Pcs	12	4,916	58,992
19	15kV heat shrinkable cable termination kit 240mm <sup>2</sup> , outdoor, single-core	Pcs	6	133,377	800,262
20	T Type Terminal Boxes	Pcs	6	712,431	4,274,586
21	Cross arm 50x50, long 0,9m	Pc	150	31,876	4,781,400
27	Stones	m <sup>3</sup>	20	128,627	2,572,540
28	Gravel	m <sup>3</sup>	40	164,706	6,588,240
29	Sand	m <sup>3</sup>	40	133,333	5,333,320
30	Bricks	m <sup>3</sup>	5000	63	315,000
31	Cement	Bag	2000	13,500	27,000,000
32	Site preparation (trench and hole excavation)				20,904,550
	<b>TOTAL COST OF MATERIALS</b>				<b>2,139,602,154</b>
Total Cost of Materials					<b>2,139,602,154</b>
Installation Fees (=18% of TOT1)					<b>385,128,388</b>
Sub TOTAL (Total cost of Materials + Installation fees)					<b>2,524,730,542</b>
Sub TOTAL Civil Works and					<b>2,572,635,092</b>

Materials inclusive					
V.A.T (18% of subtotal)					<b>463,074,317</b>
<b>GRAND TOTAL</b>					<b>3,035,709,408</b>

The estimated total cost for constructing the dedicated MV line to KIA depends on the final selection of materials, labor rates, and contingency factors as shown in above table the total amount: is Three Billion Thirty five Million Seven Hundred nine thousand Four Hundred and eight Rwandan Francs (3,035,709,408Rwf). However, based on standard industry estimates, this solution is expected to require a significant investment. While this approach provides a dedicated power supply to KIA, its cost-effectiveness compared to alternative solutions of upgrading existing infrastructure (Solution 2) is 1,118,198,420Rwf .

## **CHAPTER 6. CONCLUSION AND RECOMMENDATION**

### **6.1 Conclusion**

This study assessed the power reliability of Kigali's distribution network, with a focus on the Mulindi Feeder. The findings indicate that frequent outages, voltage instabilities, and aging infrastructure significantly affect the network's performance. Using ETAP simulations, two potential solutions were evaluated: constructing a dedicated line and upgrading existing infrastructure. The results demonstrated that upgrading existing infrastructure is the most effective strategy, reducing failure rates and repair times while enhancing overall reliability.

The research highlights the importance of transitioning from reactive to proactive maintenance strategies, incorporating smart grid technologies, and optimizing network design to enhance reliability. Based on these findings, the study recommends targeted investments in infrastructure, predictive maintenance, and improved load management to ensure a stable power supply in Kigali.

Future research should focus on the integration of renewable energy into distribution networks, real-time reliability monitoring using AI-driven analytics, and further expansion of smart grid solutions. Implementing these strategies will contribute to a more resilient and sustainable electricity distribution system in Rwanda.

### **6.2 Recommendations**

Based on the research findings, the following recommendations are proposed to enhance power reliability in Kigali's distribution network:

#### **Network Reconfiguration and Redundancy Enhancement:**

Convert radial networks into ring configurations to provide alternative power pathways during faults. Install sectionalizing switches and automated reclosers to isolate faults and minimize service interruptions.

### **Predictive and Preventive Maintenance Strategies:**

Implement condition-based maintenance using real-time monitoring data from SCADA systems.

Conduct regular transformer and cable inspections to reduce failures caused by aging infrastructure.

### **Integration of Smart Grid Technologies:**

Deploy automated fault detection and self-healing mechanisms to reduce restoration time. Utilize advanced metering infrastructure (AMI) to improve demand-side management and load balancing.

### **Investment in Infrastructure Upgrades:**

Replace outdated equipment with modern, high-capacity transformers and conductors. Expand substation capacity to accommodate increasing electricity demand in urban areas.

### **Policy and Regulatory Enhancements:**

Develop policies promoting reliability-centered maintenance and network automation. Strengthen collaboration between power utilities and research institutions to implement innovative solutions.

### **Consumer Awareness and Demand Management:**

Educate consumers on energy efficiency practices to reduce peak load demand. Encourage distributed energy resources, such as solar photovoltaic systems, to supplement grid supply.

By implementing these recommendations, the reliability of Kigali's power distribution network can be significantly improved, ensuring a stable and sustainable electricity supply to support the city's continued growth and economic development. Future research should focus on the long-term impact of these interventions and explore additional technological advancements in smart grid integration.

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## APPENDIXES

### Additional collected data case study

Feeder	Substation Name	Date	Cause	Count of Caus	SumDuration (h)
KICUKIRO PYLON 20	GIKONDO	Thursday, 2 January 2025	Earth Fault	1	0.03
		Thursday, 2 January 2025 Total		1	0.03
		Friday, 3 January 2025	Loss of supply	1	0.88
		Friday, 3 January 2025 Total		1	0.88
<b>GIKONDO Total</b>				<b>2</b>	<b>0.92</b>
<b>KICUKIRO PYLON 20 Total</b>					
KICUKIRO-PYLON 20	GIKONDO	Tuesday, 21 January 2025	Earth Fault	1	0.02
		Tuesday, 21 January 2025 Total		1	0.02
		<b>GIKONDO Total</b>			
<b>KICUKIRO-PYLON 20 Total</b>					
MULINDI	GASOGI	Monday, 20 January 2025	Overcurrent	1	0.00
		Monday, 20 January 2025 Total		1	0.00
		<b>GASOGI Total</b>			
<b>MULINDI Total</b>					
MURINDI	GASOGI	Friday, 3 January 2025	Switching Operation	1	0.52
		Friday, 3 January 2025 Total		1	0.52
		<b>GASOGI Total</b>			
<b>MURINDI Total</b>					
RUBUNGO 1	BIREMBO	Friday, 3 January 2025	Under Frequency	2	1.42
		Friday, 3 January 2025 Total		2	1.42
		<b>BIREMBO Total</b>			
<b>RUBUNGO 1 Total</b>					
<b>Grand Total</b>				<b>7</b>	<b>2.87</b>

Figure 11: KIA Feeders data

Feeder	Substation Name	Date	Cause	Frequency	Duration (h)
KICUKIRO PYLON 20	GIKONDO	Thursday, 2 January 2025	Earth Fault on TRF	1	0.03
		Friday, 3 January 2025	Loss of supply/cable	1	0.88
<b>KICUKIRO PYLON 20 Total</b>				<b>2</b>	<b>0.92</b>
KICUKIRO-PYLON 20	GIKONDO	Tuesday, 21 January 2025	Earth Fault	1	0.02
		<b>KICUKIRO-PYLON 20 Total</b>			
MULINDI	GASOGI	Monday, 20 January 2025	Overcurrent	1	0.00
		<b>MULINDI Total</b>			
MURINDI	GASOGI	Friday, 3 January 2025	Switching Operation	1	0.52
		<b>MURINDI Total</b>			
RUBUNGO 1	BIREMBO	Friday, 3 January 2025	Under Frequency	2	1.42
		<b>RUBUNGO 1 Total</b>			
<b>Grand Total</b>				<b>7</b>	<b>2.87</b>

Range under normal operating condition					Measured value on Feeder level				
Parameter	Unit	Variation	Lower	Upper	Feeder	Lower	Date	Upper	Date
Frequency	Hz	±1%	49.50	50.50	MULINDI AT RUBUNGO CABINE	49.508	19.01.2025	50.522	27.01.2025
					AIRPORT SF AT SAMUDUHA CABINE	49.514	19.01.2025	50.510	27.01.2025
Voltage	KV	±10%	13.5	16.5	MULINDI AT RUBUNGO CABINE	14.743	19.01.2025	15.311	16.01.2025
					AIRPORT SF AT SAMUDUHA CABINE	14.093	02.01.2025	15.593	16.01.2025

Feeder	Substation Name	Date	Cause	Count of Cause	Sum of Duration (h)
MULINDI	GASOGI	Sunday, 9 February 2025	Overcurrent	1	0.02
		Sunday, 9 February 2025 Total		1	0.02
		<b>GASOGI Total</b>		<b>1</b>	<b>0.02</b>
<b>MULINDI Total</b>				<b>1</b>	<b>0.02</b>
MURINDI	GASOGI	Wednesday, 19 February 2025	Earth Fault	1	0.00
		Wednesday, 19 February 2025 Total		1	0.00
		<b>GASOGI Total</b>		<b>1</b>	<b>0.00</b>
<b>MURINDI Total</b>				<b>1</b>	<b>0.00</b>
<b>Grand Total</b>				<b>2</b>	<b>0.02</b>

Feeder	Substation Name	Date	Cause	Frequency	Duration (h)
MULINDI	GASOGI	Sunday, 9 February 2025	TRF overload	1	0.02
<b>MULINDI Total</b>				<b>1</b>	<b>0.02</b>
MURINDI	GASOGI	Wednesday, 19 February 2025	Earth Fault on bus bar	1	0.00
<b>MURINDI Total</b>				<b>1</b>	<b>0.00</b>
<b>Grand Total</b>				<b>2</b>	<b>0.02</b>

Feeder	Substation Name	Date	Cause	Count of Cause	Sum of Duration (h)	
SAMUDUHA	MULINDI CABINE	Friday, 6 December 2024	Emergency Outage	1	0.67	
		Friday, 6 December 2024 Total		1	0.67	
		Sunday, 9 February 2025	Emergency Outage	1	0.63	
		Sunday, 9 February 2025 Total		1	0.63	
		Monday, 10 February 2025	Emergency Outage	1	0.12	
		Monday, 10 February 2025 Total		1	0.12	
		Wednesday, 19 February 2025	Emergency Outage	1	0.45	
		Wednesday, 19 February 2025 Total		1	0.45	
	MULINDI CABINE Total	Saturday, 22 February 2025		Overcurrent	1	0.00
		Saturday, 22 February 2025 Total		1	0.00	
	PYLONE 20 CABINE	Monday, 20 January 2025		Earth Fault	1	0.02
				Overcurrent	1	0.00
		Monday, 20 January 2025 Total		2	0.02	
	<b>PYLONE 20 CABINE Total</b>				<b>2</b>	<b>0.02</b>
<b>SAMUDUHA Total</b>				<b>7</b>	<b>1.88</b>	
<b>Grand Total</b>				<b>7</b>	<b>1.88</b>	

Figure 12: Samuduha records

### Power Frequency

Range	Threshold	Compliance	Status
50Hz +0.5Hz / -0.5Hz	99.5	99.2	Failed
50Hz +2Hz / -3Hz	100	99.2	Failed

### Supply Voltage Variation

Range	Threshold	Compliance			Status
		U1	U2	U3	
230V +10% / -10%	95	100	100	100	Passed
230V +10% / -15%	95	100	100	100	Passed

### Flicker

Range	Threshold	Compliance			Status
		U1	U2	U3	
P <sub>lit</sub> <= 1	95	90.9	90.9	90.9	Failed

### Supply Voltage UnBalance

Range	Threshold	Compliance	Status
Voltage Negative Unbalance <= 2%	95	75.2	Failed
Voltage Zero Unbalance <= 2%	95	97.7	Passed

Figure 13: Power quality Analyze at Mulindi Feeder