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**KANAZI FEEDER VOLTAGE PROFILE IMPROVEMENT AND
MUTIGATION OF LOSSES BY USING CAPACITOR BANKS
COMBINED WITH DISTRIBUTED GENERATION
INTEGRATION.**

Declaration

I, the undersigned, hereby declare that this dissertation is my original work and has not been submitted for a degree at the University of Rwanda or any other institution. All sources referenced in the dissertation will be fully acknowledged.

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Abstract

The Kanazi feeder, part of Rwanda's expanding electricity distribution network, faces significant challenges related to voltage instability and power losses, particularly during peak demand periods. These issues are exacerbated by increasing load demand, network constraints, and inadequate reactive power compensation. This thesis investigates the integration of Distributed Generation (DG) units and capacitor banks as a cost-effective solution to improve the voltage profile and mitigate power losses in the Kanazi feeder.

The study employs a systematic approach, utilizing load flow analysis and simulation techniques in DigSILENT PowerFactory software to model the Kanazi network. Four scenarios are evaluated: the base case without any compensation, the integration of capacitor banks, the integration of DG units, and a combined approach integrating both capacitor banks and DG units. The results demonstrate that the combined integration of DG units and capacitor banks yields the most significant improvements in voltage stability and power loss reduction. Specifically, the active power loss decreased from 0.4378 MW in the base case to 0.2031 MW in the combined scenario, while the minimum line-to-line voltage improved from 26.5 kV to 29.9 kV.

The findings highlight the importance of optimal placement and sizing of DG units and capacitor banks to maximize their benefits. The study concludes that the strategic integration of these technologies can significantly enhance the performance of distribution networks, offering a sustainable and cost-effective solution for improving power quality and reducing losses. Recommendations for future research include exploring advanced optimization techniques, real-time monitoring systems, and the use of renewable-based DG units to further enhance system efficiency and reliability.

This research provides valuable insights for utility companies and policymakers in Rwanda and similar contexts, offering a practical framework for improving the reliability and efficiency of electrical distribution networks.

Abbreviation

DG: Distributed Generation

MW: Megawatt

KV: Kilovolt

V: Volt

NTL: Non-Technical losses

TL: Technical losses

I: Current through the feeder

θ : Power Factor Angle

R: Resistance of the Feeder

X: Reactance of the Feeder

V1: Sending End Voltage

V2: Receiving End Voltage

PI: Active Load Power

QI: Reactive Power

Δv : Voltage Drop

REG: Rwanda Energy Group

Pf: power factor

KW: kilowatt

Kvar: kilovars

AC: Alternating Current

V: Volt

ROA: Return on Assets

CHAPTER 1: INTRODUCTION

1.1 Background

Rwanda has made a significant stride in expanding and modernizing its electricity grid in recent decades, driven by the government's commitment to achieving universal electrification by 2024. The country's electricity supply is generated from a mix of hydropower, methane, peat, solar, and diesel plants, with an increasing emphasis on clean and renewable sources.

Electric power distribution networks are essential for delivering reliable and stable electricity to consumers. However, many distribution feeders, including the Kanazi feeder, face challenges such as voltage instability, power losses, and inefficiencies due to increasing demand and network constraints. Voltage profile improvement is crucial in maintaining power quality, ensuring operational efficiency, and minimizing technical losses[1].

One of the promising solutions to enhance voltage stability is the integration of Distributed Generation (DG) and capacitor banks into the distribution system. DG units, such as solar photovoltaic (PV) systems, small-scale hydro plants, provide localized power generation, reducing dependency on central grid supply and alleviating voltage drops. Meanwhile, capacitor banks improve reactive power compensation, reduce power losses, and enhance voltage regulation.

Integrating both DG and capacitor banks into the Kanazi feeder can offer a synergistic effect by optimizing voltage profiles, improving power factor, and enhancing overall grid performance. However, improper placement and sizing of DG and capacitor banks can lead to reverse power flow issues, voltage fluctuations, and inefficiencies. Therefore, a systematic approach using load flow analysis and optimization techniques is required to determine the optimal integration strategy.

This study focuses on analyzing the impact of DG and capacitor bank integration on the Kanazi feeder's voltage profile, identifying optimal locations and capacities to enhance stability and efficiency. By addressing these challenges, the research aims to provide a cost-effective and sustainable solution for improving power quality in distribution networks.

Several initiatives have been undertaken by the Rwandan government and its energy partners to address the issue of power losses within the national grid. These include projects to upgrade infrastructure, expand the reach of the electricity network, and improve system monitoring and

maintenance. However, localized studies, such as this assessment of the Kanazi feeder, are crucial to providing tailored solutions for specific areas of the network.

1.2 Problem Statement

Kanazi feeder experiences significant voltage profile deterioration, particularly during peak demand periods and at remote end points, resulting in poor power quality, increased energy losses, and potential equipment damage, inefficient power delivery and reduced reliability of the distribution network. Voltage drops along the feeder compromise power quality, affecting consumers and increasing operational challenges for utility providers. These issues are primarily caused by increasing load demand, network constraints, and the absence of adequate reactive power compensation.

Traditional solutions such as network reinforcement, transformer upgrades and replacing conductors are often expensive and time-consuming. However, Distributed Generation (DG) integration and capacitor bank deployment present cost-effective alternatives to improve the voltage profile and enhance system performance. Properly integrating DG can reduce the feeder's dependency on centralized power supply, while capacitor banks contribute to reactive power compensation, reducing losses and improving voltage regulation.

Despite these potential benefits, the challenge lies in determining the optimal placement and sizing of DG units and capacitor banks to maximize their impact without causing network instability. Poorly located DGs can introduce reverse power flow issues, while improperly sized capacitor banks may lead to overcompensation or harmonic distortions. This study will provide actionable recommendations that can be applied across similar feeders to improve energy distribution efficiency nationwide.

1.3 Objectives

1.3.1 Major Objectives

This research focuses on studying the voltage profile of Kanazi feeder and its improvement by using Distributed generation integration combined with capacitor banks.

1.3.2 Specific Objectives

The present work has the following Specific objectives.

- To identify the cause of the Kanazi feeder losses and the voltage profile deterioration.
- To improve the voltage profile and power factor of the Kanazi feeder by distributed generation combined with capacitor banks.
- To draw relevant conclusions and recommendations for implementation.

1.4 Scope and Limitations of the Thesis

This thesis covers, studying current power system reliability, power loss and voltage profile problems of Kanazi Feeder from Mont Kigali Substation, their causes, percentage of improvements of the respective indices by integrating Distributed Generation (DG) and capacitor banks. The various load scenarios are modeled and compared using Dig Silent Power Factory software.

1.5 Significance of the Study

This thesis might be used as a reference and may provide foundation for further research on similar areas of study by other researchers. The results of this thesis can also serve as additional assessment result for Energy Utility Corporation Ltd. Both the customers and Energy Utility Corporation Ltd will be beneficial if recommendations of this thesis are implemented.

1.6 Thesis organization

This thesis is organized into six chapters, each focusing on different aspects of the study, ultimately leading to the effective integration of Distributed Generation and Capacitor Banks into the Kanazi feeder. The following is a summary of each chapter.

Chapter 1: Introduction

This chapter provides the background, problem statement, and objectives of the study. It highlights impact of DG and capacitor bank integration on the Kanazi feeder's voltage profile, and capacities to enhance stability and efficiency of the feeder.

Chapter 2: Literature Review

This chapter outlines a comprehensive review of literature related to the voltage profile improvement and power loss minimization using Capacitor banks and distributed generations.

Chapter 3: Methodology

This chapter outlines the different methods used in this study including documentation, data collection process, Modeling, Simulation and Analysis Based on the data collected from Mont Kigali Substation and Kanazi feeder, the system is modeled and simulated using Power Factory.

Chapter 4: Kanzi Network model modeling and Simulation

The simulation was conducted to evaluate the effectiveness of combining Distributed Generators with Capacitor Banks in enhancing the voltage profile of the Kanazi feeder and reducing power losses both on the feeder and across the distribution network.

Chapter 5: Results and Discussion

In this chapter, the results of the simulations are presented and analyzed, the effectiveness of the of combining Distributed Generators with Capacitor Banks in improving the voltage profile and minimizing power losses of Kanazi feeder has been evaluated.

Chapter 6: Conclusion and Recommendations

The final chapter summarizes the findings of the study and their implications for improving voltage profile and minimizing power losses on Kanazi feeder and Conclusions are drawn that will be recommended to the power utility for practical implementation.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

The reliability and efficiency of electrical distribution systems heavily depend on maintaining an optimal voltage profile and minimizing power losses. Feeder systems, such as the Kanazi Feeder, often experience voltage drops and high-power losses due to increased loads and line impedances. Various strategies, including capacitor bank deployment and distributed generation (DG) integration, have been explored to mitigate these challenges. This literature review explores existing research on these methodologies and their combined effect on voltage profile improvement and loss reduction[2].

2.2 Voltage Profile Improvement in Distribution Feeders

Voltage stability in distribution networks is crucial for ensuring efficient power delivery. Researchers have proposed various techniques to improve voltage profiles, including the deployment of reactive power compensation devices and voltage regulators. capacitor banks provide localized reactive power support, improving voltage levels at critical points. And distributed generation sources, such as solar photovoltaic (PV) and Small Hydro power plant, contribute to voltage support by injecting real and reactive power into the system[3].

Distribution networks experience voltage drops and power losses due to resistance and reactance in transmission lines. Voltage deviations beyond acceptable limits can affect power quality, leading to inefficiencies and system instability. Studies highlight that power losses in radial distribution systems account for a significant percentage of the total energy losses in power grids. Factors influencing voltage profile and power losses include feeder length, impedance, and load variations.

Radial distribution feeders experience significant voltage drops toward their extremities, primarily due to line impedances and load variations. voltage violations are more severe in rural and semi-urban distribution networks with long feeder lengths, similar to the Kanazi feeder configuration. Voltage drops exceeding 10% of nominal values are common in such networks during peak load conditions, resulting in poor power quality and potential equipment damage[4].

2.3 Impact of Load Growth and Variable Demand

Rising load demand and shifting consumption patterns contribute to worsening voltage profile issues. A five-year study of distribution network data indicated a steady degradation of voltage profiles, driven by an annual load increase of 4-7%. The dynamic nature of load variations presents challenges that static compensation techniques alone cannot adequately address across different distribution system structures, as depicted in the following figure.

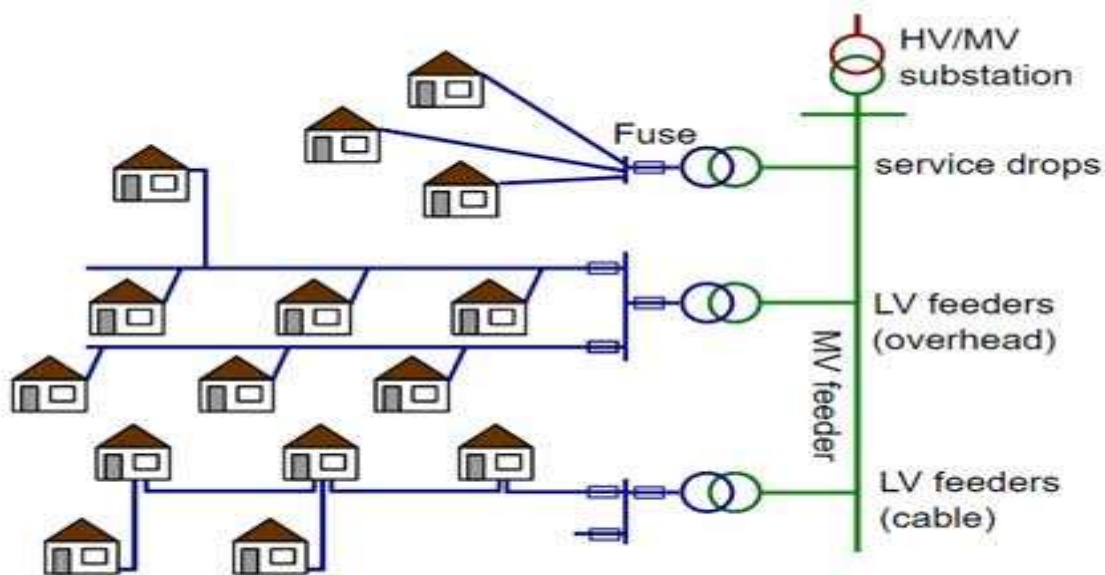


Figure 1 The Structure of a Distribution System[5]

2.4 Power Loss in Distribution Feeders

Distribution losses refer to the portion of electrical energy that is lost and not accounted for in consumer billing. They are calculated using the formula: $\text{Distribution Losses} = (\text{Energy Input to Feeder (kWh)} - \text{Billed Energy to Consumer (kWh)}) / \text{Energy Input (kWh)} \times 100$. Among all segments of the power sector, the distribution sector is often seen as the most vulnerable. Transmission losses are around 17%, while distribution losses can reach approximately 50%[6].

Distribution losses are classified into two main types: technical losses and non-technical (commercial) losses.

2.4.1 Distribution Network Losses

Technical losses occur due to energy dissipation in conductors and electrical equipment used in transmission lines, transformers, and distribution networks. These losses, which average around 22.5%, depend on network design and operational methods. The majority of losses happen in primary and secondary distribution lines, while transmission and sub-transmission lines account for roughly 30% of total losses. Losses are inevitable in electricity distribution and cannot be completely eliminated. However, proper planning of distribution systems can help keep them within acceptable limits.

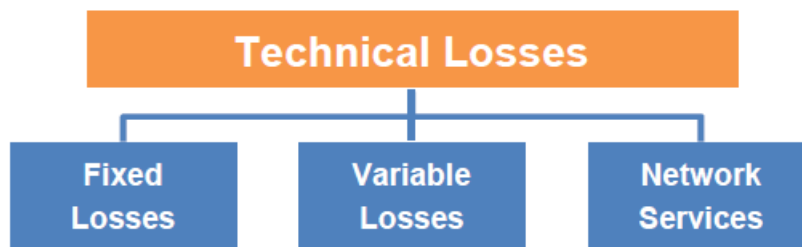


Figure 2 Classifications of Technical Losses[7]

2.4.1.1 Fixed (Permanent) Technical Losses

These losses do not depend on current levels and manifest as heat and noise. They occur as long as the transformer is energized, accounting for about one-third of technical losses. Factors affecting fixed losses include:

- Corona losses
- Leakage current losses
- Dielectric losses
- Open-circuit losses
- Continuous load on measuring and control element

2.4.1.2 Variable Technical Losses

Variable losses fluctuate with the amount of electricity distributed and are proportional to the square of the current. A 1% increase in current results in a more than 1% rise in losses. These losses represent two-thirds to three-quarters of total technical losses. To reduce them, increasing the cross-sectional area of conductors can be an effective solution. The trade-off lies in balancing

capital investment against potential energy savings. Variable losses comprise Joule losses in transmission lines, impedance losses, and contact resistance losses[8].

2.4.2 Causes of Technical Losses

Technical losses in power distribution are caused by several factors, including long distribution lines, particularly 30kV and 400V lines in rural areas, which result in high resistance and significant I^2R losses. Unplanned expansion of transmission and distribution systems leads to inefficiencies, further increasing losses. Insufficient conductor size, where undersized conductors are used instead of those selected based on kVA-km capacity, causes excessive energy dissipation. Improper transformer placement away from load centers results in voltage drops and increased line losses. A low power factor (PF) in low-tension circuits, typically between 0.65 and 0.75, raises current draw and energy losses. Poor workmanship, including improper connections and excessive joints, contributes to power loss. Imbalanced load distribution in three-phase systems creates voltage fluctuations and unnecessary energy losses. Variations in load factor (LF), due to fluctuating power demand, lead to inefficient power utilization and peak power losses. Incorrect transformer sizing and optimization cause unnecessary losses from both load losses (I^2R losses) and no-load losses (core magnetization losses). Additional factors include unequal phase load distribution in low-tension networks, power leaks and energy theft, overloaded lines and transformers, suboptimal operating conditions, and low voltage at consumer terminals, which increases current draw and further amplifies losses[1].

Distribution system losses into technical and non-technical components, with technical losses comprising approximately 70-85% of total system losses in well-managed utilities. line losses in medium voltage distribution feeders typically range between 4-8% of transmitted power, with additional 3-5% losses occurring in distribution transformers. reactive power flow as a significant contributor to technical losses, accounting for 25-35% of total line losses in most distribution systems.

2.5 Capacitor Banks for Voltage Profile Improvement and Loss Reduction

Capacitor banks are extensively used in power systems to enhance voltage stability and reduce system losses. the strategic placement and sizing of capacitor banks play a crucial role in

maximizing their benefits. Recent optimization techniques, including genetic algorithms and particle swarm optimization, have been applied to determine the most effective locations for capacitor banks. These methods ensure an optimal balance between cost and performance, minimizing losses while maintaining voltage within permissible limits. Optimal placement of capacitor banks in distribution networks enhances voltage profiles and decreases power losses by compensating for reactive power demand. However, capacitor banks alone may not provide sufficient improvements in heavily loaded or long feeders, necessitating additional voltage support solutions[9].

Various capacitor bank technologies applicable to distribution systems are illustrated in the figure below. A comparison of fixed and switched configurations shows that switched capacitor banks provide 15-25% greater benefits than fixed installations due to their ability to adapt to changing system conditions.



Figure 3 Reactive Power Compensation Capacitor banks[9]

2.5.1 Optimal Placement and Sizing Methodologies

Genetic algorithm-based optimization achieved 5-8% better results than analytical methods for complex feeder configurations. a multi-objective optimization framework specifically for capacitor placement, balancing voltage profile improvement, loss reduction, and implementation costs. Their approach demonstrated that strategically placed smaller capacitors often outperform fewer large installations, particularly in feeders with non-uniform load distributions[10].

2.5.2 Method of Finding Optimal Location and size for Capacitor banks in the Network.

To obtain the optimum benefit of shunt power capacitor applications on the distribution system, the capacitor banks should be located where they produce the maximum loss reduction, provide the maximum voltage benefits, and are as close to the load as possible. When this is not practical, several “rules of thumb” have been utilized for locating capacitors[11].

These include the following:

- a) For uniformly distributed loads, the capacitor should be placed two-thirds of the distance from the substation.
- b) For uniformly decreasing distributed loads, the capacitor should be placed one-half of the distance from the substation.
- c) For maximum voltage rise, the capacitor should be placed near the end of the line.

More specifically, capacitor banks are required at locations where field measurements indicate a low-voltage or low-power factor problem. This information can be obtained as follows:

- a) By making voltage measurements during full-load and light-load conditions at various points on the feeder; and
- b) By making kilowatt and kilovolt ampere measurements on the feeder at minimum and maximum daily loads, and during a typical 24 h period.

Once these measurements have been obtained, the capacitor banks may be connected grounded wye, ungrounded wye, or delta as illustrated in the below figure.

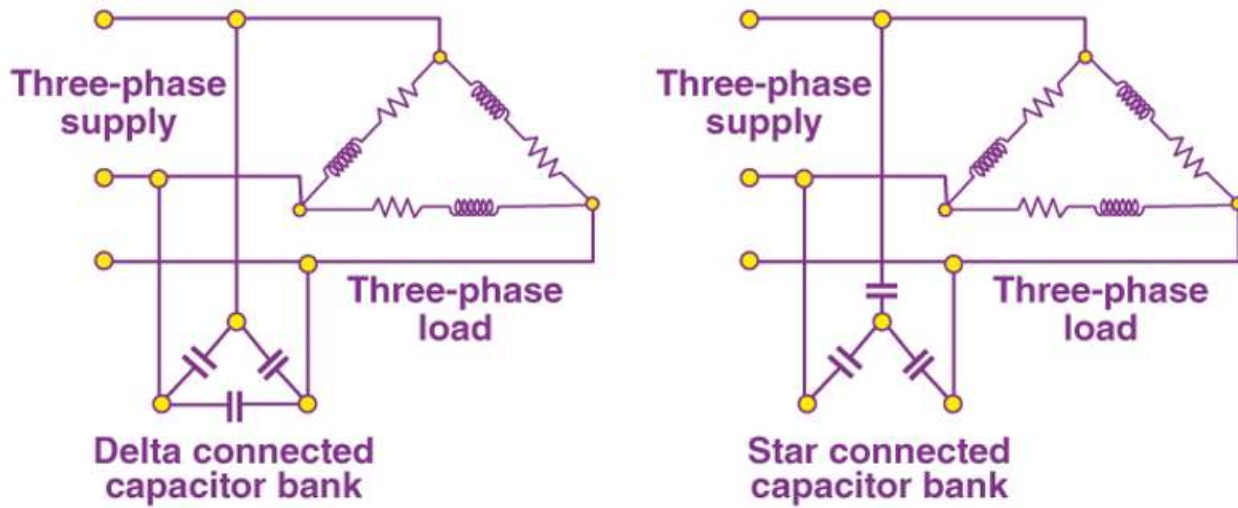


Figure 4 Star and Delta connection of Capacitors[1]

2.6 Distributed Generation Integration in Distribution Networks[12]

The integration of DG, particularly renewable energy sources, is increasingly being adopted to enhance voltage stability and efficiency in distribution networks. DG units contribute real power generation and reactive power support, reducing the burden on centralized power plants. DG integration significantly improves voltage profiles and mitigates feeder losses. However, improper placement and sizing of DG units can lead to voltage instability and power quality issues.

2.7 Mitigation of distribution losses

Power losses in electrical distribution systems are classified into technical (I^2R losses) and non-technical losses. Several studies emphasize the role of capacitor banks in reducing technical losses by improving power factor and minimizing reactive power flow. optimal capacitor placement in radial distribution systems reduces line losses by up to 30%. Additionally, the integration of DG has been shown to mitigate losses by supplying power closer to the load, thereby reducing the current magnitude in transmission lines.

Optimally placed capacitor banks can reduce technical losses by 10-30% in typical distribution feeders. Field studies across multiple utility systems verified that reactive power compensation

significantly decreases line current magnitudes, with consequent quadratic reduction in resistive losses.

Power losses in distribution systems vary with numerous factors depending on the system configuration, such as level of power losses in transmission and distribution lines, transformers, capacitors, insulators, etc. Power losses could be categorized as reactive power loss and real power loss. The resistance of the lines causes the real power loss while the reactive elements are responsible for reactive power loss, normally, the real power losses draw more attention for the utilities, as they reduce the capacity of the network of transmitting power to the customers. However, the reactive power losses are also to be taken into considerations. This is due to the fact that the reactive power flow in the system need to be maintained at a minimum possible value for sufficient voltage level.

The total reactive and real power losses in a distribution system can be calculated using the below illustrated formulas.

$$Q_{\text{Loss}} = \sum_{i=1}^n |I_i|^2 X_i \quad (\text{for total reactive power losses})$$

$$P_{\text{Loss}} = \sum_{i=1}^{nbr} |I_i|^2 r_i \quad (\text{for total real power losses})$$

Where n is the total number of branches in the network, $|I_i|$ is the magnitude of current flow in the branch I , r_i and x_i are the resistance and reactance of branch i , respectively.

2.7.1 Strategies for Minimizing Power Losses in Distribution Lines

Distribution network forms the final stage of power system and ended by the consumers. The problems which may rise in the distribution network affect the entire system. one of these problems is the voltage drop which must be reduced to keep the voltages at load points within the standard limits. To achieve this the voltage at different nodes of the system must be controlled. The voltage control actually means reactive power control. Consequently, this result in a reduction of power loss which has a great concern by the electrical power supply utilities.[5]

2.7.1.1 Voltage Drop in Distribution Systems

The growing demand for electrical energy has led to issues with voltage stability and power losses in transmission and distribution systems. Over time, the increasing load demand has

strained power transmission networks, which now face capacity limitations. These challenges arise from the need to balance voltage levels and maintain network stability. Consequently, power systems are operating below their full capacity, resulting in suboptimal performance, reduced power transfer, and voltage instability. If left unaddressed, these issues could lead to total system failure, undermining the efficiency and investment in transmission and distribution infrastructure.

A basic overview on voltage drop in a distribution system is shown in figure below.

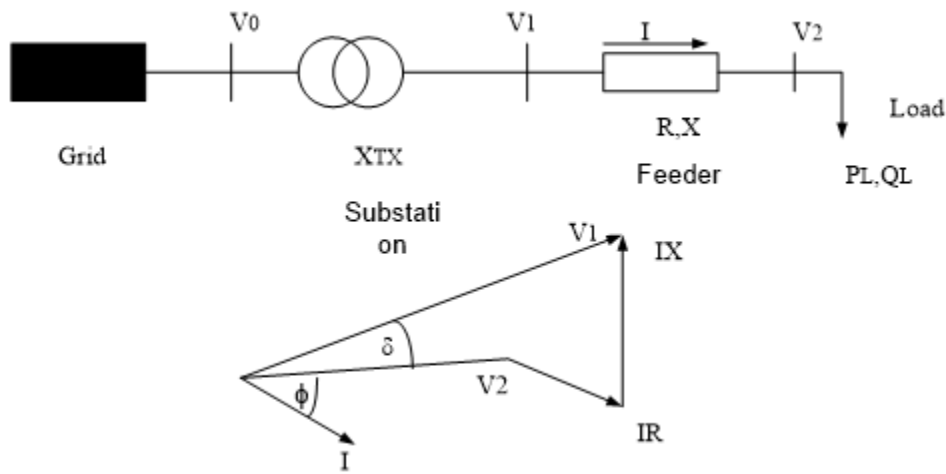


Figure 5 One line diagram and corresponding phasor diagram[11]

The current I as a function of the load complex apparent power $S = P_L - jQ_L$ and the load voltage V_2 will be $I = \left[\frac{S}{V_2} \right] = \frac{P_L - jQ_L}{V_2}$

The voltage drop on the feeder is given by:

$$V_1 - V_2 = I(R + jX) = IRCos\theta = \frac{RP_L + XQ_L - j(XP_L - RQ_L)}{V_2}$$

For small power flow, the voltage angle δ between V_2 and V_1 in the above equation is small and the voltage drop $\Delta v = |V_1 - V_2|$ can be approximated by $\Delta v \cong \frac{RP_L + jXQ_L}{V_2}$

Where:

- I : Current through the feeder
- θ : Power Factor Angle
- R : Resistance of the Feeder
- X : Reactance of the Feeder
- V_1 : Sending End Voltage

Improving voltage is a critical factor for ensuring power quality and system stability. Addressing voltage instability issues requires sufficient reactive power support at the right locations. Utilities employ various reactive compensation devices for this purpose, each with unique features and limitations. Flexible AC Transmission System (FACTS) devices are specifically designed to enhance system stability, improve controllability, and boost power transfer capacity.

Below are different methods which are used to put power losses at as low level as possible:

2.7.1.2 Network reconfiguring/restructuring

The concept of restructuring the topology of the distribution network to minimize losses can be recognized as being cost effective, therefore the interest to efficiency conscious electric utilities. Electrical distribution networks are mostly figured as radial for proper coordination; distribution feeders may be frequently reconfigured by opening and closing switches while considering all load requirements and maintaining a radial network. This results in a proper planning of system to reduce loss and improve efficiency of the system[13].

2.7.1.3 Tap changer transformers and voltage regulators.

Tap changer can vary the number of turns in one side of the transformer and thereby, change the transformer ratio, normally this can vary between 10-15% in steps of 0.6-2.1%. there are several options to design the control of the voltage, one of them is to set a nominal value of the voltage with a deadland in a point of line, and to control it with an integral controller.

Tap changing transformer has the advantage of being able to regulate the voltage at the bus. With this method, the appropriate tap settings are required to compensate for the voltage drops in the distribution system.

2.7.1.4 Capacitor placement

The majority power system loads, and delivery apparatus (line and transformer) are inductive in nature and therefore operate at lagging power factor. This lagging power factor bring the need of power system for additional var flow, which results in reduced system capacity, increased system losses, and reduced system voltage. Shunt capacitor banks are able to compensate for var requirements, but bank size, location, capacitor control method, and cost considerations are to be optimized during the design stage[14].

The figure below indicates how the application of shunt capacitors increases the system capacity and reduces system losses by reducing var flow. The system is reduced from KVA_1 to KVA_2

By the additional capacitive Kilovar, shown in the below figure as $Ckvar$, $Kvar_1$ represent reactive power before inserting capacitors, $Kvar_2$ represent reactive power after inserting capacitors and KW represent active power.

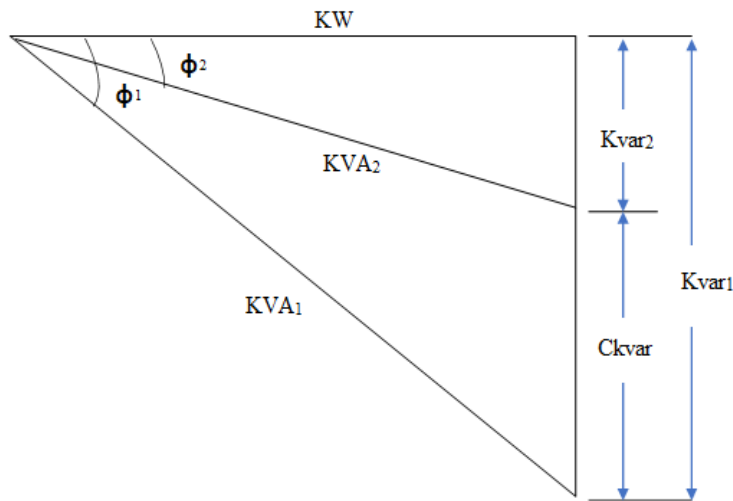


Figure 6 power triangle showing how $Ckvar$ reduces $Kvar$ [15]

2.7.2 Purpose of shunt capacitor application in distribution network

As described in the IEEE std 1036-1992 (IEEE guide for application of shunt power capacitors), the purposes of shunt capacitor applications are explained below:

2.7.2.1 Var support

Var support incorporates many different benefits of shunt capacitors, such as improved voltage profile and power factor, reduced system losses and reactive power requirements at the generation and increased steady-state stability limits. Capacitive Vars are sized and located at transmission and distribution substations to supply vars close to the load centers or to provide midway support across heavily loaded transmission circuits. On some distribution and transmission systems, a significant reduction in losses may be achieved by the installation of shunt power capacitors[10].

The installation of shunt power capacitors can reduce current flow through the system from the point of the capacitor installation back to the generation. Since power losses are directly

proportional to the square of the current, a reduction of current flow results in a much greater reduction of power losses. Capacitors are often installed as close to the load as possible for this reason.

The ratio of the system losses associated with the local load, with and without capacitors installed, can be estimated with the following formula. The formula assumes constant kilowatt and constant voltage at the load. This reduction in losses will reduce the generation fuel requirement to supply these losses as well as the system equipment costs to supply the losses at peak load.

2.7.3 Distributed Generators

The mitigation of distribution losses using distributed generators (DGs) involves strategically integrating small-scale power generation sources, such as solar panels, wind turbines, and cogeneration units, closer to load centers. By generating electricity near consumption points, DGs reduce the distance power must travel, thereby minimizing I^2R losses in transmission and distribution lines. Additionally, DGs help improve voltage profiles, enhance power factor correction, and reduce overloading on transformers and feeders. When properly sized and optimally placed, distributed generators support reactive power compensation, stabilize voltage fluctuations, and improve overall system efficiency, leading to lower technical losses and a more reliable distribution network[8].

2.8 Gaps in Existing Research

Despite significant advancements in voltage profile improvement and loss mitigation using capacitor banks and distributed generation (DG), several research gaps remain. One key area lacking comprehensive study is the optimal coordination of capacitor placement and DG integration under dynamic load conditions, as most existing studies focus on static or simplified scenarios. Additionally, the impact of real-time control strategies and adaptive algorithms for adjusting capacitor banks in response to varying generation and load patterns is not well explored. The interaction between different DG technologies and capacitor banks in terms of power quality, harmonics, and transient stability also requires further investigation. Moreover,

the long-term effects of high DG penetration on capacitor bank efficiency and the overall reliability of the distribution network remain understudied.[8]

Table 1: Related Research Papers

Title	Author	Paper Overview	Gaps Remain
Impact of Capacitor Bank and DG Integration on Distribution Network Reliability and Power Quality	Singh, A.K., & Kumar, R. (2023)	This study analyzes the technical and power quality impacts of capacitor banks and DG integration, using probabilistic models for load and generation. It quantified improvements in reliability indices (SAIDI, SAIFI), voltage profile, and loss reduction. The research also addressed power quality metrics like harmonics, voltage sags, and flicker.	The research doesn't fully explore the impact of different DG technologies on power quality when combined with capacitor banks. More detailed analysis is needed on harmonic interactions, especially during fault conditions or transients.
Reactive Power Compensation in Distribution Networks with Coordinated Control of Capacitor Banks and Distributed Energy Resources	Martinez, J.A., & Gonzalez, D.M. (2023)	Martinez and Gonzalez created a hierarchical control framework for coordinating capacitor banks with inverter-based DG units.	The communication infrastructure requirements are significant, posing challenges in feeders with limited monitoring. The economic analysis overlooked maintenance costs and the impact of equipment lifetime.
Optimal Placement and Sizing of Distributed Generation and Capacitor Banks in Distribution Systems	Rao, V.S., & Reddy, V.P. (2022)	This research presents a hybrid optimization algorithm combining particle swarm and genetic algorithms for the joint placement of DG units and capacitor banks.	The research uses idealized load profiles and doesn't fully address the stochastic nature of renewable DG sources.

2.9 Opportunities for Future Research

Future research in voltage profile improvement and loss mitigation through the integration of capacitor banks and distributed generation (DG) presents several promising opportunities. One key area is the development of advanced, real-time adaptive control algorithms that can better coordinate capacitor bank operations with fluctuating DG outputs, particularly in response to dynamic load and renewable generation patterns. Exploring the integration of energy storage systems with capacitor banks and DG could further enhance voltage regulation and loss reduction, especially during periods of high renewable output or grid disturbances. Additionally, research could focus on the optimization of capacitor placement and sizing strategies under different grid conditions, taking into account the stochastic nature of renewable generation. Power quality issues, such as harmonics and voltage sags, also warrant further investigation, especially regarding the interaction between various DG technologies (solar, wind, biomass) and capacitor banks. Finally, assessing the long-term economic and reliability impacts of high DG penetration in combination with capacitor banks could provide valuable insights for smart grid development and infrastructure planning.

CHAPTER 3: METHODOLOGY

3.1. Introduction

This chapter of the research project focuses on the documentation and methodology used to achieve the research objectives. It includes a review of relevant materials, such as literature, data collection, analysis, modeling, and simulation, to assess the effectiveness of the proposed strategy. This approach provides a thorough understanding of the voltage profile of the Kanazi feeder and associated losses while outlining a structured method for integrating Distributed Generators and Capacitor Banks to address the issue.

3.2 Data Collection

Data were collected through the direct involvement of the researcher and from previous reports provided by the Rwanda Energy Group (REG). The collected data include the load parameters of the Kanazi feeder, such as active power, reactive power, power factor, and voltage. In the report given by Rwanda Energy Group (REG) Kanazi feeder has in total 180 Distribution transformers of different KVA ratings that have in total 21,075 KVA and where total installed active power of the feeder is 17,913.75 KW and total Installed reactive power of the feeder is 11,101.94621 KVAR.

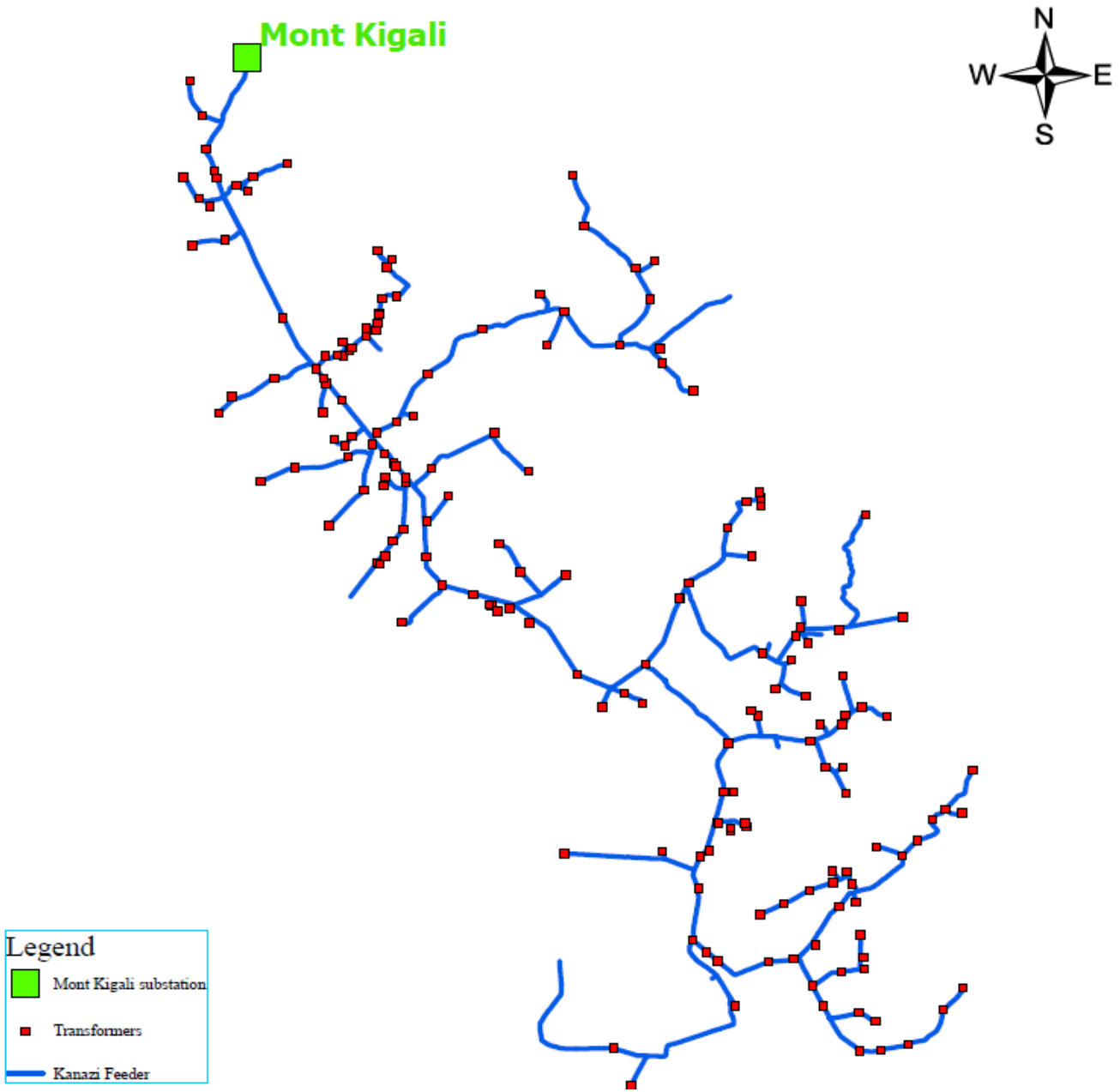


Figure 7 Kanazi Feeder Network Map

3.2.1 Data collection from Mont Kigali Substation

The Mont Kigali Substation, as illustrated in the figure 8 below, is located in Nyarugenge District within the city of Kigali. It receives power through four 110kV transmission lines from the Jabana, Gahanga, Kigoma, and Gikondo substations. The incoming 110kV voltage is stepped down using two power transformers: a 110/30kV transformer and a 110/15kV transformer, each with a capacity of 20MVA. Additionally, the substation features two 30kV medium-voltage outgoing feeders, Kanazi Feeder and Kiyumba Feeder as well as two 15kV outgoing feeders, Nyamirambo and Nyarurama Feeders as shown in the figure 9 below, which presents the single-line diagram of the Mont Kigali Substation.



Figure 8 Photo Image for Mont Kigali Substation

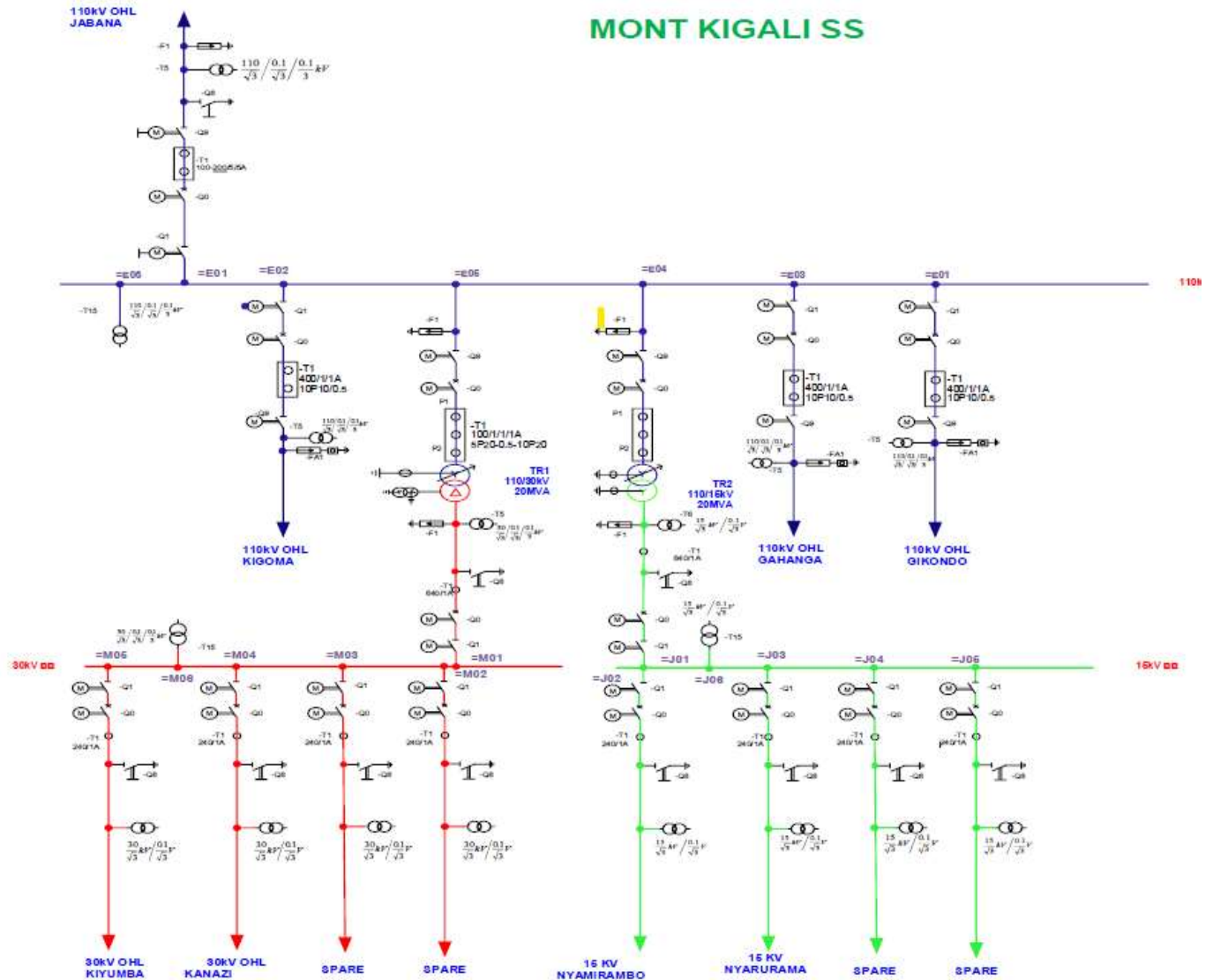


Figure 9 Mont Kigali Substation Single Line Diagram

All the buses of Kanazi feeder have a voltage level of 30KV where the minimum and the maximum voltage limits for all buses are considered at $\pm 5\%$. And in simulating the network in Power Factory shows that voltage magnitude are below acceptable limits.

Table 2: Average Load Profile and Voltage Profile of Kanazi feeder at Mont Kigali Substation

Dates	Hour	KANAZI 30KV								
		U1-2	U2-3	U3-1	IL1	IL2	IL3	P	Q	PF
3/1/2024	8:00	31.7	31.2	31.5	82.1	79.2	79.2	4.3	0	1
	9:00	32.4	31.9	32.1	82.1	86.4	79.2	4.51	0	1
	10:00	31.9	31.8	31.6	83.5	86	79.2	4.42	0	1
	11:00	31.9	31.5	31.7	84.2	83.7	83.6	4.55	0	1
	12:00	31.9	32	32.2	75	78.5	74.6	4.25	0	1
	13:00	31.9	32	32.2	75	78.5	74.6	4.01	0	1
	14:00	31.9	32	32	75	78.9	74.6	4.12	0	1
	15:00	31.4	31.4	31.1	81	81.6	81.3	4.44	0	1
	16:00	32	31.5	31.7	90.5	87.8	87.9	4.9	0	1
	17:00	31.8	31.4	31.2	83.9	87.8	87.9	4.86	0	1

	Hour	KANAZI 30KV								
		U1-2	U2-3	U3-1	IL1	IL2	IL3	P	Q	PF
13/6/2024	8:00	32	31.6	32	96.1	95.4	95.7	5.3	0	1
	9:00	31.4	31.1	31.2	93.7	97.7	93.6	4.99	0	1
	10:00	31.8	32	31.5	95.7	97.8	95.3	5.15	0	1
	11:00	31.8	31.4	31.4	102.1	97.6	95.4	5.34	0	1
	12:00	31.8	31.5	31.4	96.1	99.4	97.8	5.33	0	1
	13:00	31.9	31.6	31.4	92.5	92.9	91.2	5.03	0	1
	14:00	31.7	31.3	31.4	101	98.4	98.7	5.28	0	1
	15:00	32	31.5	31.3	114.1	111.1	111.5	5.91	0.68	1
	16:00	31.4	31.1	31.1	113.3	114.8	111	6.22	1.36	1
	17:00	31.7	31.5	31.5	114.1	113.2	110.2	6.16	0.99	1

	Hour	KANAZI 30KV								
		U1-2	U2-3	U3-1	IL1	IL2	IL3	P	Q	PF
12/12/2024	8:00	31.6	31.2	31.1	86.9	88.2	86.8	4.81	0	1
	9:00	31.9	31.3	31.2	99.5	96.5	98.8	5.24	0.41	0.99
	10:00	31.3	31.3	31.4	100	101	104	5.5	0.65	0.99

11:00	31.3	31.3	31.4	94.4	96.7	95.4	5.18	0.34	1
12:00	31.8	31.3	31.4	91.4	97.9	89.6	4.99	0.35	1
13:00	31.9	31.3	31.7	98	98.1	97.1	5.15	0.3	1
14:00	31.4	31.3	31.2	91.6	98.1	90.9	5.12	0.32	1
15:00	31.4	31.3	31.2	105	105.6	103.2	5.56	0.61	1
16:00	31.4	31.3	31.2	110.1	108.9	102.9	5.63	0.98	0.99
17:00	31.9	31.5	31.7	89.4	90.8	87.8	4.75	0	1

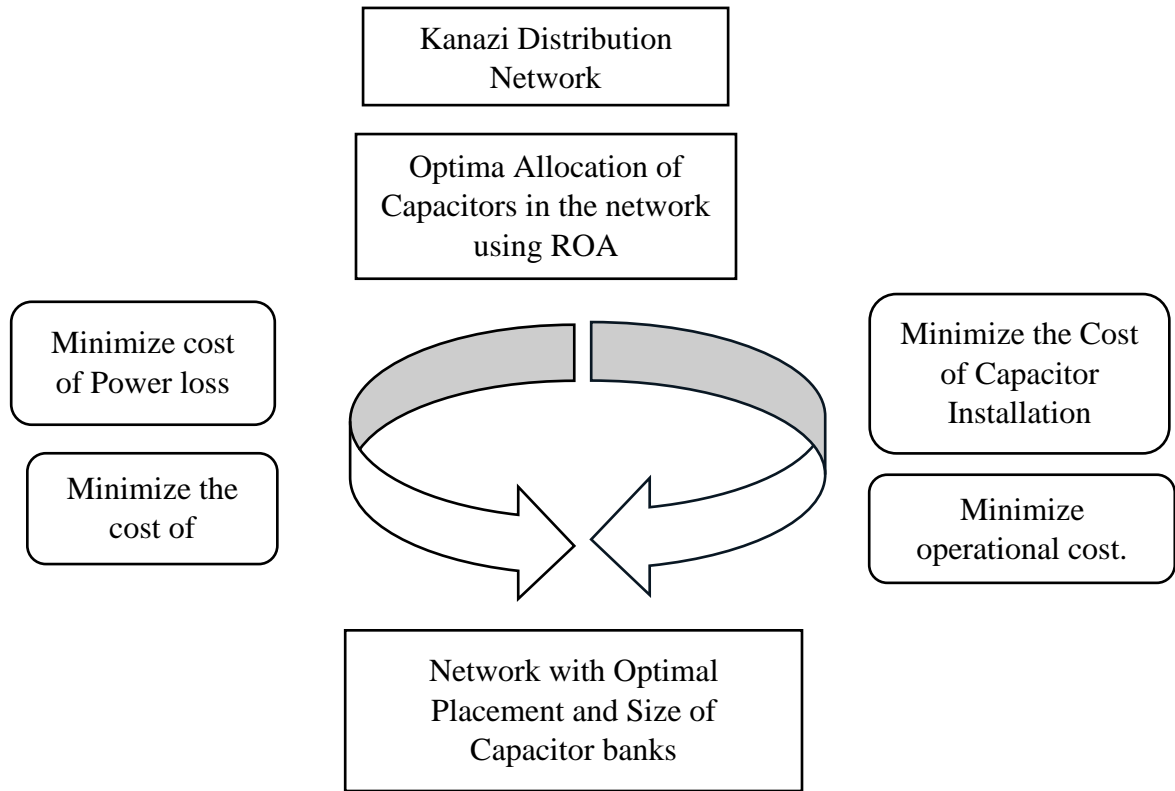
3.3 Data Analysis and calculation of KVAR Required for the feeder.

The Kanazi feeder is currently delivering an apparent power of 21,075 kVA to the load with a power factor of 0.85. To improve the power factor to 0.95, we need to determine the required KVAR capacitor bank. The installed apparent power (S_1) is 21,075 kVA, and the initial power factor ($\cos(\phi_1)$) is 0.85. The useful power (P) is calculated as $P = S_1 \times \cos(\phi_1) = 21,075 \text{ kVA} \times 0.85 = 17,913.75 \text{ kW}$. After connecting the capacitor bank, the desired power factor ($\cos(\phi_2)$) is 0.95. With the useful power remaining constant at 17,913.75 kW, the new apparent power (S_2) will be $S_2 = P / \cos(\phi_2) = 17,913.75 \text{ kW} / 0.95 = 18,856.58 \text{ kVA}$. This demonstrates that capacitor banks reduce unused power, thereby alleviating the feeder's burden. The initial phase angle (ϕ_1) is $\cos^{-1}(0.85) = 31.788^\circ$, and the new phase angle (ϕ_2) is $\cos^{-1}(0.95) = 18.195^\circ$. The required reactive power (Q_c) is calculated as $Q_c = P \times (\tan(\phi_1) - \tan(\phi_2)) = 17,913.75 \text{ kW} \times (\tan(31.788^\circ) - \tan(18.195^\circ)) = 5,737.89 \text{ kVAR}$, or approximately 5.74 MVAR. This capacitor bank will effectively improve the power factor to the desired level.

3.4 Location for optimal placement of capacitor banks and Distributed generations

Using Power Factory, capacitor banks and distributed generation units were strategically placed at various locations within the Kanazi feeder network model, targeting weak buses to achieve maximum loss reduction and optimal voltage profile improvement. The results for each scenario were recorded and compared to determine the optimal placement, based on the locations yielding the highest loss reduction and voltage profile enhancement.

Mathematical model of the capacitor bank allocation in electrical distribution network.



3.5 Evaluation of the performance of the proposed techniques

To evaluate the performance of the proposed techniques, I have simulated the Kanazi network model under four different scenarios. In the first scenario, the network was analyzed without integrating capacitor banks or distributed generation units. In the second scenario, capacitor banks were integrated into the network. In the third scenario, a distributed generation unit was added. Finally, in the fourth scenario, both capacitor banks and the distributed generation unit were combined within the Kanazi network model.

We then compared the reduction in power losses and improvements in the voltage profile across all scenarios. The goal was to determine whether maximum loss reduction and optimal voltage profile enhancement were achieved while ensuring that the chosen locations aligned with the research objectives.

CHAPTER 4. KANZI NETWORK MODEL MODELING AND SIMULATION

The simulation was conducted to evaluate the effectiveness of combining Distributed Generators with Capacitor Banks in enhancing the voltage profile of the Kanazi feeder and reducing power losses both on the feeder and across the distribution network.

4.1. Simulation of Kanzi Network model before integration of Capacitor Banks and Distributed generation unit.

During this stage, the Kanazi network model is simulated using PowerFactory software. The results obtained from simulating the Kanazi network model in PowerFactory show the voltage profile and technical parameters at the base case, as illustrated in Figure 10 and Table 3 below.

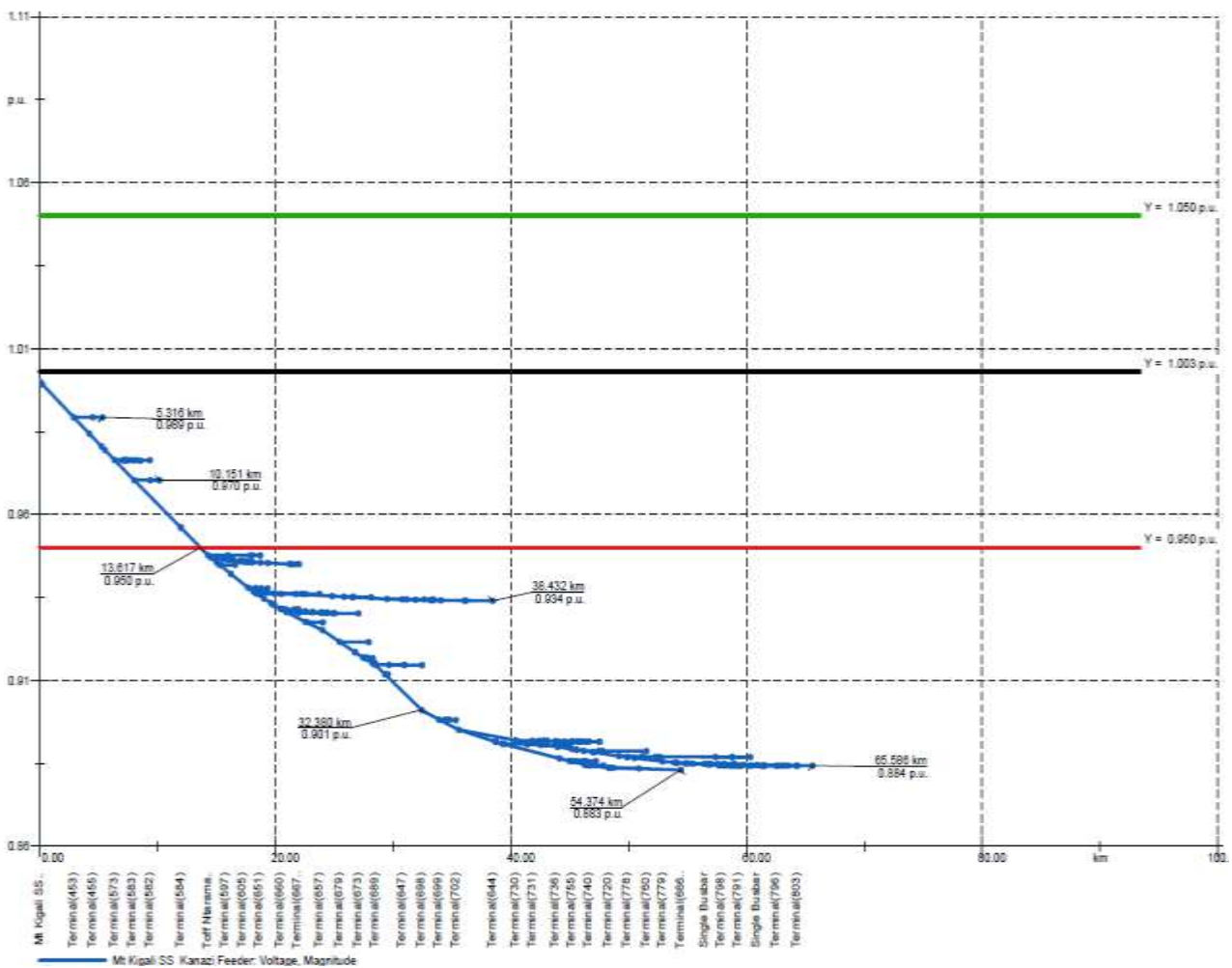


Figure 10 Kanazi Feeder Voltage profile at Base (Case 1)

Table 3: Technical parameters of Kanazi network model before integration of Capacitor banks and distributed generations unit.

Name	Total Active Power, Infeed	Total Load, Active Power	Losses, P	Max. Loading	Max. Voltage Drop	Total Reactive Power, Infeed	Total Apparent Power, Infeed
	MW	MW	MW	%	%	Mvar	MVA
Mt Kigali SS_ KANAZI	6.339	5.901	0.4378	38.658	11.699	4.3	7.7
		Maximum Voltage (Line-Line)	Minimum Voltage (Line-Line)	Total Load, Power Factor	Power Factor Measurement	Infeed, Power Factor	Total Power Factor, Infeed
		kV	kV				
		30	26.5	0.8	0.8	0.826	0.826

Seven locations along the feeder have been identified as reference points for the entire feeder. These locations are recorded in Table 4, which shows the T-off locations on the Kanazi feeder.

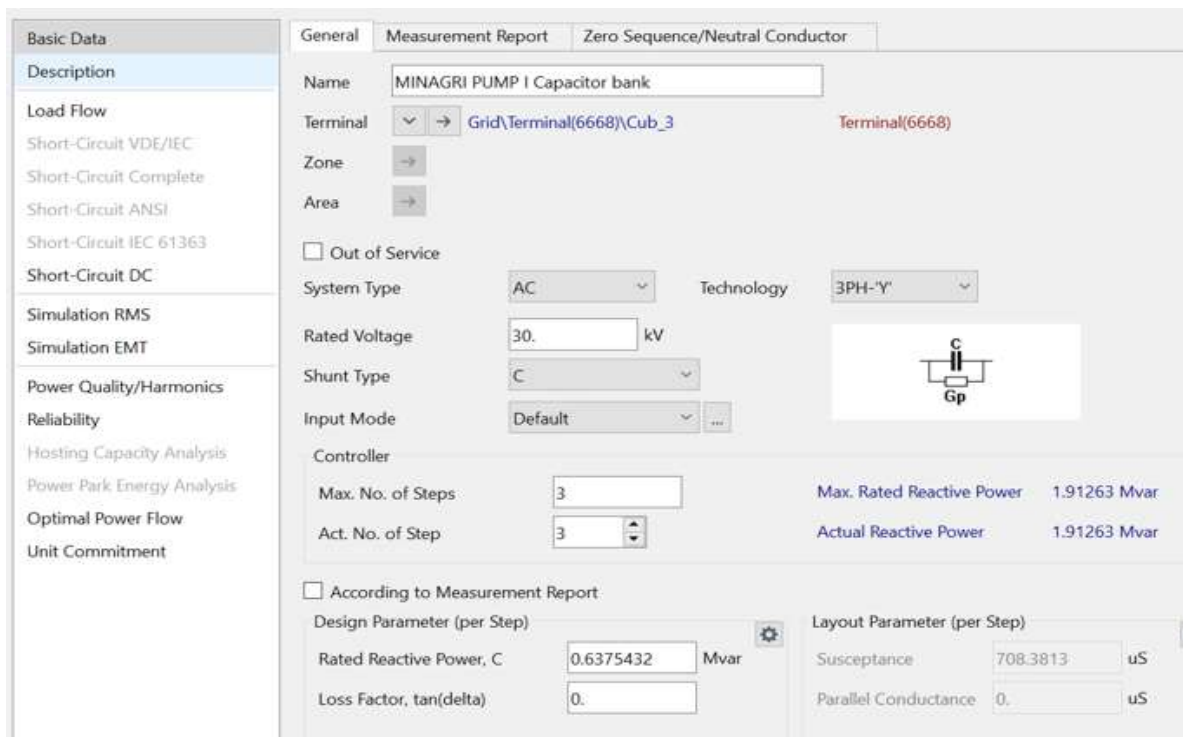
Table 4: Recorded T-off locations on Kanazi feeder before

No	Location	Distance (Km)	Voltage (pu)
1	T-off Rwesero	5.316	0.989
2	T-off Rubungo	10.151	0.970
3	T-ff Ntarama	13.617	0.950
4	T-off Mbyo	32.380	0.901
5	T-off Coperative Imbere Heza	38.432	0.934
6	T-off Minagri Pump	54.374	0.883
7	T-off Kivusha	65.586	0.884

4.2 Integration of Capacitor Banks in Kanazi Network Model (Case 2)

During this stage, the voltage profile of the Kanazi feeder with capacitor banks is simulated using PowerFactory software. Connecting a capacitor bank to only one location in the Kanazi network model fails to significantly improve the voltage profile across all buses of the feeder, even when reactive and active power are reduced. However, when capacitor banks are connected at multiple locations, better results are achieved, including reduced power losses, improved voltage profiles, and an enhanced power factor.

Referring to the Kanazi Network Model in the appendix, three locations with voltage profiles below acceptable limits have been identified: T-off Kavure, Bugesera District Office, and Ramiro. The total MVAR required for the feeder is calculated to be 5.737888673 MVAR. To address this, three capacitor banks with the following parameters have been selected: each capacitor has a rated reactive power of 0.6375432 MVAR, and the maximum rated reactive power of the capacitor bank is 1.91263 MVAR as shown in the below Figure 13.



The screenshot displays the configuration window for a capacitor bank in PowerFactory. The left sidebar lists various analysis options, with 'Basic Data' selected. The main window is divided into several sections:

- General:** Name: MINAGRI PUMP I Capacitor bank; Terminal: Grid\Terminal(6668)\Cub_3; Zone: ; Area: ; Out of Service: ; System Type: AC; Technology: 3PH-'Y'; Rated Voltage: 30. kV; Shunt Type: C; Input Mode: Default.
- Controller:** Max. No. of Steps: 3; Act. No. of Step: 3; Max. Rated Reactive Power: 1.91263 Mvar; Actual Reactive Power: 1.91263 Mvar.
- According to Measurement Report:** ; Design Parameter (per Step): Rated Reactive Power, C: 0.6375432 Mvar; Loss Factor, tan(delta): 0.
- Layout Parameter (per Step):** Susceptance: 708.3813 uS; Parallel Conductance: 0. uS.

A schematic diagram of a capacitor bank is shown in the center-right area, labeled with 'C' and 'Gp'.

Figure 11 Technical parameters of selected capacitor banks

As indicated by the technical parameters of the Kanazi feeder, the power loss results were analyzed before and after the integration of capacitor banks. Initially, the active power loss was 0.4378 MW, and the minimum line-to-line voltage was 26.5 kV. After installing the capacitor banks, the active power loss decreased to 0.403 MW, while the minimum line-to-line voltage improved to 28.6 kV, as shown in Table 5 and Figure 13 below.

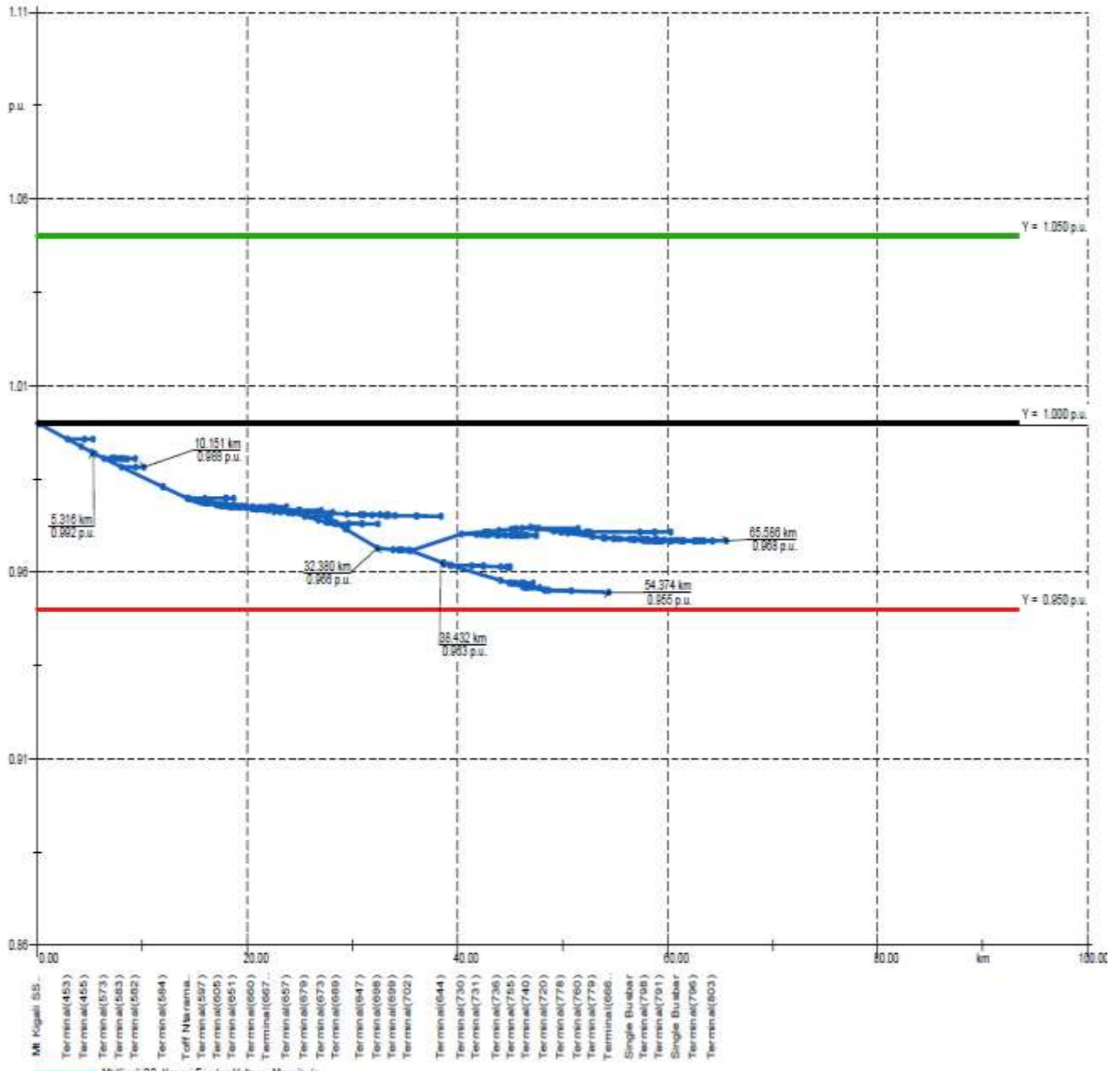


Figure 12 Kanazi Feeder Voltage profile in the system with three connected capacitor banks

Table 5: Technical parameters of Kanazi network model after integration of Three Capacitor banks.

Name	Total Active Power, Infeed	Total Load, Active Power	Losses, P	Max. Loading	Max. Voltage Drop	Total Reactive Power, Infeed	Total Apparent Power, Infeed
	MW	MW	MW	%	%	Mvar	MVA
Mt Kigali SS_ KANAZI	6.304	5.901	0.403	43.743	4.743	-1.2	6.4
		Maximum Voltage (Line-Line)	Minimum Voltage (Line-Line)	Total Load, Power Factor	Power Factor Measurement	Infeed, Power Factor	Total Power Factor, Infeed
		kV	kV				
		30	28.6	0.8	0.8	0.981	0.981

Seven locations along the feeder have been identified as reference points for the entire feeder, after the integration of capacitor banks. These locations are recorded in Table 6, which shows the T-off locations on the Kanazi feeder.

Table 6: Recorded T-off locations on Kanazi feeder after integration of Three Capacitor Banks

No	Location	Distance (Km)	Voltage (pu)
1	T-off Rwesero	5.316	0.992
2	T-off Rubungo	10.151	0.988
3	T-off Ntarama	13.617	0.97
4	T-off Mbyo	32.380	0.966
5	T-off Coperative Imbere Heza	38.432	0.963
6	T-off Minagri Pump	54.374	0.955
7	T-off Kivusha	65.586	0.968

4.3 Integration of Three Distributed Generation unit (Case 3)

At this stage, the Kanazi network model was simulated in PowerFactory software with three distributed generation (DG) units. When these DG units were connected at the same locations where capacitor banks were previously installed, better results were achieved, including a further reduction in power losses and improved voltage profiles.

Table 7 Technical Characteristic of the Distributed Generation used.

Generator_1	Generator_2	Gnerator_3
S=3.052 MVA	S=0.977 MVA	S=2.987 MVA
P=0.950 MW	P=0.950 MW	P=0.950 MW
U1l=30.0 kV	U1l=30.0 kV	U1l=30.0 kV
I=58.733 A	I=18.798 A	I=18.798 A
Q=2.900 Mvar	Q=0.227 Mvar	Q=0.227 Mvar

As shown by the technical parameters of the Kanazi feeder, the voltage profile and power loss were analyzed before and after the integration of distributed generation (DG) units. Initially, with only capacitor banks integrated, the active power loss was 0.403 MW, and the minimum line-to-line voltage was 28.6 kV. However, after incorporating distributed generation units, the active power loss further decreased to 0.1694 MW, while the minimum line-to-line voltage improved to 29.5 kV, as shown in Figure 15 and Table 8 below.

Table 8: Technical parameters of Kanazi network model after integration of Three Distributed Generations units

Name	Total Active Power, Infeed	Total Load, Active Power	Losses , P	Max. Loading	Max. Voltage Drop	Total Reactive Power, Infeed	Total Apparent Power, Infeed
Mt Kigali SS_ KANAZI	MW	MW	MW	%	%	Mvar	MVA
	3.22	5.901	0.1694	76.296	1.64	-2	6.4+
		Maximum Voltage (Line-Line)	Minimum Voltage (Line-Line)	Total Load, Power Factor	Power Factor Measurement	Infeed, Power Factor	Total Power Factor, Infeed
		kV	kV				
	30	29.5	0.8	0.8	0.845	0.845	

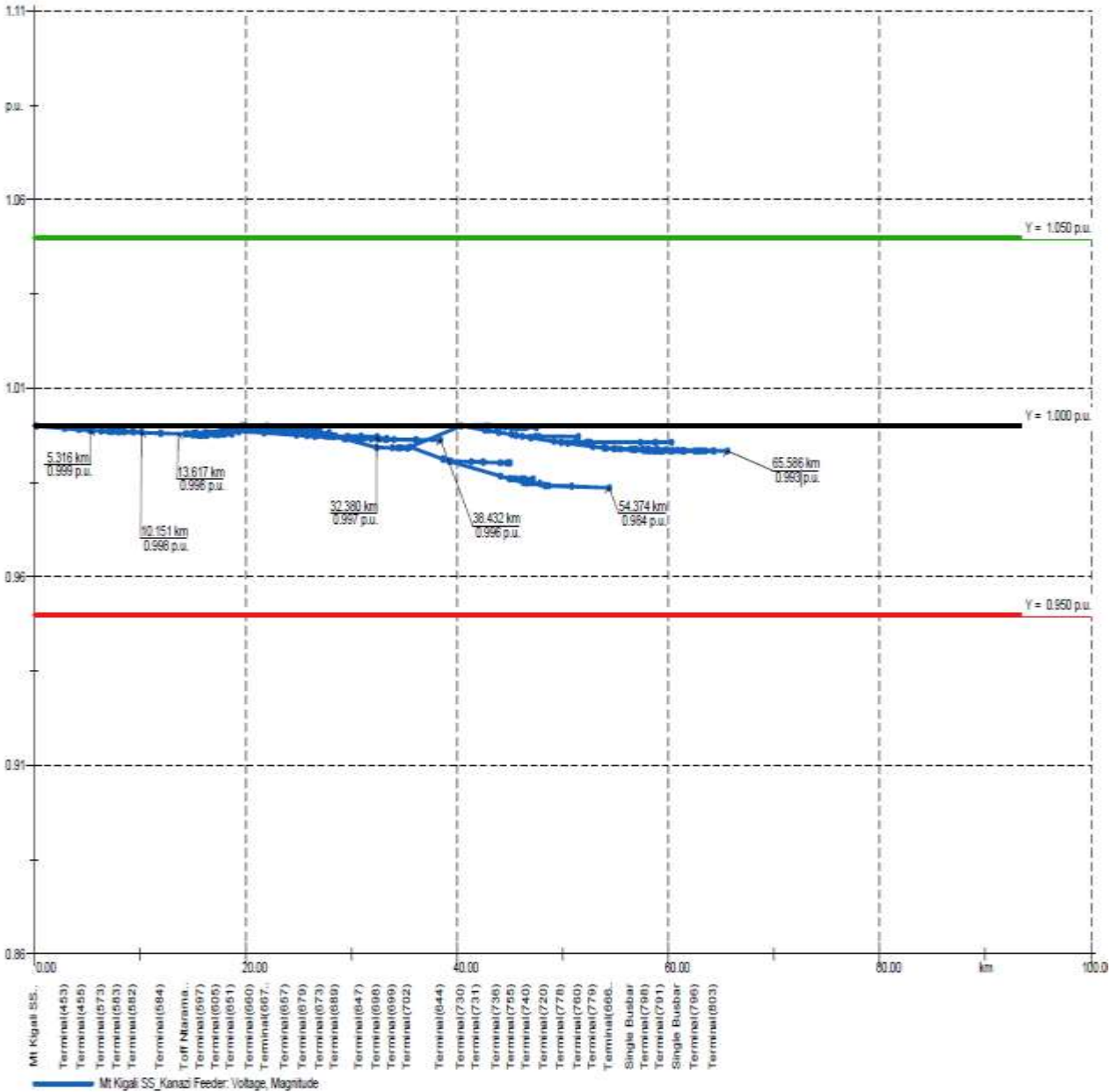


Figure 13 Voltage profile in the system with three Distributed Generations units

Seven locations along the feeder have been identified as reference points for the entire feeder after the integration of distributed generation (DG) units. These locations are recorded in Table 9, which shows the distance versus voltage (p.u.) of the T-off locations on the Kanazi feeder.

Table 9: Recorded T-off locations on Kanazi feeder after integration of Three Distributed Generations units

No	Location	Distance (Km)	Voltage (pu)
1	T-off Rwesero	5.316	0.999
2	T-off Rubungo	10.151	0.998
3	T-ff Ntarama	13.617	0.998
4	T-off Mbyo	32.380	0.997
5	T-off Coperative Imbere Heza	38.432	0.996
6	T-off Minagri Pump	54.374	0.984
7	T-off Kivusha	65.586	0.993

4.4 Integration of Three Distributed Generation unit combined with Two Capacitor Banks (Case 4.)

At this stage, the Kanazi network model was simulated in PowerFactory software with three distributed generation (DG) units combined with two capacitor banks. The DG units were placed at the same locations where capacitor banks had previously been installed. Additionally, one capacitor bank shared a location with a DG unit at T-off Kavure, while the other was placed at a new location, T-off Bugesera District Office. This configuration yielded the best results, achieving further reductions in power losses and enhanced voltage profiles.

As shown by the technical parameters of the Kanazi feeder, the voltage profile and power loss were analyzed before and after the integration of distributed generation (DG) units combined with capacitor banks. Initially, with only distributed generation units, the active power loss was 0.1694 MW, and the minimum line-to-line voltage was 29.5 kV. However, after incorporating both distributed generation units and capacitor banks, the active power loss further decreased to 0.2031 MW, while the minimum line-to-line voltage improved to 29.9 kV, as shown in Figure 16 and Table 10 below.

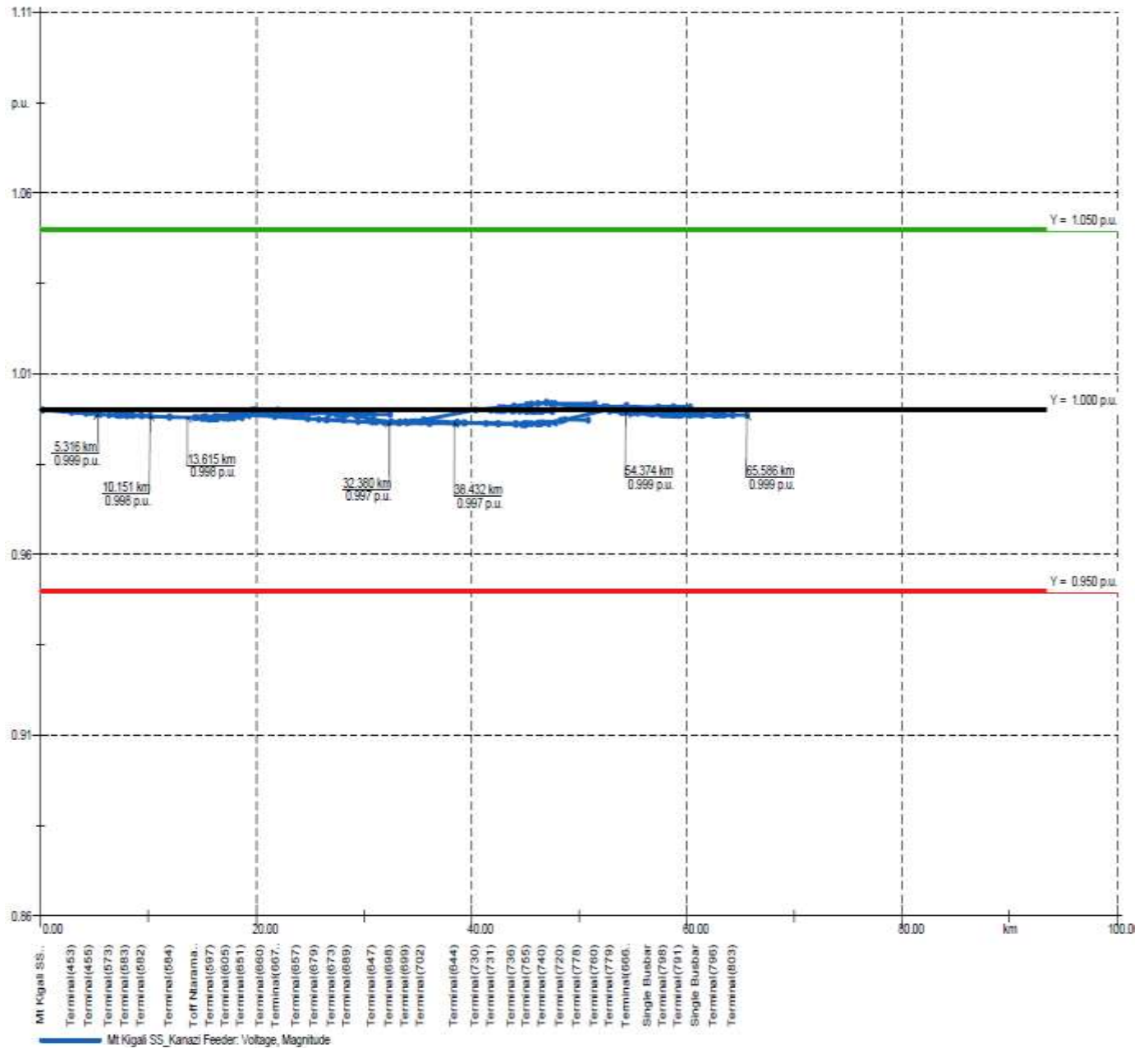


Figure 14 Kanazi Feeder Voltage profile in the system with three Distributed Generations units combined with Two Capacitor Banks

Table 10: Technical parameters of Kanazi network model after integration of Three Distributed Generations units and Two Capacitor Banks

Name	Total Active Power, Infeed	Total Load, Active Power	Losses, P	Max. Loading	Max. Voltage Drop	Total Reactive Power, Infeed	Total Apparent Power, Infeed
	MW	MW	MW	%	%	Mvar	MVA
Mt Kigali SS_ KANAZI	3.254	5.901	0.2031	64.356	0.407	-2.1	3.9+
		Maximum Voltage (Line-Line)	Minimum Voltage (Line-Line)	Total Load, Power Factor	Power Factor Measurement	Infeed, Power Factor	Total Power Factor, Infeed
		kV	kV				
		30.1	29.9	0.8	0.8	0.845	0.845

Seven locations along the feeder have been identified as reference points for the entire feeder after the integration of distributed generation (DG) units combined with Capacitor Banks. These locations are recorded in Table 11, which shows the distance versus voltage (p.u.) of the T-off locations on the Kanazi feeder.

Table 11: Recorded T-off locations on Kanazi feeder after integration of Three Distributed Generations units combined with Two Capacitor banks.

No	Location	Distance (Km)	Voltage (p.u)
1	T-off Rwesero	5.316	0.999
2	T-off Rubungo	10.151	0.998
3	T-ff Ntarama	13.617	0.998
4	T-off Mbyo	32.380	0.997
5	T-off Coperative Imbere Heza	38.432	0.997
6	T-off Minagri Pump	54.374	0.999
7	T-off Kivusha	65.586	0.999

CHAPTER 5: RESULTS & DISCUSSION

This chapter presents the results obtained from the simulation of the Kanazi feeder network under four different scenarios: the base case (without compensation), integration of capacitor banks, integration of Distributed Generation (DG) units, and the combined integration of both capacitor banks and DG units. The results are analyzed to evaluate the effectiveness of these strategies in improving the voltage profile and reducing power losses in the Kanazi feeder.

5.1 Combined Recorded T-off locations on Kanazi feeder for Voltage vs Distance.

The voltage profiles at seven selected T-off locations along the Kanazi feeder were recorded and compared across the four scenarios. Table 12 summarizes the per-unit voltage values at these locations, while Figure 17 illustrates the voltage versus distance curve for each scenario.

Table 12: Per unit Voltage vs Distance for seven selected locations

T-off Names	Distance (Km)	Base Voltage (p.u)	SC1 Voltage (p.u)	SC2 Voltage (p.u)	SC3 Voltage (p.u)
T-off Rwesero	5.316	0.989	0.992	0.999	0.999
T-off Rubungo	10.151	0.97	0.988	0.998	0.998
T-off Ntarama	13.617	0.95	0.97	0.998	0.998
T-off Mbyo	32.38	0.901	0.966	0.997	0.997
T-off Coperative Imbere Heza	38.432	0.934	0.963	0.996	0.997
T-off Minagri Pump	54.374	0.883	0.955	0.984	0.999
T-off Kivusha	65.586	0.884	0.968	0.993	0.999

Per Unit Voltage vs. Distance Curve

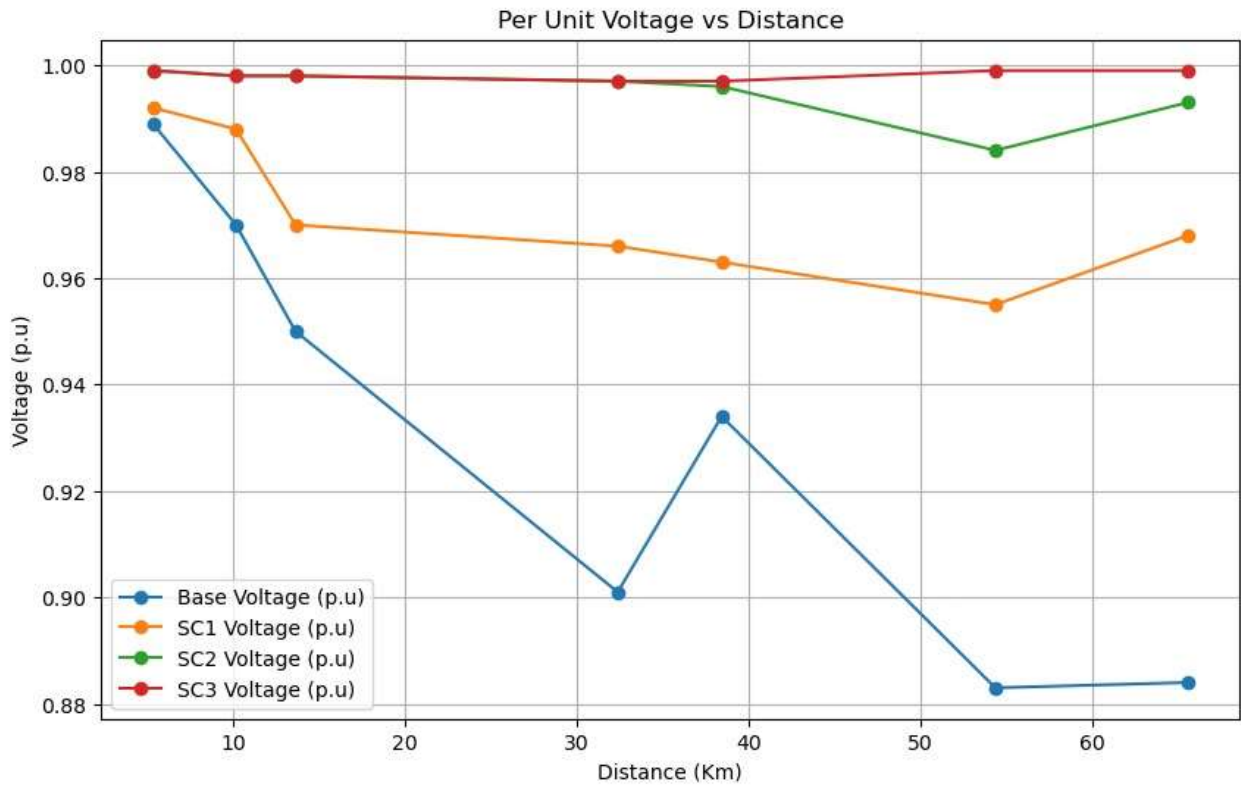
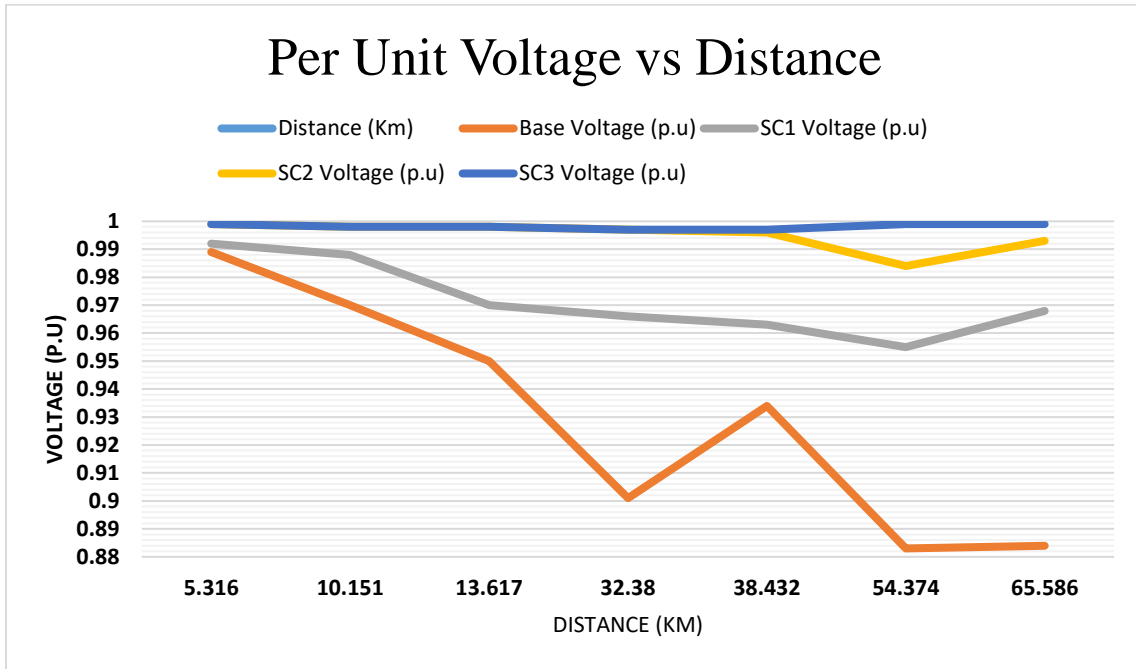


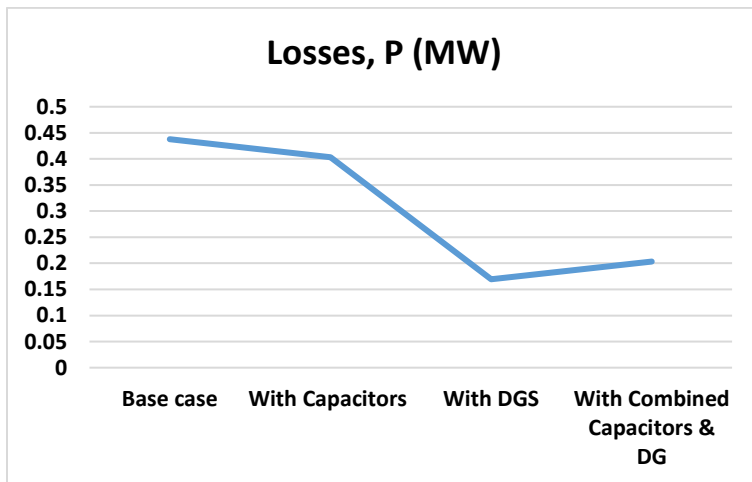
Figure 15 Per unit Voltage vs Distance curve

The voltage profiles show significant improvements across all scenarios, with the combined integration of capacitor banks and DG units (SC3) achieving the highest voltage levels at all T-off locations. The base case exhibited voltage drops below acceptable limits, particularly at remote locations such as T-off Minagri Pump and T-off Kivusha. However, the integration of capacitor banks (SC1) and DG units (SC2) improved the voltage profile, with the combined approach (SC3) ensuring that the voltage remained within acceptable limits across the entire feeder.

The active power losses (P) for the Kanazi feeder were recorded for each scenario, as summarized in Table 13.

Table 13: Combined Recorded losses P(MW) for Kanazi feeder

Scenarios	Losses, P (MW)
Base case	0.4378
With Capacitors (SC1)	0.403
With DGs (SC2)	0.1694
With Combined Capacitors & DG (SC3)	0.2031



The results indicate that the integration of capacitor banks (SC1) reduced active power losses by approximately **8%**, while the integration of DG units (SC2) achieved a more significant reduction of **61%**. The combined approach (SC3) resulted in a **54%** reduction in active power losses compared to the base case. Although the combined scenario did not achieve the lowest losses, it provided the best overall improvement in voltage stability and power loss reduction.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

This study aimed to address the challenges of voltage instability and power losses in the Kanazi feeder by exploring the integration of Distributed Generation (DG) units and capacitor banks. Through a structured approach involving data collection, modeling, and simulation using DigSILENT PowerFactory software, the research evaluated four scenarios: the base case, integration of capacitor banks, integration of DG units, and a combined approach integrating both technologies. The results demonstrated that the combined integration of DG units and capacitor banks provided the most significant improvements in voltage stability and power loss reduction.

Key findings include:

- The integration of capacitor banks alone reduced active power losses from 0.4378 MW to 0.403 MW and improved the minimum line-to-line voltage from 26.5 kV to 28.6 kV.
- The integration of DG units further reduced active power losses to 0.1694 MW and improved the minimum line-to-line voltage to 29.5 kV.
- The combined integration of DG units and capacitor banks resulted in the lowest active power losses (0.2031 MW) and the highest minimum line-to-line voltage (29.9 kV), demonstrating the synergistic effect of these technologies.

The study concludes that the strategic placement and sizing of DG units and capacitor banks are critical for maximizing their benefits. This approach not only improves voltage stability and reduces power losses but also enhances the overall efficiency and reliability of the distribution network. The findings provide a practical and cost-effective solution for addressing voltage profile deterioration and power loss issues in the Kanazi feeder and similar distribution networks.

6.2 Recommendation

Based on the findings of this study, the following recommendations are proposed for further research and practical implementation:

1. **Optimal Sizing and Placement:** Conduct further studies to determine the optimal sizing and placement of capacitor banks and DG units to maximize loss reduction and voltage profile improvement. Advanced optimization techniques, such as genetic algorithms or particle swarm optimization, could be employed to identify the best locations and capacities.
2. **Dynamic Load Conditions:** Investigate the impact of varying load conditions on the effectiveness of capacitor banks and DG integration. This will ensure that the proposed solutions remain reliable under different operational scenarios, including peak and off-peak demand periods.
3. **Real-Time Monitoring Systems:** Implement real-time monitoring systems to track voltage variations and power losses continuously. This will enable utilities to optimize the performance of capacitor banks and DG units dynamically, ensuring consistent voltage stability and minimal losses.
4. **Renewable-Based DG Units:** Explore the use of renewable energy-based DG units, such as solar photovoltaic systems, to enhance sustainability while improving voltage stability. This aligns with Rwanda's commitment to clean and renewable energy sources.
5. **Economic and Reliability Analysis:** Conduct a comprehensive economic analysis to evaluate the cost-effectiveness of integrating capacitor banks and DG units. Additionally, assess the long-term reliability impacts of high DG penetration on the distribution network.

By adopting these recommendations, utility companies and policymakers can enhance the performance of distribution networks, reduce power losses, and improve voltage stability, ultimately contributing to a more reliable and efficient electricity supply for consumers.

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Appendices

Table 14: List of all Transformers connected on Kanazi feeder.

Total List Transformers installed on Kanazi Feeder						
	Description	Act. Power	React. Power.	App. Power	I	Pow. Factor
No	Transformer Name	kW	kvar	kVA	kA	
1	ACM LTD	85	52.67827	100	0.001925	0.85
2	ACOTE MTN NGENDA	267.75	165.9366	315	0.006062	0.85
3	AIRTEL-KAGASA	21.25	13.16957	25	0.000481	0.85
4	ARETE PUBLIC LIGHT	21.25	13.16957	25	0.000481	0.85
5	ARRETE CENTRE	21.25	13.16957	25	0.000481	0.85
6	AYABARAMBA	21.25	13.16957	25	0.000481	0.85
7	BAMBOO RIVERSIDE LTD	42.5	26.33914	50	0.000962	0.85
8	BATIMA CENTRE	212.5	131.6957	250	0.004811	0.85
9	BENIMPUWE	21.25	13.16957	25	0.000481	0.85
10	BIDUDU	21.25	13.16957	25	0.000481	0.85
11	BLUE LAKES VILLAGE	85	52.67827	100	0.001925	0.85
12	BRIGHT -LIGHT	21.25	13.16957	25	0.000481	0.85
13	BUGESERA AGRIBUSINESS COMPANY	850	526.7827	1000	0.019245	0.85
14	BUGESERA-DISTRICT-OFFICE	212.5	131.6957	250	0.004811	0.85
15	BUHORO	12.75	7.90174	15	0.000289	0.85
16	BUTAMWA	21.25	13.16957	25	0.000481	0.85
17	CONCASSEUR AYABARAMBA	21.25	13.16957	25	0.000481	0.85
18	CRYSTAL BOTTLING Co	340	210.7131	400	0.007698	0.85
19	CYERU PUBLIC LIGHT	21.25	13.16957	25	0.000481	0.85

			7		1	
20	DIHIRO I CENTER	21.25	13.1695 7	25	0.00048 1	0.85
21	DIHIRO II PUMP	21.25	13.1695 7	25	0.00048 1	0.85
22	DIHIRO1	21.25	13.1695 7	25	0.00048 1	0.85
23	DIHIRO2	21.25	13.1695 7	25	0.00048 1	0.85
24	E.P NYARUBANDE /RUNZENZE	42.5	26.3391 4	50	0.00096 2	0.85
25	EP KAMABUYE	42.5	26.3391 4	50	0.00096 2	0.85
26	ETO NYAMATA	85	52.6782 7	100	0.00192 5	0.85
27	FARM/KAMPEKA(1)	12.75	7.90174	15	0.00028 9	0.85
28	GACUCU	42.5	26.3391 4	50	0.00096 2	0.85
29	GAHARWA	21.25	13.1695 7	25	0.00048 1	0.85
30	GAHEMBE	85	52.6782 7	100	0.00192 5	0.85
31	GAKAMBA I	42.5	26.3391 4	50	0.00096 2	0.85
32	GAKO APEX ACADEMY	136	84.2852 2	160	0.00307 9	0.85
33	GAKO MILITARY CAMP	340	210.713 1	400	0.00769 8	0.85
34	GAKO MYARIRO FARM	42.5	26.3391 4	50	0.00096 2	0.85
35	GAKO MYARIRO RF	42.5	26.3391 4	50	0.00096 2	0.85
36	GASENGA	21.25	13.1695 7	25	0.00048 1	0.85
37	GASENYI	12.75	7.90174	15	0.00028 9	0.85
38	GASHORA CENTRE	212.5	131.695 7	250	0.00481 1	0.85
39	GASORO VILLAGE	12.75	7.90174	15	0.00028 9	0.85
40	GATARE(3)	85	52.6782 7	100	0.00192 5	0.85
41	GATERA CONCRASSEUR	21.25	13.1695 7	25	0.00048 1	0.85

42	GIKURAZO	12.75	7.90174	15	0.00028 9	0.85
43	HCR PUMPING GASHORA	85	52.6782 7	100	0.00192 5	0.85
44	IHARA	12.75	7.90174	15	0.00028 9	0.85
45	ISAR KARAMA	21.25	13.1695 7	25	0.00048 1	0.85
46	KABEZA	85	52.6782 7	100	0.00192 5	0.85
47	KABEZA_KANZENZE	21.25	13.1695 7	25	0.00048 1	0.85
48	KABUKUBA JURU	212.5	131.695 7	250	0.00481 1	0.85
49	KABUYE	21.25	13.1695 7	25	0.00048 1	0.85
50	KAGASA	42.5	26.3391 4	50	0.00096 2	0.85
51	KAGOMASI	42.5	26.3391 4	50	0.00096 2	0.85
52	KAMATAMU	21.25	13.1695 7	25	0.00048 1	0.85
53	KAMATAMU II	21.25	13.1695 7	25	0.00048 1	0.85
54	KAMIBIRIZI	42.5	26.3391 4	50	0.00096 2	0.85
55	KAMUDUSI	12.75	7.90174	15	0.00028 9	0.85
56	KANAZI CELL OFFICE	42.5	26.3391 4	50	0.00096 2	0.85
57	KANZENZE ABATURAGE	85	52.6782 7	100	0.00192 5	0.85
58	KANZENZE CELL OFFICE	85	52.6782 7	100	0.00192 5	0.85
59	KANZENZE PUBLIC LIGHT	21.25	13.1695 7	25	0.00048 1	0.85
60	KARAMBI	21.25	13.1695 7	25	0.00048 1	0.85
61	KARIZINGI	21.25	13.1695 7	25	0.00048 1	0.85
62	KARUMUNA	85	52.6782 7	100	0.00192 5	0.85
63	KARUMUNA LEATHER	425	263.391 4	500	0.00962 3	0.85
64	KARUMUNA WPS	42.5	26.3391 4	50	0.00096 2	0.85

65	KAVURE	21.25	13.1695 7	25	0.00048 1	0.85
66	KAYENZI I CARRIERE	42.5	26.3391 4	50	0.00096 2	0.85
67	KAYENZI II MAJORO	212.5	131.695 7	250	0.00481 1	0.85
68	KAYOVU	21.25	13.1695 7	25	0.00048 1	0.85
69	KAZIRAMIRE	21.25	13.1695 7	25	0.00048 1	0.85
70	KIBENGA	85	52.6782 7	100	0.00192 5	0.85
71	KIGINA	12.75	7.90174	15	0.00028 9	0.85
72	KIMPALA	12.75	7.90174	15	0.00028 9	0.85
73	KINDONYI	42.5	26.3391 4	50	0.00096 2	0.85
74	KINIHIRA	42.5	26.3391 4	50	0.00096 2	0.85
75	KINTAMBWE /RUSINGIZA	12.75	7.90174	15	0.00028 9	0.85
76	KINTAMBWE CELL	12.75	7.90174	15	0.00028 9	0.85
77	KINYANA	12.75	7.90174	15	0.00028 9	0.85
78	KINYARA	42.5	26.3391 4	50	0.00096 2	0.85
79	KIVUSHA	21.25	13.1695 7	25	0.00048 1	0.85
80	KOPERATIVE IMBERE HEZA	212.5	131.695 7	250	0.00481 1	0.85
81	LA PALISSE GASHORA	85	52.6782 7	100	0.00192 5	0.85
82	LA PALISSE NYAMATA	850	526.782 7	1000	0.01924 5	0.85
83	LAKESIDE FISH FARM	85	52.6782 7	100	0.00192 5	0.85
84	LISIERE	21.25	13.1695 7	25	0.00048 1	0.85
85	MANEBU LTD	212.5	131.695 7	250	0.00481 1	0.85
86	MARANYUNDO PUMPING STATIO N	136	84.2852 2	160	0.00307 9	0.85
87	MAVOKA	21.25	13.1695 7	25	0.00048 1	0.85

88	MAYANGE A	170	105.356 5	200	0.00384 9	0.85
89	MAYANGE RICE	212.5	131.695 7	250	0.00481 1	0.85
90	MAYANGE WORLD MEAT	12.75	7.90174	15	0.00028 9	0.85
91	MAYANGE-HEALTH-CENTER	42.5	26.3391 4	50	0.00096 2	0.85
92	MBUGANZELI 1	21.25	13.1695 7	25	0.00048 1	0.85
93	MBUGANZELI 2	12.75	7.90174	15	0.00028 9	0.85
94	MBUGANZERI AGAKIRIRO	212.5	131.695 7	250	0.00481 1	0.85
95	MBYO	85	52.6782 7	100	0.00192 5	0.85
96	MINAGRI PUMP I	340	210.713 1	400	0.00769 8	0.85
97	MINAGRI PUMP II	212.5	131.695 7	250	0.00481 1	0.85
98	MINAGRI STORE RICE	212.5	131.695 7	250	0.00481 1	0.85
99	MINE RWERU	12.75	7.90174	15	0.00028 9	0.85
100	MIRAYI LAKE HOTEL	21.25	13.1695 7	25	0.00048 1	0.85
101	MONT KIGALI	21.25	13.1695 7	25	0.00048 1	0.85
102	MTN-NGENDA	42.5	26.3391 4	50	0.00096 2	0.85
103	MUBILIGI PAUL CONCASER	212.5	131.695 7	250	0.00481 1	0.85
104	MUGINA	12.75	7.90174	15	0.00028 9	0.85
105	MUJWIRI CENTER	21.25	13.1695 7	25	0.00048 1	0.85
106	MURAMA	42.5	26.3391 4	50	0.00096 2	0.85
107	MURAMBI (1)	21.25	13.1695 7	25	0.00048 1	0.85
108	MUSOVU LASIERA	21.25	13.1695 7	25	0.00048 1	0.85
109	MUYOBORO	21.25	13.1695 7	25	0.00048 1	0.85
110	MWENDO (1)	21.25	13.1695 7	25	0.00048 1	0.8

111	MWOGO SECTOR OFFICE	42.5	26.3391 4	50	0.00096 2	0.85
112	MWOGO ZOA HOSPITAL	21.25	13.1695 7	25	0.00048 1	0.85
113	NELSON MANDELA-SCHOOL	12.75	7.90174	15	0.00028 9	0.85
114	NEMBA ANCIEN DOUANE	12.75	7.90174	15	0.00028 9	0.85
115	NEMBA DOUANE	212.5	131.695 7	250	0.00481 1	0.85
116	NEMBA VILLAGE	21.25	13.1695 7	25	0.00048 1	0.85
117	NEW OFFICE BUGESERA	136	84.2852 2	160	0.00307 9	0.85
118	NKANGA RUZO	12.75	7.90174	15	0.00028 9	0.85
119	NKANIKA	42.5	26.3391 4	50	0.00096 2	0.85
120	NMI NTARAMA	42.5	26.3391 4	50	0.00096 2	0.85
121	NTARAMA SECTOR OFFICE	21.25	13.1695 7	25	0.00048 1	0.85
122	NTARE SCHOOL	340	210.713 1	400	0.00769 8	0.85
123	NUMERO CENTRE	21.25	13.1695 7	25	0.00048 1	0.85
124	NYABAGENDWA CENTRE	85	52.6782 7	100	0.00192 5	0.85
125	NYABIVUMU	42.5	26.3391 4	50	0.00096 2	0.85
126	NYAGATOVU	85	52.6782 7	100	0.00192 5	0.85
127	NYAKABINGO	12.75	7.90174	15	0.00028 9	0.85
128	NYAKABINGO KAJEVUBA	12.75	7.90174	15	0.00028 9	0.85
129	NYAKABINGO KIVUMU	12.75	7.90174	15	0.00028 9	0.85
130	NYAKWIBEREKA	21.25	13.1695 7	25	0.00048 1	0.85
131	NYAMATA AGAKIRIRO	340	210.713 1	400	0.00769 8	0.85
132	NYAMATA HOPITAL	136	84.2852 2	160	0.00307 9	0.85
133	NYAMATA VILLE	170	105.356 5	200	0.00384 9	0.85

134	NYARUNAZI	42.5	26.3391 4	50	0.00096 2	0.85
135	NYIRAGISEKE BWEMA	12.75	7.90174	15	0.00028 9	0.85
136	NYIRAGISEKE TERMINAL	212.5	131.695 7	250	0.00481 1	0.85
137	NYIRAMATUNTU	21.25	13.1695 7	25	0.00048 1	0.85
138	NYIRARUBOMBOZA	12.75	7.90174	15	0.00028 9	0.85
139	NYIRARUBOMBOZA1	12.75	7.90174	15	0.00028 9	0.85
140	NYIRARUBOMBOZA2	12.75	7.90174	15	0.00028 9	0.85
141	NZANGWA	212.5	131.695 7	250	0.00481 1	0.85
142	PADAB RURAMBI PUMP1	136	84.2852 2	160	0.00307 9	0.85
143	PADAB RURAMBI PUMP2	136	84.2852 2	160	0.00307 9	0.85
144	PALAST ROCK HOTEL	42.5	26.3391 4	50	0.00096 2	0.85
145	PEAL FEEDMILL HOUSE	425	263.391 4	500	0.00962 3	0.85
146	QUIOSQUE	21.25	13.1695 7	25	0.00048 1	0.85
147	RADAR	340	210.713 1	400	0.00769 8	0.85
148	RAFIKI FOUNDATION	340	210.713 1	400	0.00769 8	0.85
149	RAMIRO	21.25	13.1695 7	25	0.00048 1	0.85
150	RCS MAGERAGERE	212.5	131.695 7	250	0.00481 1	0.85
151	RDB WATER PUMP	42.5	26.3391 4	50	0.00096 2	0.85
152	RDB BUGESERA	85	52.6782 7	100	0.00192 5	0.85
153	REBERO KAMABUYE	21.25	13.1695 7	25	0.00048 1	0.85
154	RILIIMA PRISON	21.25	13.1695 7	25	0.00048 1	0.85
155	RILIMA BUHORO	12.75	7.90174	15	0.00028 9	0.85
156	RILIMA CENTRE ORTHOPEDIC	212.5	131.695 7	250	0.00481 1	0.85

157	RILIMA MARKET	12.75	7.90174	15	0.00028 9	0.85
158	ROND POINT	42.5	26.3391 4	50	0.00096 2	0.85
159	RUBIRA	12.75	7.90174	15	0.00028 9	0.85
160	RUBUNGO (1)	21.25	13.1695 7	25	0.00048 1	0.85
161	RUBUNGO (2)	21.25	13.1695 7	25	0.00048 1	0.85
162	RUGANDO CONCASSEUR	340	210.713 1	400	0.00769 8	0.85
163	RUGUNGA	42.5	26.3391 4	50	0.00096 2	0.85
164	RUGUNGA (1)	21.25	13.1695 7	25	0.00048 1	0.85
165	RUTETE	12.75	7.90174	15	0.00028 9	0.85
166	RWAKIBILIZI	170	105.356 5	200	0.00384 9	0.85
167	RWAKIBIRIZI CENTRE	85	52.6782 7	100	0.00192 5	0.85
168	RWANDA GIRLS-GASHORA	170	105.356 5	200	0.00384 9	0.85
169	RWANDA QUARRIMG COMPANY	21.25	13.1695 7	25	0.00048 1	0.85
170	RWESERO	21.25	13.1695 7	25	0.00048 1	0.85
171	RWEZA	21.25	13.1695 7	25	0.00048 1	0.85
172	RWIMINAZI	12.75	7.90174	15	0.00028 9	0.85
173	SOSOMA LTD	340	210.713 1	400	0.00769 8	0.85
174	SUMMER PALACE	255	158.034 8	300	0.00577 4	0.85
175	TOMINI MAYANGE	127.5	79.0174	150	0.00288 7	0.85
176	TRIBU INDUSTRY	136	84.2852 2	160	0.00307 9	0.85
177	TRUST INDUSTIES	850	526.782 7	1000	0.01924 5	0.85
178	UMUNARA NEMBA	212.5	131.695 7	250	0.00481 1	0.85
179	WASAC PUMP GASHORA	850	526.782 7	1000	0.01924 5	0.85

180	WORD-VISION-NYABAGENDWA	212.5	131.695 7	250	0.00481 1	0.85
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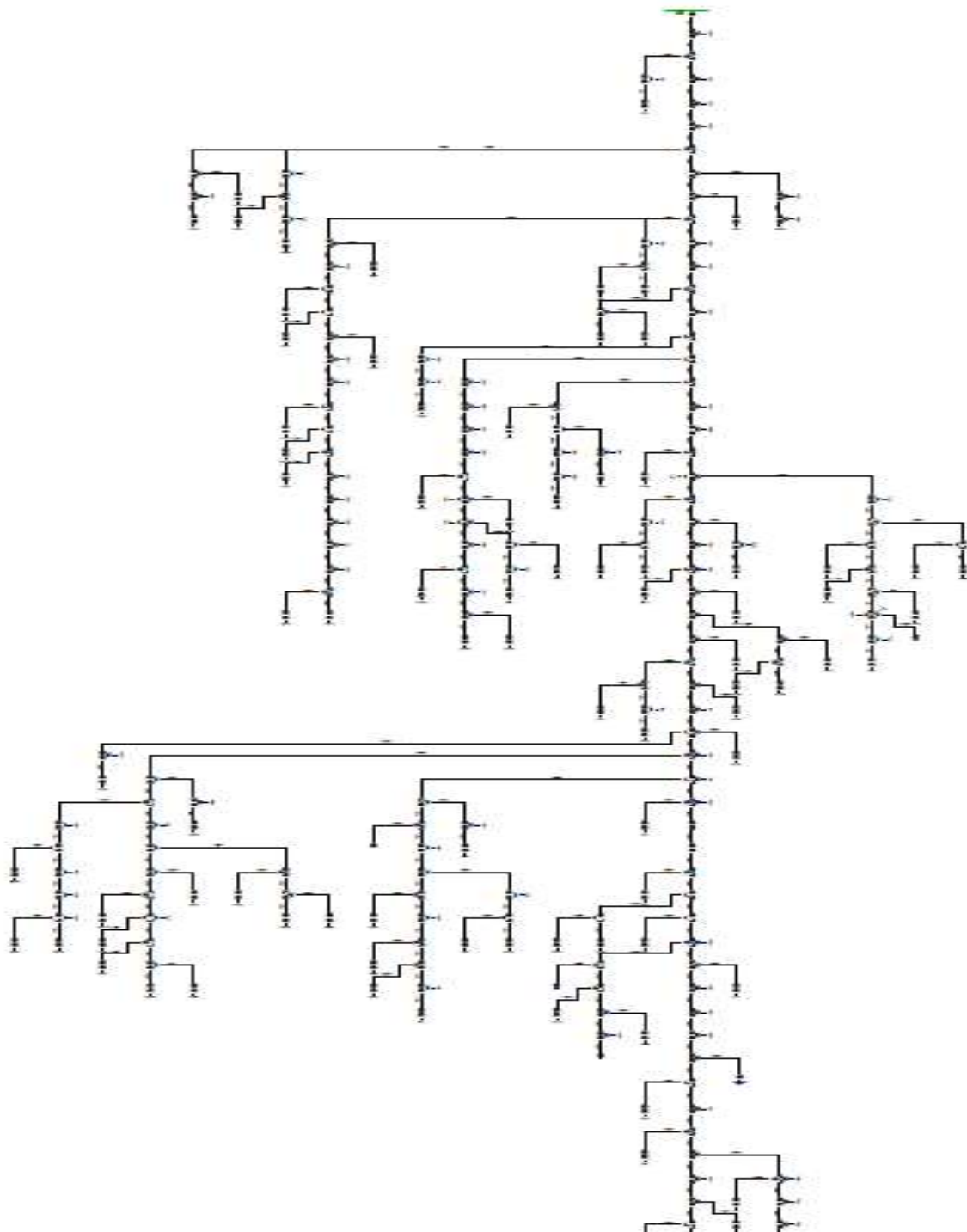


Figure 16 Kanazi Feeder SLD without results-Base (Case1)

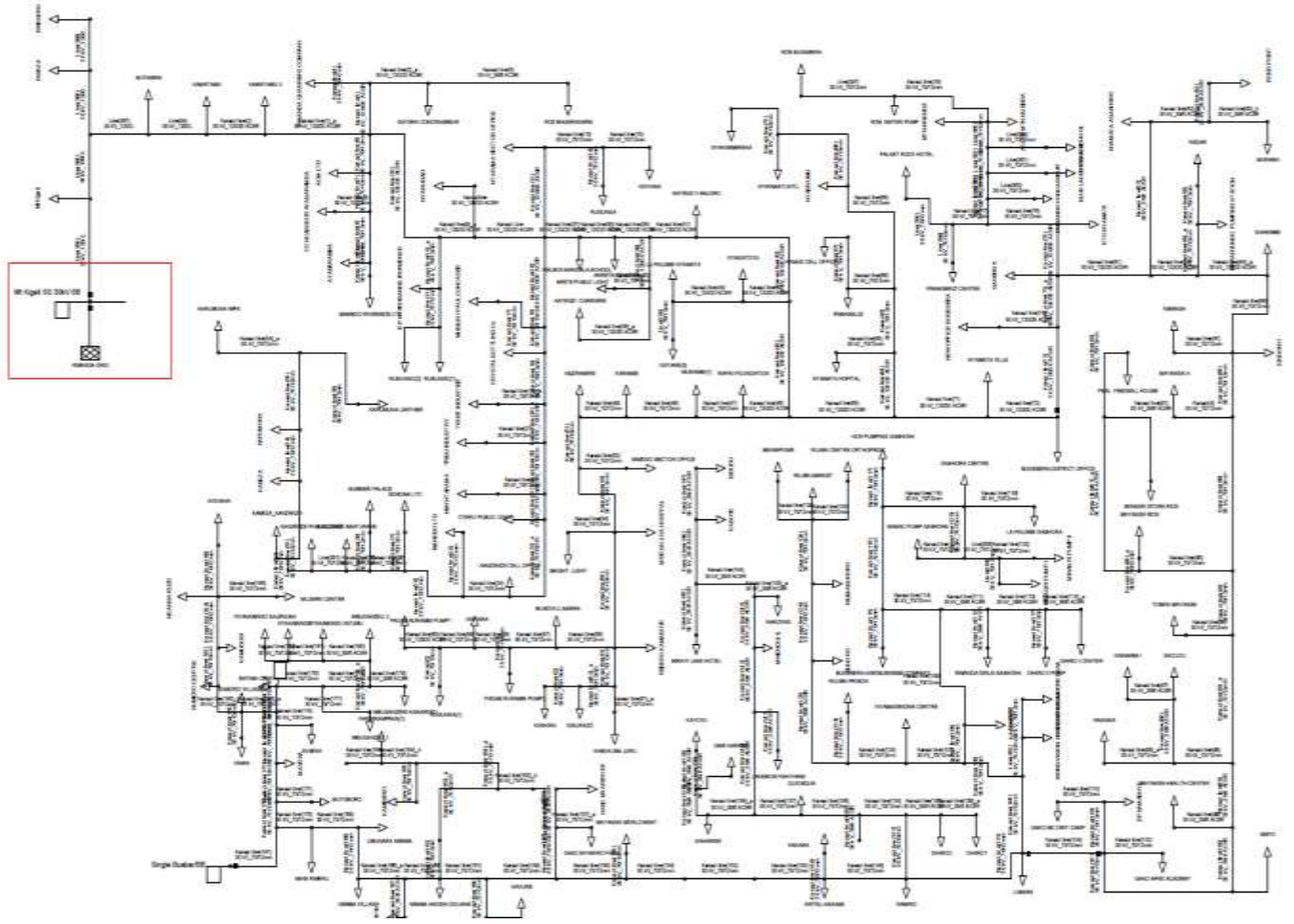


Figure 17 Kanazi Feeder SLD without results-Base (Case1)

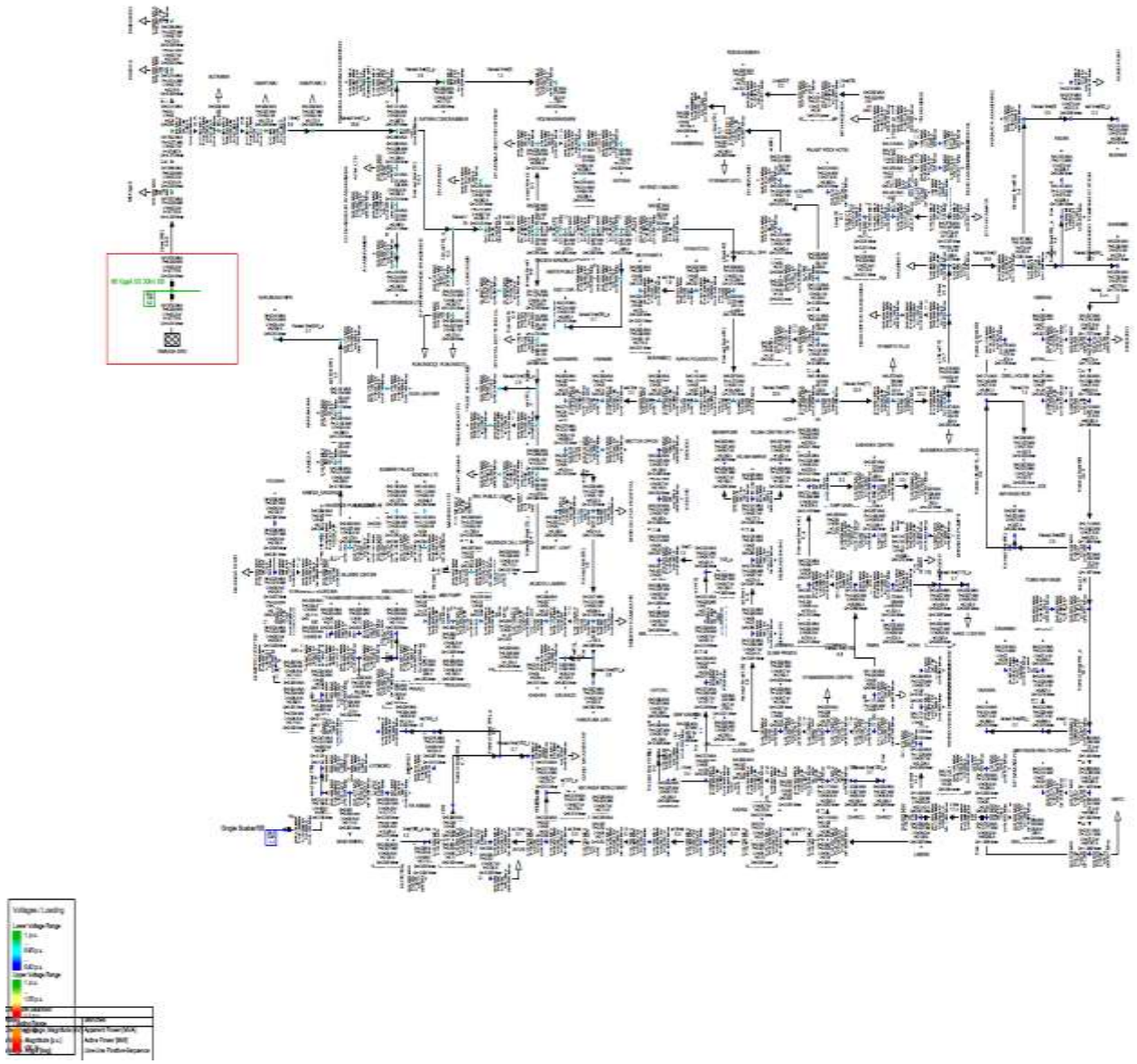


Figure 18 Kanazi Feeder SLD with results-Base (Case1)

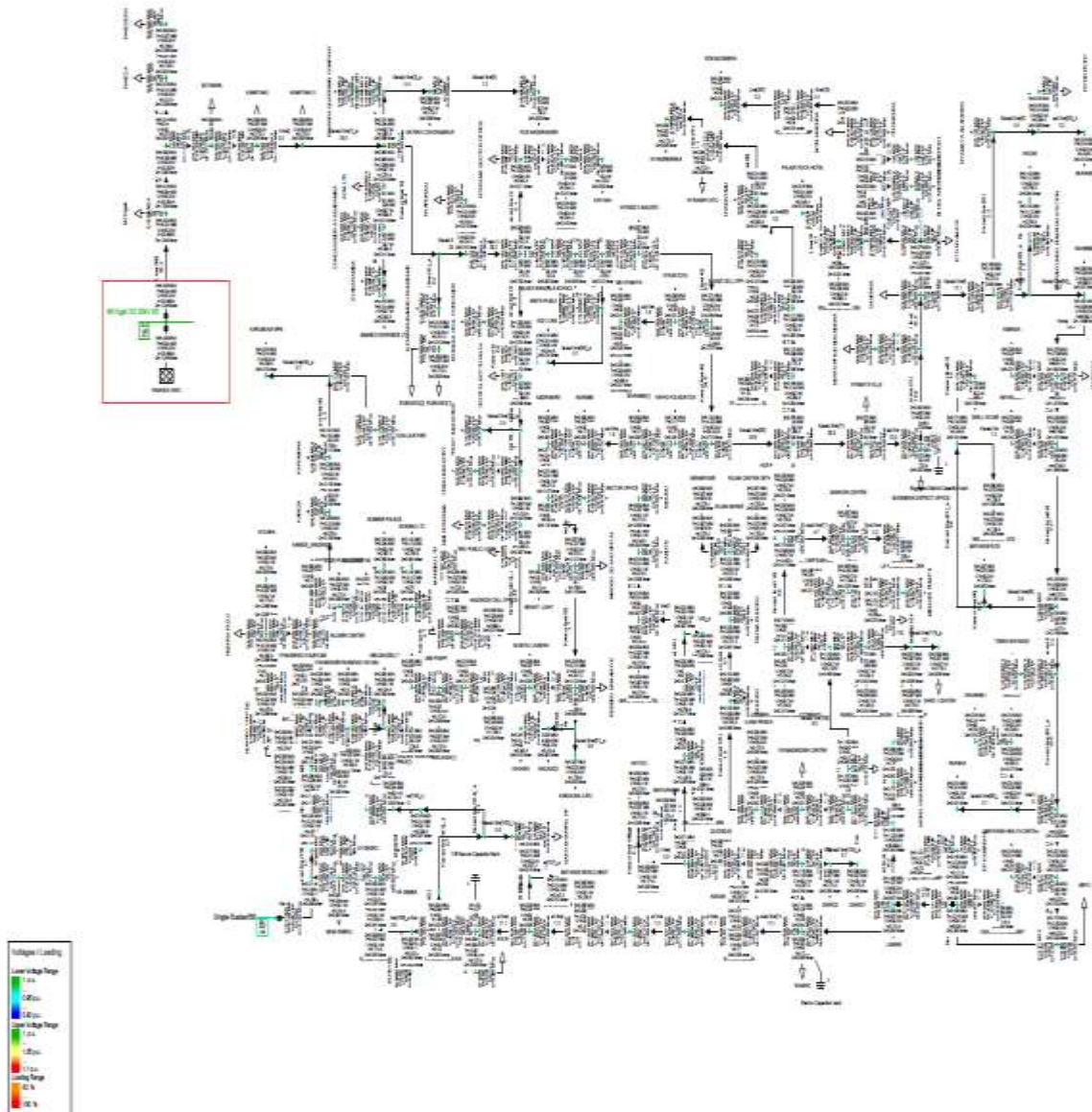


Figure 19 Kanazi Feeder SLD with results-Base + 3capacitor banks

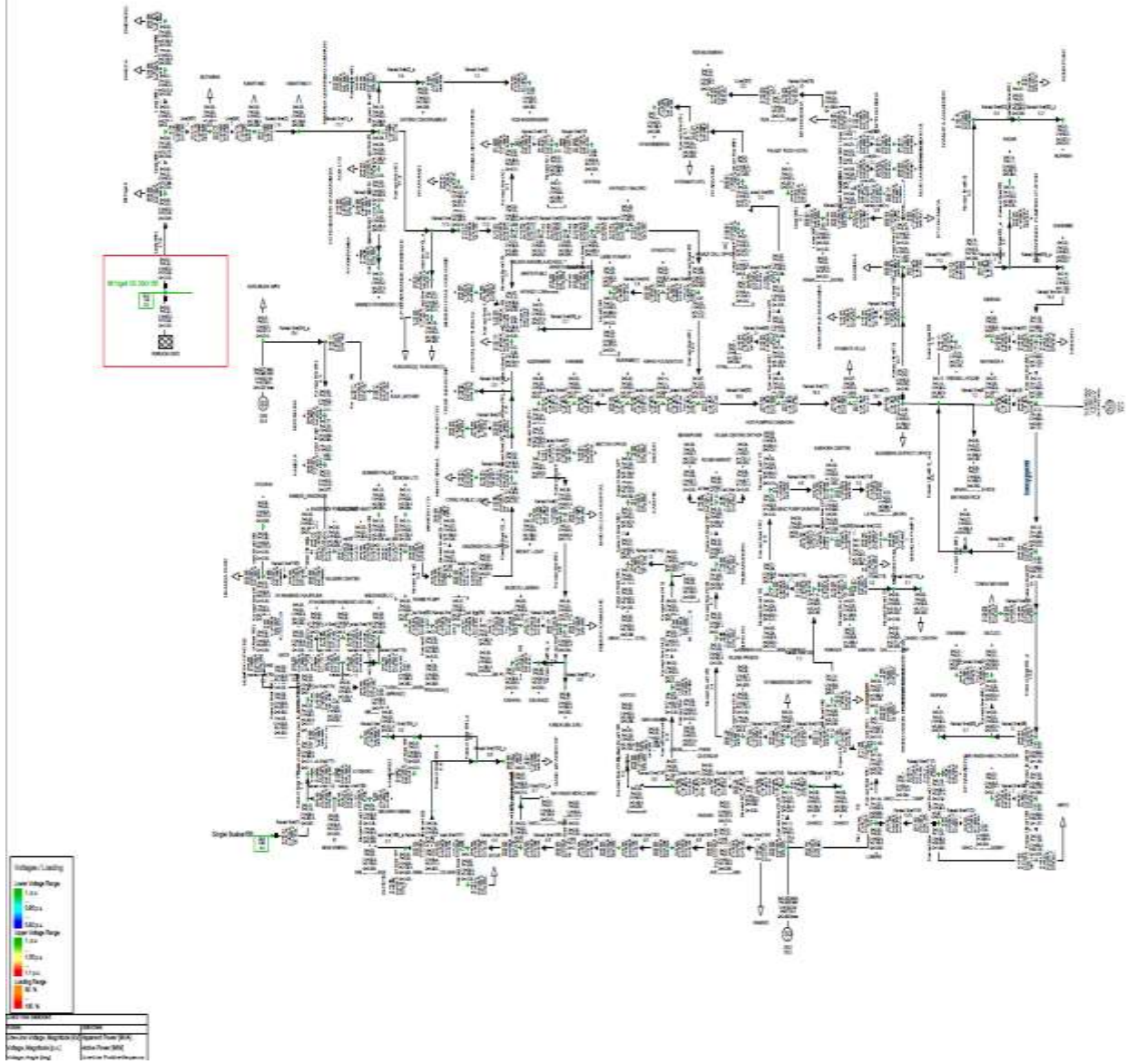


Figure 20 Kanazi Feeder SLD with results-Base + 3DG

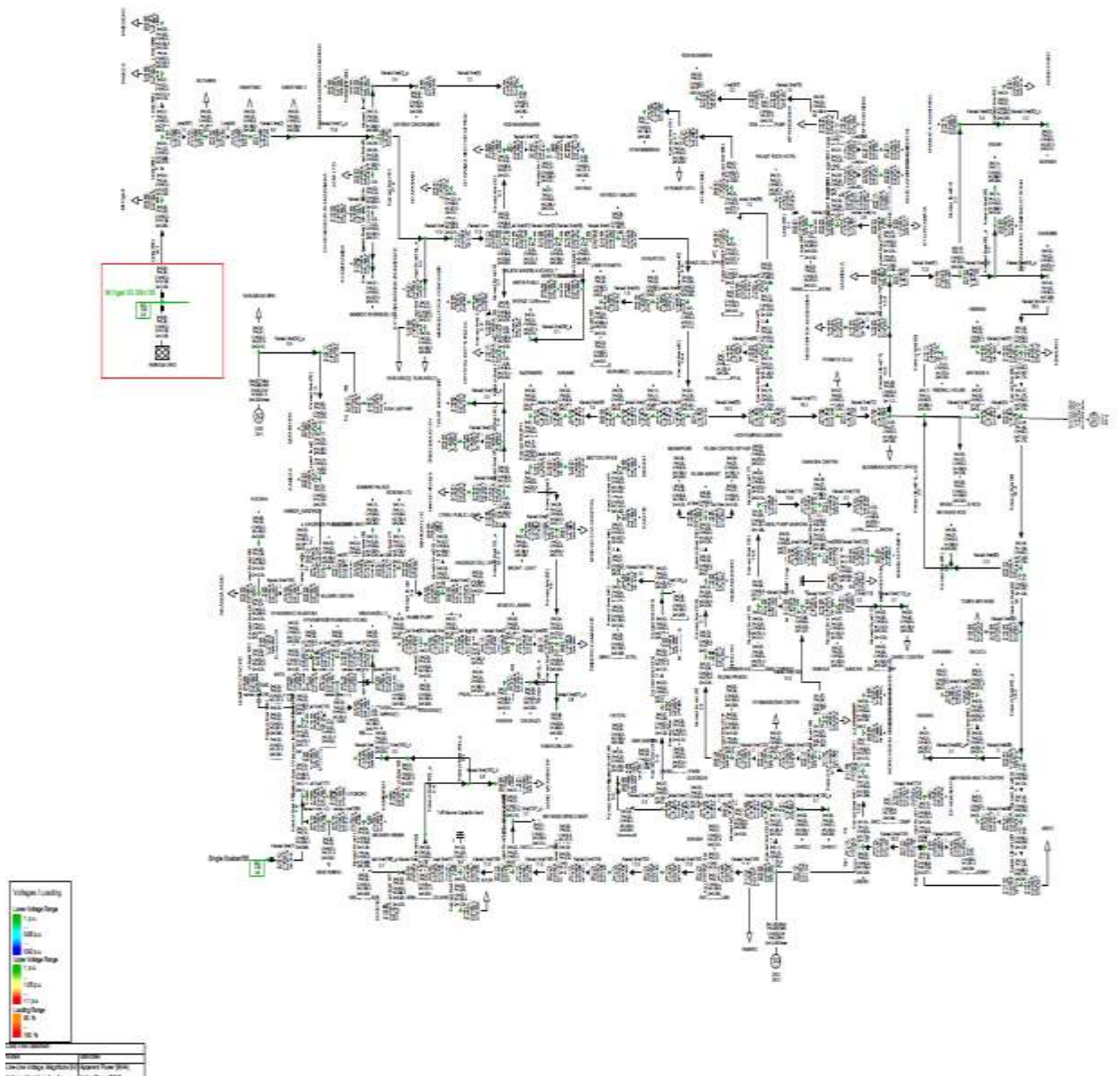


Figure 21 Feeder SLD with results-Base + 3DG & Capacitor banks