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FINAL YEAR PROJECT REPORT

NETWORK RECONFIGURATION AS A COST-EFFECTIVE STRATEGY FOR TECHNICAL LOSSES REDUCITION ON THE BUSITEMA TIIRA - TOFF

BY

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AREA OF STUDY: SMART GRID TECHNOLOGY, UGANDA'S DISTRIBUTION NETWORK

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ABSTRACT

Electrical distribution networks experience the highest concentration of technical power losses within utility systems, driven by physical line properties and loading patterns. In Uganda, long radial feeders serving mixed consumer segments frequently suffer from severe voltage degradation and heavy line losses. The Busitema-Tiira 33kV T-off feeder is a critical radial infrastructure segment serving a heterogeneous load profile, including intense inductive mining loads in Tiira, residential loads across trading centers, and the Busitema University main campus. Operating under un-optimized configuration, the feeder suffers from severe technical power losses and failure to optimally evacuate power from the local 4MW grid-connected solar plant. Traditional physical reinforcements remain capital-intensive, highlighting the need for cost-effective operational alternatives. This study investigates network reconfiguration as a low-cost strategy to optimize system performance without extensive capital asset installation. Relying on operational data from the Uganda Electricity Distribution Company Limited **(UEDCL),** a high-fidelity model of the T-off grid segment was built and validated using DIgSILENT PowerFactory and Power World Simulator. An AC power flow engine executing the Newton-Raphson method was used to establish a baseline state and locate loss hotspots. A multi-source optimization model was implemented by proposing a 33kV dedicated feeder line from the **UETCL** Tororo Substation, coordinated through three automated Tie Switches (Normally Open) and two Sectionalizing Switches (Normally Closed) using the Tie Open Point Optimization module. The optimization framework successfully shifted the feeder structure into an optimal radial state. Under peak conditions, active technical power losses were reduced by 41.19%, dropping from a baseline of 26.9 kW to 15.8 kW. This technical recovery translates into an annualized energy savings of 97,130.88 kWh, yielding UGX 31,878,354.82 in recovered utility revenue. The findings prove that network reconfiguration, paired with strategic automation, can drastically expand power system load-carrying capability and lower operational overhead. This approach serves as a viable, scalable operational model for electricity distribution companies across Uganda aiming to optimize efficiency on long radial feeders.

Keywords: Network Reconfiguration, Technical Losses, DIgSILENT PowerFactory, Feeder Optimization, Uganda Distribution Grid, Load-Carrying Capability

DECLARATION

We, **MOSES BYONABYE & PRODE ATWEBEMBEIRE,** the undersigned, declare that this report is our original work except where due acknowledgement has been made. And it has never been submitted to this university or any other institute of learning for partial fulfillment of any award.

Signature: .... Date ....6/17/2026..................

Signature: .... Date ....6/17/2026..................

APPROVAL

This is to certify that this work was done under the supervision of **Professor Richard Okou** & **Mr. FRANK MBABAALI** and has been approved for submission to the Department of Electrical Engineering at Busitema University.

Main Supervisor**: Professor Richard Okou**

Signature……………………………………… Date 6/27/2026 ……………………………………

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Signature……………………………………… Date 6/18/2026 ……………………………………

DEDICATION

We dedicate this research to the Department of Electrical Engineering, Faculty of Engineering & Technology, Busitema University, and the Uganda Electricity Distribution Company Limited **(UEDCL).**

May this work serve as a foundation for further studies and contribute towards improving the reliability and efficiency of power Distribution Networks in Uganda.

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SDG	Sustainable Development Goal
SCADA	Supervisory Control and Data Acquisition
UEDCL	Uganda Electricity Distribution Company Limited
UETCL	Uganda Electricity Transmission Company Limited
ACSR	Aluminum Conductor, Steel Reinforced
AAAC	All Aluminum Alloy conductor
OLTC	On -Load-Tap-Changers
MINLP	Mixed-Integer Nonlinear Programming
PSO	Particle Swarm Optimization
ACO	Ant Colony Optimization
MW	Mega Watt
BSP	Bulk Supply Point
CAIDI	Customer Average Interruption Duration Index
SAIDI	Systems Average Interruptions Duration Index
DPL	DIgSILENT Programming Language
DSL	DIgSILENT Simulation Language
IEEE	Institute of Electrical and Electronics Engineers
MINLP	Mixed-Integer Nonlinear Programming
MISOCP	Mixed-Integer Second-Order Cone Programming
GA	Genetic Algorithm

CHAPTER ONE

1.1 BACKGROUND

Electric power distribution systems are critical in ensuring reliable and efficient delivery of electricity to end-users(Javid et al., 2024). However, one of the persistent challenges faced by utilities worldwide is technical losses, the unavoidable energy dissipations that occur due to resistance in conductors, transformer inefficiencies, and other inherent characteristics of electrical equipment. These losses not only reduce the efficiency of power delivery but also increase operational costs, thereby affecting both utilities and consumers.

In Uganda, like many developing countries, technical losses in distribution networks remain a significant concern. The Busitema Tiira feeder, which supplies electricity to communities around Busitema University and Tiira town, has experienced notable losses due to factors such as long radial feeder lines, uneven load distribution, and inadequate network optimization. These inefficiencies contribute to higher operational costs, reduced voltage profiles, and poor reliability of supply.

One promising approach to address this challenge is network reconfiguration.

Network reconfiguration involves altering the topology of distribution feeders by opening and closing sectionalizing and tie switches. This process redistributes loads, balances currents, and minimizes power losses without requiring major infrastructure investments(*Power Distribution Network Reconfiguration Techniques: A Thorough Review*, n.d.). Unlike costly solutions such as upgrading conductors or installing new substations, reconfiguration is a cost-effective strategy that leverages existing assets to improve system performance.

Globally, studies have shown that feeder reconfiguration can lead to: reduction of active power losses, improvement of voltage stability, enhanced reliability indices, and better utilization of existing infrastructure

Applying this strategy to the Busitema Tiira feeder is particularly relevant because of its radial structure and the growing demand for electricity in the region. By systematically analyzing load flow and identifying optimal switching operations, the feeder can achieve significant reductions in technical losses, thereby improving efficiency and lowering costs for the utility.

Thus, this study seeks to explore network reconfiguration as a cost-effective strategy for technical loss reduction on the Busitema Tiira feeder, providing insights into how distribution utilities in Uganda can adopt innovative yet affordable solutions to enhance power delivery.

1.2 Problem Statement

Technical losses in Uganda's distribution network, primarily due to resistive losses in conductors and transformers, represent a significant drain on national economic resources. These losses are exacerbated by rapid and unplanned urbanization, aging infrastructure operating beyond optimal capacity, and static network operation that fails to adapt to daily and seasonal load variations.

Traditional solutions, such as constructing new lines or upgrading feeders and distributed generation, are capital-intensive and time-consuming ***(Karue & Murage, 2022).***

As a cost-effective alternative, network reconfiguration, strategically altering the open/closed status of sectionalizing and tie-switches, can redirect power flow to reduce losses.

However, identifying optimal configurations in complex, meshed networks is computationally intensive and impractical to perform manually.

This Research proposes the use of **Dig SILENT Power Factory** to model and analyze the Busitema–Tiira T-Off, providing a scientific basis for reconfiguration decisions aimed at minimizing technical losses and improving operational efficiency.

1.3 Main Objective

To develop a model of a Busitema tiira T-off aimed at demonstrating technical loss reduction achievable through network reconfiguration,

1.3.1 Specific Objectives:

1. To conduct a comprehensive baseline analysis to identify loss hotspots, overloaded sections, and voltage violations under current operating conditions.
2. To determine the optimal network configuration using Power Factory's optimization functions to minimize losses while respecting all operational constraints.
3. To quantify the magnitude of technical loss reduction by comparing the load-carrying capability and loss figures of the existing versus the optimized configuration.

1.3.2 Research Questions

1. What are the existing loss hotspots, overloaded stations, and voltage violations under the current operating conditions?
2. What is the optimal network configuration that minimizes technical losses while maintaining voltage limits and equipment loading within permissible limits?
3. What is the magnitude of technical loss reduction achieved through optimized network reconfiguration compared to the existing one?

1.4 JUSTIFICATION

Despite UEDCL's efforts to improve Distribution efficiency, the Busitema Tiira T- Off experiences high losses and voltage drop due to sub-optimal configuration & the heterogeneous nature of the loads, which consist of mining loads in Tiira town and the neighboring communities, residential loads in Ajuket Village, Busitema Trading center, and Ndaiga Trading center. This results in revenue losses, poor quality & increased operational costs,

Methods of loss reduction, such as distributive generation and network reinforcement, or equipment upgrade, are capital-intensive and time-consuming. Network reconfiguration, on the other hand, offers a cost-effective strategy by using existing switch positions to determine the optimal reconfiguration, which can be implemented through software optimization and control algorithms available in Dig Silent Power Factory Software.

The Busitema Tiira T-off was selected due to its strategic importance in supplying Busitema University, which is a major academic institution. Its location also offers logistical advantages for us since it's near our academic institution its easier for data collection, while its operational challenges present a valuable opportunity to demonstrate cost-effective loss reduction strategies that can be scaled across Uganda's distribution network by developing a model to demonstrate this potential, which provides an evidence-based approach to guide distribution engineers and decision-makers in improving feeder performance with minimal investment

1.5 SIGNIFICANCE

Network reconfiguration is a smart grid innovation technology that enhances infrastructure performance without costly upgrades

This study is significant because it provides **UEDCL** with a low-cost implementable solution to reduce technical losses and improve voltage reduce technical losses and improve voltage profiles on the Busitema tiira **T – Off** without capital investment in new infrastructure, thereby enhancing the revenue recovery.

This study addresses the persistent issue of technical losses on the **Busitema Tiira T-OFF** using a cost-effective approach. By applying network reconfiguration techniques, the research offers a practical solution that minimizes energy waste without requiring expensive infrastructure upgrades. Therefore, this supports the Sustainable Development Goals, for example

SDG7, which highlights affordable and clean energy. By minimizing energy waste, our strategy supports sustainable energy use and operational efficiency, which is in line with **SDG 12**. Reducing energy waste prevents unnecessary generation, which indirectly cuts carbon emissions and supports climate actions.

The findings benefit utility providers by improving operational efficiency and reliability and can serve as a scalable model for other feeders in Uganda's distribution network.

1.6 SCOPE OF THE RESEARCH STUDY

1.6.1 Conceptual scope

The study is limited to Busitema tiira T-off operated by UEDCL, technically covering load flow analysis, technical loss evaluation, and optimization of feeder configuration through selective opening and closing of sectionalizing and tie switches

The analysis was carried out using **Dig Silent Power Factory 15.1 & Power World Simulator** by utilizing the 2024 feeder load data, Conductor parameters, and network topology obtained from UEDCL. It evaluates optimization techniques, economic viability, and operational impacts, with a focus on enhancing voltage profiles and reliability in Uganda's power distribution context It does not cover non-technical losses, transient analysis, or physical implementation of proposed reconfiguration; characteristics of other feeders are out of scope

1.6.2 Geographical scope.

This study focuses on the Busitema Tiira feeder in Eastern Uganda, analyzing technical losses and evaluating network reconfiguration as a cost-effective mitigation strategy. The geographical scope is limited to this T-off, which serves the areas Busitema Tiira, Ndaiga, and other surrounding areas.

1.6.3 Time scope

The study was conducted over a period of eight 10 months, spanning from August 2025 to June 2026. This timeframe was divided into four distinct operational phases to ensure systematic completion of the project objectives:

1.6.3.1 Conceptualization and Preliminary Research (August to September 2025)

Formulating the research problem statement, setting the project scope, and performing an extensive literature review on smart grid technologies, distribution network optimization, and technical loss mitigation models within the sub-Saharan utility context.

1.6.3.2 Field Data Acquisition and Processing (September 2025 to January 2026)

Collaborating with power utility companies in Uganda, specifically Uganda Electricity Distribution Company Limited (UEDCL), to gather physical line parameters, transformer datasheets, grid layouts, SCADA logs, and peak demand data for the Busitema-Tiira 33kV T-off.

1.6.3.3 Network Modeling and Optimization Simulations (Jan 2026 to March 2026)

Building the high-fidelity virtual grid architecture in DIgSILENT PowerFactory v15.1 to execute baseline Newton-Raphson load flows. This phase included implementing the proposed multi-source dedicated feeder line, defining grid operational constraints, and running the Tie Open Point Optimization heuristic search algorithms.

1.6.3.4 Cross-Validation, Financial Appraisal, and Report Compilation (April 2026 to June 2026)

Exporting the finalized, optimal switching layout into Power World Simulator for platform cross-validation and load scalability stress-testing. This final phase concluded with the completion of the techno-economic viability calculations (NPV and Payback Period) and the academic technical report compilation.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

This chapter presents a comprehensive review of the literature about network reconfiguration as a cost-effective strategy for reducing technical losses on distribution networks, with specific application to the Busitema Tiira T-Off. The review examines the theoretical foundations of technical losses in distribution systems, traditional and modern loss reduction methods, the principles and mechanisms of network reconfiguration, and the capabilities of DIGSILENT Power Factory for reconfiguration analysis. The chapter concludes by identifying research gaps that justify the present study.

2.2 Technical Losses in Distribution Networks

2.2.1 Fundamental Nature of Technical Losses

Technical losses in electrical power distribution systems represent an inherent physical phenomenon arising from the dissipation of electrical energy as heat due to conductor resistance. These losses are fundamentally expressed by the I^2R formula, where I represents the current flowing through a conductor, and R represents the resistance of that conductor **(Kalambe & Agnihotri, 2014)**For alternating current systems, additional losses arise from skin effect (non-uniform current distribution across conductor cross-section) and proximity effect (magnetic interaction between adjacent conductors), though these typically account for a small fraction of total I^2R losses

The voltage drop along distribution feeders has a direct and compounding relationship with losses. As voltage decreases due to line impedance, the current must increase to deliver the same power to downstream loads, expressed by the relationship $P = VI \cos\varphi$. This creates a self-reinforcing cycle: voltage depression leads to higher currents, which in turn cause greater voltage drops and increased I^2R losses. This phenomenon is particularly pronounced on long radial feeders where endpoints may experience significant voltage sag under peak load conditions **(Kalambe & Agnihotri, 2014)**

2.3 Root Causes of Elevated Technical Losses

A comprehensive review by **(Obiora et al., 2025)** identifies numerous root causes that contribute to technical loss levels exceeding theoretically calculated minima across distribution networks. These causes can be categorized as line-related, loading-related, transformer-related, power quality-related, and installation and operational causes.

Line-related causes include lengthy distribution lines, which represent a primary contributor as resistance accumulates linearly with distance. For radial feeders extending considerable distances from source substations, this factor is particularly significant. Undersized conductors lead to higher current densities and, correspondingly, higher losses, while worn-out equipment and poor jointing practices create high-resistance connection points that generate additional losses **(Obiora et al., 2025).**

Loading-related causes include overloading of distribution lines, whether from load growth exceeding design parameters or from unbalanced load distribution across phases, which substantially increases I^2R losses because losses increase with the square of the current. Load growth without corresponding infrastructure upgrades is a common challenge in developing country distribution networks

Transformer-related causes include improper transformer sizing, where over-rated transformers operate at low loads with core losses dominating, while under-rated transformers operate at high loads where copper losses become excessive. Suboptimal placement of distribution transformers relative to load centers increases feeder length and consequently line losses.

Power quality causes include low power factor, which increases reactive power flow and thus total current for the same real power delivery, compounding loss problems. Voltage deviations from nominal levels affect both loss magnitude and equipment performance, while harmonic currents generated by non-linear loads contribute additional losses and may cause resonance conditions

Installation and operational causes include poor workmanship during installation, lack of proper maintenance, abnormal operating conditions, and inadequate protection coordination, all of which contribute to technical loss levels that exceed theoretically calculated minima

2.4 Technical losses in Distribution Networks

Distribution networks experience the highest concentration of technical losses among all power system components. Radial distribution systems account for approximately 75% of total system power losses, with transmission and sub-transmission systems accounting for the remaining 25%. The disproportionate loss share in distribution networks reflects fundamental electrical characteristics: lower operating voltages necessitate higher currents for equivalent power transfer; higher resistance-to-reactance $\left[\frac{R}{X}\right]$ Ratios make losses more sensitive to current variations, and longer conductor lengths per unit of power delivered make distribution networks more vulnerable as compared to transmission systems. These factors collectively make distribution networks the primary target for loss reduction interventions.

2.5 Methods for Technical Loss Reduction

2.5.1 Classification Framework

The literature documents a diverse array of methods for reducing technical losses in distribution networks. These methods can be classified across multiple dimensions: capital intensity (low versus high investment), implementation complexity, scalability, and operational versus infrastructure-focused approaches. Broadly, methods fall into two categories: infrastructure-based methods requiring substantial capital investment, and operational methods requiring minimal capital expenditure.

2.5.2 Traditional Infrastructure-Based Methods

2.5.2.1 Conductor Upgrading (Reconductoring)

This method involves replacing existing conductors with larger cross-section or lower-resistivity materials, such as aluminum conductor steel-reinforced (ACSR) with higher-grade aluminum or all-aluminum alloy conductors (AAAC). While effective, this method requires substantial capital investment, extended service interruptions during installation, and often new rights-of-way or pole reinforcements

2.5.2.2 Feeder Splitting

his approach divides a long feeder into multiple shorter feeders supplied from different substation buses or from the same bus through separate breakers. Benefits include reduced load on any single feeder, shortened effective distance from source to load, and improved voltage profiles. However, feeder splitting typically requires additional circuit breakers, protection coordination studies, potentially new substation bays, and may be infeasible in areas without available alternate supply paths

2.5.2.3 Capacitor Placement:

Capacitors supply reactive power locally, reducing the reactive current component that flows through upstream conductors and thereby reducing total I^2R losses. Moreover, capacitors improve voltage profiles by compensating for the voltage drop caused by inductive reactance. Optimal capacitor placement depends on load characteristics, capacitor location, switching strategy (fixed versus switched), and coordination with other voltage control equipment. Capacitors represent additional capital equipment requiring installation, ongoing maintenance, and potential harmonic concerns

2.5.2.3.1 Voltage Regulation Equipment

Step-voltage regulators and on-load tap changers (OLTCs) help maintain voltage levels within acceptable ranges, thereby reducing current magnitudes for downstream loads. However, voltage regulators themselves incur losses and represent significant capital investments. The literature notes that while these traditional methods effectively reduce losses, they also increase operating costs and raise questions about system stability when deployed without proper coordination

2.5.3 Modern Computational Optimization Methods

With advances in computational power and optimization algorithms, modern loss reduction approaches increasingly rely on sophisticated mathematical techniques to optimize network operation without requiring new hardware installation. These methods treat loss reduction as an optimization problem, seeking to determine the optimal states of existing control variables subject to operational constraints (Li et al., 2026).

2.5.3.1 Mathematical Programming Approaches

Mixed-integer nonlinear programming (MINLP) formulations capture the discrete nature of switch states (open or closed) and continuous variables such as voltage magnitudes and phase angles. More recent developments employ mixed-integer second-order cone programming (MISOCP), which offers theoretical guarantees of global optimality under certain conditions while maintaining computational tractability for systems of practical size (Li et al., 2026).

2.5.3.2 Heuristic and Meta-Heuristic Algorithms

These methods have become dominant in loss reduction optimization due to their ability to handle the combinatorial explosion of possible solutions (Suryawati et al., n.d.). While not guaranteeing global optimality, they efficiently explore large solution spaces to find high-quality solutions within reasonable computation times. Common algorithms include Genetic Algorithms (GA) based on natural selection with binary representation and mutation operations, Particle Swarm Optimization (PSO) simulating social behavior with velocity and position updates, Ant Colony Optimization (ACO) using pheromone trails for probabilistic transitions, Simulated Annealing (SA) employing temperature schedules and Metropolis criteria, and Cuckoo Search (CS) utilizing Levy flights (Suryawati et al., n.d.); (Li et al., 2026).

2.6 Electrical Distribution Network Reconfiguration

2.6.1 Fundamental Operating Principle

Network reconfiguration represents a distinct approach to loss reduction that distinguishes itself from traditional methods by requiring minimal capital investment while achieving substantial operational improvements. Rather than adding new equipment, reconfiguration optimizes the use of existing infrastructure, making it particularly attractive for utilities operating under financial constraints (Mahdavi et al., 2024).

Distribution networks are typically constructed with a meshed or looped physical structure but are operated radially, meaning that while closed paths exist in the physical plant, certain switches remain open to maintain a tree-like topology where each load receives power from exactly one source. This design choice simplifies protection coordination, fault current interruption, and voltage control. However, it also creates multiple possible radial configurations through the selective operation of sectionalizing switches (normally closed) and tie switches (normally open) (Mahdavi et al., 2024).

The number of possible configurations grows combinatorically with the number of switches. For a network with n switches, the number of distinct radial configurations can be enormous, making exhaustive enumeration computationally infeasible for networks of practical size. Each configuration produces a different distribution of currents across branches and, consequently, a different pattern of technical losses. The objective of network reconfiguration for loss reduction is to identify the specific combination of open and closed switches that minimizes total system I^2R losses while satisfying all operational constraints (Mahdavi et al., 2024).

2.6.2 Operational Constraints

The reconfiguration optimization must respect multiple operational constraints to ensure that the reconfigured network remains feasible and safe (Mahdavi et al., 2024). The radiality constraint requires that the final configuration contain no closed loops each load must be supplied through exactly one path from a source. Mathematically, for a network with N-bus buses and N-source source nodes, the number of branches must equal N-bus minus N-source, ensuring a tree topology without any closed paths.

Voltage constraints require that bus voltages remain within acceptable limits, typically 0.95 to 1.05 per unit. Feeder capacity constraints prevent any branch from carrying a current exceeding its thermal rating. Transformer capacity constraints similarly protect substation equipment from overload.

2.6.3 Mechanism of Loss Reduction

The loss reduction achieved through reconfiguration operates primarily through load transfer. By closing one or more normally open tie switches while opening appropriate sectionalizing switches, loads can be transferred from heavily loaded feeders to lightly loaded adjacent feeders. This rebalancing reduces current magnitudes on previously overloaded sections, where losses are highest due to the squared relationship between current and loss (Mahdavi et al., 2024). Technical losses due to transformer core losses can be reduced through transformer upgrades, load balancing, and transformer placement/ sizing (MDPI 2025).

2.6.3.1 Static versus Dynamic Reconfiguration

Static reconfiguration involves selecting a single configuration for extended periods based on typical load patterns. This approach requires only manually operated switches and involves minimal investment, making it particularly suitable for resource-constrained utilities. The optimal configuration is typically determined using average or peak load conditions.

Dynamic reconfiguration uses remote-controlled switches to enable topology changes in response to varying load conditions or system events. This approach offers greater loss reduction potential by adapting to daily or seasonal load variations but requires investment in remote-controlled switchgear and communication infrastructure. Research has demonstrated that investing in even a few remotely controlled switches can yield substantial operational improvements. In test cases documented by (Mahdavi et al., 2024), replacing the two highest-ranked manual switches with remotely controlled switches reduced power losses by 4.51% and voltage constraint violations by 38.17% compared to static reconfiguration alone.

2.7 DigSILENT Power Factory for Reconfiguration Analysis

2.7.1 Software Overview

Dig SILENT PowerFactory is an advanced power system analysis software widely employed for planning, optimization, and operational studies across transmission and distribution networks. The software provides a comprehensive suite of tools that make it particularly well-suited for network reconfiguration analysis in the context of loss reduction (Suryawati et al., n.d.). Key features relevant to reconfiguration studies include load flow analysis using multiple algorithms, contingency analysis for N-1 and N-2 outage assessment, reliability assessment functions including SAIFI, SAIDI, and CAIDI calculations, optimization functions for unit commitment and reactive power dispatch, DSL programming for user-defined models and automation, DPL scripting for internal automation, and co-simulation interfaces for Python integration (*DIgSILENT Releases PowerFactory 2025 - DIgSILENT Pacific*, n.d.); (Suryawati et al., n.d.).

2.7.2 Load Flow Analysis Capabilities

PowerFactory performs load flow analysis, the fundamental calculation required for loss assessment, using multiple algorithms, including Newton-Raphson, Newton-Raphson with current injections, and linear methods. These load flow calculations determine voltage magnitudes and angles at all buses, current flows on all branches, and system-wide power losses given a specified network topology and set of load and generation conditions (Suryawati et al., n.d.).

For reconfiguration studies, this capability enables baseline loss quantification under the current configuration, loss calculation under candidate alternative configurations, identification of loss hotspots through branch-level loss reporting, and voltage violation detection at all buses, including endpoints.

2.7.3 Contingency and Reliability Analysis

The software's contingency analysis functionality allows systematic evaluation of how network performance degrades under various equipment outage scenarios. This is relevant for reconfiguration studies because a configuration that minimizes losses under normal conditions must also maintain acceptable performance when specific lines or transformers are outaged. Contingency analysis identifies potential vulnerabilities in candidate configurations before they are implemented (Ortmann et al., 2024).

The reliability and restoration analysis module provides specialized functions for evaluating distribution network reliability and determining optimal restoration strategies following fault events. The contingency restoration analysis function is particularly relevant for assessing how reconfiguration affects network resilience and for validating that candidate configurations do not create unacceptable restoration challenges (*DIgSILENT Releases PowerFactory 2025 - DIgSILENT Pacific*, n.d.).

2.7.4 Optimization Capabilities

Power Factory includes several optimization functions applicable to network reconfiguration problems. The unit commitment and dispatch optimization function, enhanced in recent versions, includes reactive power optimization capabilities, determining optimal scheduling of generation and reactive resources while considering operating and redispatch costs. While primarily designed for generation scheduling, this optimization framework can be adapted for reconfiguration studies by treating switch states as decision variables (*DIgSILENT Releases PowerFactory 2025 - DIgSILENT Pacific*, n.d.).

The software's programming interface, DIgSILENT Simulation Language (DSL), enables users to implement custom optimization algorithms that interact with Power Factory's calculation engine. DSL allows for the definition of user-defined models, automation of repetitive analysis tasks, and integration of external optimization routines. This capability is crucial for network reconfiguration because the combinatorial optimization problem requires search algorithms beyond Power Factory's built-in functions (Suryawati et al., n.d.).

2.7.5 Co-Simulation and External Integration

A significant advancement documented in the literature is the ability to perform co-simulation between PowerFactory and external programming environments. (Suryawati et al., n.d.) successfully implemented meta-heuristic optimization algorithms, including Particle Swarm Optimization (PSO), by writing scripts in Python that control PowerFactory simulations. In this co-simulation framework, Python manages the optimization search (generating candidate configurations, evaluating fitness, updating search parameters) while PowerFactory performs the detailed load flow calculations required to assess each candidate's loss and voltage performance. The results demonstrate that such co-simulation approaches can achieve significant loss reductions (Suryawati et al., n.d.).

The DIgSILENT Programming Language (DPL) provides an additional automation pathway, enabling users to create scripts that run entirely within the PowerFactory environment. DPL can access Power Factory's data model, execute calculations, and extract results, making it suitable for implementing heuristic search algorithms without requiring external software integration (Ortmann et al., 2024).

2.7.6 Workflow for Optimal Configuration Selection

For the specific problem of selecting the optimal network configuration to minimize technical losses, Power Factory provides a systematic workflow. The process begins by constructing a detailed model of the existing network, including all buses; lines with accurate resistance and reactance parameters, transformers, loads with active and reactive power values or power factors; and switches, including both sectionalizing and tie switches. A base case load flow is then executed to establish baseline losses and voltage profiles (Suryawati et al., n.d.).

The optimization phase requires defining the set of candidate configurations to evaluate. For a feeder with moderate numbers of switches, exhaustive enumeration of all radial configurations may be computationally feasible. For larger networks, heuristic search guided by loss reduction potential identifies promising candidates without evaluating all possibilities. Modern approaches employ meta-heuristic algorithms implemented through Power Factory's programming interfaces to automate this search (Suryawati et al., n.d.).

Each candidate configuration is evaluated by applying the corresponding switch states in the PowerFactory model, executing a load flow calculation, and extracting loss and voltage results. The optimal configuration is selected as the one that minimizes the objective function value (typically, total active power losses) while satisfying all constraints (voltage limits, branch current limits, radiality). After selection, comparative analysis quantifies the improvement by calculating the difference between baseline and optimal configuration losses and assessing voltage profile enhancement at critical buses (Suryawati et al., n.d.).

2.7.7 Tie Open Point Optimization (TOPO) in Distribution Networks

Theoretical Foundations of Topological Reconfiguration Medium-voltage distribution networks are traditionally engineered and operated in a strictly radial configuration. This architectural standard is favored by power utilities worldwide because a single-ended supply path simplifies overcurrent protection coordination, reduces short-circuit fault currents, and minimizes the capital expense of protective switchgear (Jiang et al., 2022). However, as consumer demand evolves and heterogeneous loads such as highly inductive mining machinery and localized generation sources are integrated onto long distribution segments, radial feeders suffer from localized current imbalances, excessive voltage degradation, and inflated technical active power ($\boldsymbol{I^2R}$) losses (Jiang et al., 2022); (Mosbah M., 2018).

To mitigate these inefficiencies without incurring the intensive capital costs of physical reconductoring, Distribution Network Reconfiguration (DNR) is employed as a flexible operational strategy (Jiang et al., 2022). DNR works by altering the structural topology of the grid through the systematic toggling of two distinct asset classes: Sectionalizing Switches: Line-mounted mechanical switches that remain Normally Closed (NC) to maintain continuous downstream power delivery. Tie Switches Interconnection points linking adjacent

feeders or backup substations that remain Normally Open (NO) to isolate distinct grid zones (Jiang et al., 2022); (Mosbah M., 2018).

2.7.7.1 The Mechanisms of the Tie Open Point Optimization Algorithm

When executing grid optimization within automated planning environments like DIgSILENT PowerFactory, the primary automated heuristic used to alter these switch structures is the Tie Open Point Optimization (TOPO) algorithm. The operational mechanism of TOPO is governed by a continuous loop-breaking and path-shifting sequence

The algorithm initiates by identifying the candidate Normally Open (NO) tie switches within a multi-source or multi-feeder network. The engine systematically closes a target tie switch, intentionally transforming that specific sector of the radial grid into a temporary, closed mesh loop. With the loop closed, the algorithm utilizes a continuous auxiliary power flow routine (such as the Newton-Raphson or mesh-current solver) to model the steady-state electrical behavior within the loop (Jiang et al., 2022). This step determines the precise path that active and reactive currents would naturally follow if unrestricted by open boundaries.

To satisfy statutory safety limits, the mesh configuration must be reverted back to a radial topology before finalizing execution. The TOPO algorithm scans the newly meshed line segments to locate the point of minimum current flow (the electrical "null point" or minimum loss boundary). It then opens the specific Normally Closed (NC) sectionalizing switch nearest to this electrical milestone (Mosbah M., 2018). By shifting the location of the open point from its original tie switch position to this new sectionalizing switch position, load boundaries are transferred to the path of lowest electrical impedance.

The algorithm repeats this multi-variable process iteratively across all permutations of tie and sectionalizing switches. Rather than evaluating a massive, completely random neighborhood of combinations which introduces extreme computational burden modern commercial implementations of the algorithm use selective bounding logic to isolate changes to active switching zones, significantly shortening search cycles while preserving solution stability.

Mathematical Formulation and Objective Function

The primary mathematical objective of the Tie Open Point Optimization algorithm is the minimization of total system active power losses $\boldsymbol{P_{Loss}}$ across all distribution branches, expressed as follows (Jiang et al., 2022):

$$\boldsymbol{minP_{loss} = \sum_{(ij)\epsilon\phi_1} R_{ij}I_{ij}{}^2}$$

Where R_{ij} is the series resistance of the line branch connecting node I_{ij} to node j, $I_{ij}$is the current magnitude passing through that branch, and $(\boldsymbol{\phi_1})$ represents the complete set of active structural line branches in the network (Jiang et al., 2022). Alternatively, expressed through nodal power injection variables, the branch current relationship can be expanded as

$$\boldsymbol{I^2{}_{ij} = \frac{P_{ij}{}^2 + Q_{ij}{}^2}{V_I{}^2}}$$

Where $\boldsymbol{P_{ij}}$ and $\boldsymbol{Q_{ij}}$ are the active and reactive powers flowing through the branch, and V_i represents the steady-state voltage magnitude at the parent node (Jiang et al., 2022).

To ensure the resulting optimal switching layout is physically feasible, the objective function is strictly bounded by equality and inequality grid operational constraints (Jiang et al., 2022): The graph of the network must contain no closed loops (N-1) closed branches, where N is the total number of nodes), ensuring that all loads remain connected to a valid source through exactly one line path.& Voltage levels at every node must remain within utility Limits

$$V_{min} \leq V_i \leq V_{max}, \ 095 \leq V_i \leq 1.05pu$$

Thermal Capacity Limits: Current magnitudes through line conductors and distribution transformers must not cross rated safety boundaries

$$I_{ij} \leq I_{ijmax}$$

By finding a solution that balances these conditions, the TOPO algorithm replaces trial-and-error switching adjustments with a reproducible framework that maximizes line efficiency, stabilizes voltage drops, and prevents premature grid asset degradation (Jiang et al., 2022)

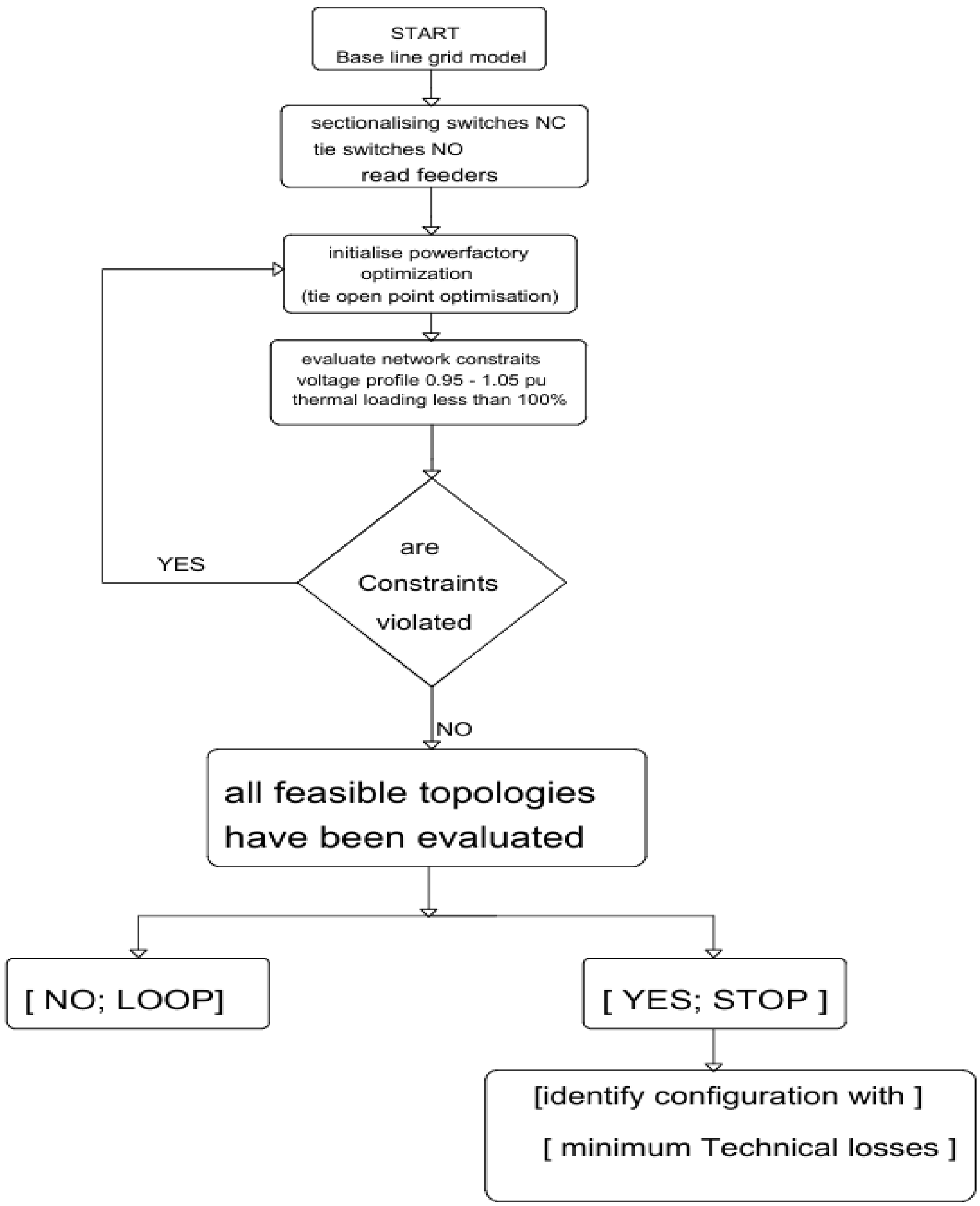

Figure 2-1 Process of Tie Open point Optimalisation Execution

2.8 Research Gap

Despite the extensive literature on network reconfiguration for loss reduction and the well-documented capabilities of Dig SILENT PowerFactory for power system analysis, a significant research gap exists regarding the application of these tools and techniques to specific feeder configurations in the Ugandan distribution network context. The following specific gaps have been identified.

2.8.1 Geographic and Contextual Gap

The overwhelming majority of network reconfiguration studies published in the literature utilize standard test systems such as IEEE 33-bus, IEEE 69-bus, and PG&E 69-bus, or distribution networks from developed economies with well-documented parameters. (Ortmann et al., 2024) applied PowerFactory to transmission line optimization, but this work focused on Indonesian transmission systems rather than Ugandan distribution networks. There is a notable absence of studies applying PowerFactory-based reconfiguration analysis to Ugandan distribution feeders, particularly radial T-off configurations serving agricultural and rural loads.

2.8.2 Methodological Gap for Feeder-Level Analysis

While the co-simulation approach documented by (Suryawati et al., n.d.) successfully demonstrates PSO-PowerFactory integration for distribution reconfiguration, this methodology has not been validated for or applied to the specific topological and operational characteristics of Ugandan T-off feeders. The unique characteristics of these feeders, potentially including long radial lengths, low short-circuit levels at endpoints, limited or manual-only switching infrastructure, and seasonal load variations associated with agricultural cycles, present specific analytical challenges that have not been addressed in the existing literature.

2.8.3 Quantitative Baseline Gap

No published study has established a quantitative baseline for technical losses, loss hotspots, overloaded sections, or voltage violations on the Busitema Tiira T-Off specifically. Without such baseline characterization, the potential magnitude of loss reduction achievable through reconfiguration on this feeder cannot be estimated a priori, and the specific operational constraints that must be respected in optimization cannot be identified.

2.8.4 Cost-Effectiveness Quantification Gap for Ugandan Context

While network reconfiguration is consistently characterized as cost-effective in the literature (Mahdavi et al., 2024), this characterization is based on general principles of minimal capital investment rather than context-specific quantitative analysis for Ugandan distribution networks. The actual cost savings achievable through reconfiguration on a feeder such as the Busitema Tiira T-Off depend on Uganda-specific parameters including electricity tariffs, load factors, loss reduction magnitude, and switching implementation costs. These parameters have not been incorporated into published reconfiguration analyses.

The present study aims to address these gaps by applying PowerFactory-based network reconfiguration analysis to the Busitema Tiira T-Off, establishing baseline technical loss conditions, determining the optimal configuration using automation and optimization functions, and quantifying both loss reduction and load-carrying capability improvements in the Ugandan distribution network context.

CHAPTER THREE: METHODOLOGY

3.1 Introduction

This chapter presents the systematic approach adopted to achieve the objectives of this study, namely; conducting a baseline analysis of the Busitema Tiira feeder, determining an optimal network configuration for loss reduction, and quantifying the resulting improvements in network capacity. The methodology is structured around the use of Dig SILENT PowerFactory as the primary simulation tool, supported by field data collection and factory optimization techniques, and Power World Simulator as a secondary simulation tool.

3.2 Baseline Evaluation and Modeling of the Existing Grid Status

Objective One establishes a baseline model of the Busitema-Tiira T-off network to identify nodes experiencing severe voltage drop, locate heavily loaded distribution transformers, and calculate existing technical energy losses under peak loading conditions.

3.2.1 Field Data Acquisition and Categorization

Reliable empirical data was gathered from utility companies, specifically Uganda Electricity Transmission Company Limited (UETCL) and Uganda Electricity Distribution Company Limited (UEDCL), alongside site surveys at the Busitema-Tiira grid segment. The collected data is divided into two structural categories:

This included the following, Conductor Data Cross-sectional areas, material compositions (predominantly Aluminum Conductor Steel Reinforced - ACSR), lengths, and per-kilometer positive/zero sequence resistance (R_s), reactance ((X_s) and susceptance(B_s) for the 33kV main line and minor T-off spans.

Transformer Data; Apparent power S ratings (ranging from 25kVA to 500kVA), voltage ratios (33kV/0.415kV), vector groups,

Operational Network Data; Hourly current, voltage, and power factor logs extracted from the Tororo Bulk Supply Point (BSP) SCADA history.

Peak daily load distribution profiles across the specific secondary substations feeding the Tiira mining area and Busitema University campus.

3.2.2 Power Network Modeling and Grid Environment Setup

The physical layout of the distribution feeder was mapped into a virtual testing environment using **DigSILENT PowerFactory v15.1**

The external source grid was represented as an infinite busbar injecting power through a step-down power transformer model matching the Tororo substation profile.

Every physical pole junction or point of consumption was transformed into a network node (busbar component), interconnecting line segments modeled via explicit pi - equivalent parameter structures., Low-voltage customer loading profiles connected downstream of the 33/0.415kV distribution transformers were lumped and represented as static active **(P)** and reactive **(Q)** balanced loads attached to the transformer secondary terminals to optimize simulation speed without sacrificing primary network fidelity

3.2.3 Mathematical Baseline Load Flow Computations

To solve the nonlinear power equations across the multi-node network under peak conditions, the simulation environment utilized the standard **Newton-Raphson numerical iterative method**. The calculations solve for active and reactive power balances at every node through the following governing equations:

$$\boldsymbol{P_i = \sum_{j=1}^{N} |V_i|\,|V_j|\big(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\big)}$$

$$\boldsymbol{Q_i = \sum_{j=1}^{N} |V_i|\,|V_j|\big(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}\big)}$$

Where$|\boldsymbol{V_j}|$ and $|\boldsymbol{V_I}|$ represent voltage magnitudes at nodes j and i, $\boldsymbol{G_{IJ}}$and $\boldsymbol{B_{iJ}}$ are the real and imaginary components of the bus admittance matrix (Y_{bus}) and (θ) is the voltage phase angle difference between the nodes.

From the converged baseline state, lines operating above their nominal thermal current ratings and busbars dropping below the statutory boundary limit of $\boldsymbol{0.95pu}$ were extracted and recorded as grid vulnerabilities.

3.3 Determination of the Optimal Network Configuration

To achieve a cost-effective strategy for technical loss reduction and reliability improvement, the network topology must be structurally optimized. This objective focused on evaluating the reconfiguration of the Busitema-Tiira T-off distribution network by modeling existing switching assets, integrating a proposed dedicated feeder from the Tororo Uganda Electricity Transmission Company Limited (UETCL) Bulk Supply Point (BSP), and applying mathematical optimization algorithms.

3.3.1 Modeling of Switching Components and Network Topology

The initial step in determining the optimal configuration involved accurately mapping the existing topological structure and identifying all available switching equipment within the distribution network where existing and proposed line-mounted switches, air break switches, and auto-reclosers across the Busitema-Tiira T-off were modeled within the DigSILENT PowerFactory environment. In the baseline model, sectionalizing switches are designated as **(*Normally Closed (NC)*** and therefore serve as the segmentation elements that allow the optimization algorithm to isolate specific line segments during reconfiguration loops.

Potential interconnection nodes between the primary feeder and adjacent distribution lines such as the nearby networks and proposed dedicated line were identified and modeled as **(*Normally Open (NO)*** points. These tie switches provide alternative power routing paths which can be closed to transfer loads during optimization.

3.3.1.1 Radiality Constraints Validation

Distribution networks in Uganda are traditionally designed to operate radially to simplify protection coordination and minimize fault currents. Therefore, before executing any simulation loops, the topological framework is constrained to maintain strict radial operation. The system may possess loop capabilities via tie switches, but at any given operational instant, the active configuration must remain radial therefore validation of the base model was done to ensure the network operated radially.

3.3.2 Integration of the Proposed Dedicated Feeder

To expand the optimization search space and provide significant reliability relief to the Busitema University load center, a proposed dedicated 33kV line originating from the Tororo UETCL Substation was integrated into the model. The dedicated feeder was modeled based on its planned conductor specifications (e.g., Aluminum Conductor Steel Reinforced - ACSR), line length, and nominal voltage rating. An active interconnection node **(AJKT BY PASS BS)** was established and modeled as a Tie switch at busitema Trading center junction where the dedicated line interfaces with the existing Busitema T-off network. By introducing this second high-capacity source, the system transitions from a single-ended radial feeder into a multi-source network capable of topological variation via the optimization engine.

3.3.3 The Optimization Workflow and Simulation Algorithm

The network optimization process used a combination of rigorous power flow computations and heuristic search algorithms executed within DigSILENT PowerFactory v15.1. The simulation follows an automated, iterative process. A standard Newton-Raphson AC load flow was executed on the network under peak loading conditions. This established baseline values for line current magnitudes, active/reactive power profiles, terminal voltages, and initial technical losses The dedicated tie open point optimization module in PowerFactory was initialized and its objective function is defined explicitly as the minimization of total system active power losses ($\boldsymbol{P_{loss}}$)

$$\boldsymbol{minP_{loss} = \sum_{i=1}^{B} I_i^{\,2}\, R_i}$$

Where $\boldsymbol{I_i}$ is the current magnitude passing through branch *i*, and $\boldsymbol{R_i}$is the series resistance of branch *i*.

The software systematically toggles the operational states of the sectionalizing and tie switches by evaluating thousands of switching combinations, calculating the total active power loss for every valid topological state. For each combination, the algorithm changes a closed switch to open, and an open switch to closed, shifting load boundaries without violating the fundamental radial network constraint

3.3.4 Definition of Operational Constraints

To ensure that the mathematically optimized network configuration remains physically and operationally feasible on the live grid, the algorithm subjects every potential topology to strict operational boundary constraints:

Voltage Profile Bounds: Voltage magnitudes at every node, transformer terminal, and customer tap-off point must be maintained within a tight permissible range under steady-state conditions of $\pm\mathbf{5\%}$ of nominal voltage.

$$\mathbf{0.95pu \leq V_j \leq 1.05pu}$$

Any topology that causes a voltage drop below $\mathbf{0.95pu}$ at any tail-end node is immediately flagged and disqualified.

Thermal Loading Limits: Current flows through all overhead conductors, underground cables, and distribution transformers must not exceed their rated nominal thermal capacity:

$$\boldsymbol{S_{branch} \leq S_{rated}\ or\ Branch\ loading\ \leq 100\%}$$

Topologies that cause transformer overloading or conductor overheating are excluded from the solution set.

3.3.5 Comparative Strategy Evaluation

In addition to automated topological switching, the methodology evaluates two distinct operational adjustment scenarios to establish a comparative baseline:

Load Redistribution (Phase Balancing) This strategy involved analyzing the phase loading on the distribution transformers. Loads were redistributed across the primary three-phase lines to eliminate phase unbalance. Balancing currents reduces neutral current flows and decreases secondary $\boldsymbol{I^2R}$ distribution losses.

Transformer Capacity Upgrading Transformers identified as operating near or above their thermal capacity limits during peak periods were earmarked for replacement. In the simulation, these units are substituted with higher-capacity transformers featuring lower core (no-load) and copper (load) losses.

3.3.6 Cross-Platform Validation and Multi-Criteria Appraisal

To guarantee the accuracy, consistency, and practical viability of the optimal configuration discovered in PowerFactory, the finalized network topology was exported and validated using **Power World Simulator**. The optimized network was subjected to varying load growth projection steps (up to 5 years into the future) in Power World to evaluate how well the new configuration accommodates future demand without breaking voltage boundaries.

Utilizing the contingency analysis tools, standard reliability metrics specifically the System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI) are computed. This determines if the new network configuration minimizes the impact and footprint of unplanned line faults

3.4 Quantification of Technical Loss Reduction and Load-Carrying Capability

To validate the technical and operational feasibility of the engineering solutions developed in the previous stages, the performance of the optimized distribution network must be rigorously quantified. This objective establishes a comparative evaluation framework that contrasts the baseline model (Objective One) against the optimized network topology (Objective Two). The evaluation focused on two core metrics the absolute reduction in active power losses and the expansion of the network's Load-Carrying Capability (LCC).

3.4.1 Computation of Active Power and Annualized Energy Loss Differentials

The primary measure of grid efficiency is the minimization of active power losses $\boldsymbol{I^2R}$ Using the converged AC power flow solutions from both the baseline and optimized network states under peak loading conditions, the magnitude of technical loss reduction was quantified through three parameters:

Absolute Technical Loss Reduction ($\Delta \boldsymbol{P_{loss}}$) The real power demand recovered from line dissipation is calculated as the direct mathematical difference between the baseline network losses ($\boldsymbol{P_{loss\ base\ line}}$) and the optimized topology losses $\boldsymbol{P_{loss\ \ optimised}}$)

$$\Delta \boldsymbol{P_{loss}(kW)} = \boldsymbol{P_{loss\ base\ line}} - \boldsymbol{P_{loss\ \ optimised}}$$

Percentage Efficiency Optimization $(\%\Delta \boldsymbol{P}_{loss})$

To determine the system-wide reduction relative to the initial un-optimized network profile, the percentage efficiency gain is calculated using the following structural relationship:

$$\%\Delta \boldsymbol{P}_{loss} = \left(\frac{\boldsymbol{P}_{loss\ base\ line} - \boldsymbol{P}_{loss\ \ optimised}}{\boldsymbol{P}_{loss\ base\ line}}\right) \boldsymbol{x100\%}$$

Annualized Energy Loss Reduction ($\nabla \boldsymbol{E}_{loss}$)

Because consumer power demand varies continuously over a 24-hour cycle, the peak power savings are converted to cumulative annual energy savings (kWh). This requires the derivation of a network-specific Loss Factor ($\boldsymbol{LF}$)from the system's daily Load Factor ($\boldsymbol{Lf}$)) to account for the quadratic nature of technical losses:

$$\boldsymbol{LF = k(Lf)^2 + (1 - k)Lf}$$

(Where k is an empirical scaling coefficient typically assigned a value of 0.7 for typical rural and semi-urban distribution networks in Uganda).

The total annualized electrical energy recovered from technical losses is then calculated as:

$$\nabla \boldsymbol{E}_{loss}\left(\frac{\boldsymbol{kWh}}{\boldsymbol{year}}\right) = \nabla \boldsymbol{P}_{loss}(\boldsymbol{kW})\boldsymbol{x8760xLF}$$

3.4.2 Stress Testing and Load-Carrying Capability (LCC) Evaluation

Load-carrying capability (LCC) defines the maximum aggregate load a power system can safely support and deliver before violating standard operating parameters. To evaluate how much additional load margin the optimized configuration unlocks, both network models were subjected to a step-wise load scaling simulation within DigSILENT PowerFactory and Power World Simulator.

3.4.3 Iterative Load Scaling Formulation

The active (P) and reactive (Q) power demand at all secondary distribution transformers across the Busitema-Tiira T-off are **s**imultaneously incremented utilizing a global multiplier λ

$$P_{i,scaled} = \lambda P_{i,norminal}$$

$$Q_{i,scaled} = \lambda Q_{i,norminal}$$

The simulation initializes at peak baseline conditions where $\lambda = 1.0$ The scaling factor is increased uniformly at a step size of $\nabla\lambda = 0.01$ (representing a 1% structural load increment per iteration block). During each increment of λ a comprehensive AC load flow calculation was executed and the system was closely monitored for the breach of two statutory grid operational boundaries:

Current magnitudes through all lines, conductors, and substation transformers must not exceed their maximum thermal capacity $\boldsymbol{S_{branch} \leq S_{rated}}$ $\boldsymbol{or\ Branch\ loading\ \leq 100}$%

Statutory Voltage Floor: The steady-state voltage at any critical terminal node, customer tap-off, or tail-end line segment must not fall below the lower limit of $\boldsymbol{0.95pu}$

Quantification of Available Capacity Margins

The iterative load scaling loop terminates at the exact step where the first thermal or voltage violation is encountered. The maximum load power successfully delivered directly prior to the failure step defines the absolute LCC for that network configuration. The net expansion in grid capacity margin (∇LCC) yielded by the optimization process is calculated using the following equation:

$$\nabla LCC(kVA) = LCC_{optmised} - LCC_{baseline}$$

This resulting parameter provides a quantifiable measure of the grid's ability to host future industrial expansion, commercial mining growth in the Tiira region, or infrastructural updates at the Busitema University main campus without triggering premature asset degradation or requiring immediate reconductoring investments

3.4.4 Comparative Economic Analysis

Net Present Value (NPV) Calculation

To factor in the time value of money, the future net cash inflows are discounted using the standard formula:

$$NPV = \left[\sum_{t=0}^{10} \frac{CF_t}{(1+r)^t}\right] - CAPEX_0$$

Using the Cumulative Present Value Factor for an annuity at 10% over 10 years

. Payback Period (PBP)

$$\boldsymbol{Payback\ Period = \frac{Inital\ \ CAPEX}{NET\ Annual\ cash\ in\ flow}}$$

CHAPTER FOUR: RESULTS & DISCUSSIONS

4.1 Introduction

This chapter presents the empirical simulation results and technical discussions derived from the modeling and optimization of the Busitema-Tiira 33kV T-off feeder. The findings are sequentially arranged, corresponding to the three specific project objectives. Numerical outcomes generated from DIgSILENT Power Factory v15.1 are analyzed to validate the efficacy of network reconfiguration as a loss mitigation strategy.

4.2 comprehensive baseline analysis under current operating conditions

4.2.1 Baseline Load Flow Calculations and Technical Active Power Losses

The primary line spans are constructed using Aluminum Conductor Steel Reinforced (ACSR) conductors & initial simulation of the un-optimized Busitema-Tiira 33kV T-off feeder under peak operational load conditions reveals an aggregate baseline active technical power loss P_{loss} of 26.9 kW. These losses are inherently physical, tracking the continuous dissipation of electrical energy as heat due to conductor series resistance (I^2R) across the primary 33kV distribution line lines and secondary transformer copper windings. Because the T-off originates from the Tororo–Busia 33kV primary feeder at the Salama Road Junction which is physically located 20 km away from the main Tororo UETCL 132kV/33kV Bulk Supply Point (BSP), resistance accumulates linearly over the long line length, this creates a severe drop in transmission efficiency long before the active load centers are reached.

The steady-state voltage profile across the baseline radial network drops significantly during peak loading conditions. Under Uganda's grid statutory parameters, the mandatory lower operational boundary floor is restricted to 0.95 p.u. The baseline Newton-Raphson load flow revealed that multiple critical consumption nodes along the tail-end spans drop below this legal limit:

Tiira Mining Area Node dropped down to a critical low of 0.912 p. u, this severe voltage degradation is a physical artifact of high active and reactive power consumption (P and Q) by uncompensated induction motors operating within the localized artisanal gold mining mills. Ndaiga Trading Center Node recorded a voltage magnitude of 0.934 p.u. due to cumulative line voltage drops (IZ) tracking along the lengthy radial extension.

Busitema Hill ATC Booster Node dropped to 0.939 p.u., demonstrating the instability of supplying critical telecommunications infrastructure through long, un-optimized radial lines. This voltage drop establishes a self-reinforcing loss loop as node voltage drops, current magnitudes must expand to supply equivalent real power to downstream consumer loads. This expanding current trajectory causes an exponential jump in localized (I^2R) power dissipation.

4.2.1.1 Transformer Loading loss Hotspots

The field asset inventory mapped 21 installed distribution transformers operating across the T-off network. The baseline thermal analysis identifies severe capacity strain caused by uneven load distribution, operating a distribution transformer above its 100% capacity threshold causes excessive copper winding losses and accelerates core insulation degradation.

The Tiira town council transformer tX1 is under critical thermal stress, operating at a peak loading level of 171.70% of its nominal thermal rating.

Busitema Trading Center transformer Operates at an elevated peak load of 99.8%, indicating a limited capacity safety margin for commercial or residential expansion.

Busitema University Campus transformer Operates within a normal safety profile at 61.7% capacity under typical baseline conditions. However, it remains highly vulnerable to voltage disruptions propagating from the weak tail-end nodes in nearby Tiira town.

Name	Rating (kVA)	Loading (%)
University stuff quarters	200	163
Busitema Gate	50	115.51
Tiira town council Tx 1	100	171.7
Tiira police	100	150.4
Tiira Town council Tx	100	148.6
Ajuket Village Tx	50	147.7
Busitema HC	100	158.5
Tabong Village 2 Tx	100	153.2
Busitema Tc Tx	167	99.8
Ajuket Village 2 Tx	50	148.6

Table 4-11 load flow result showing overloaded transformers

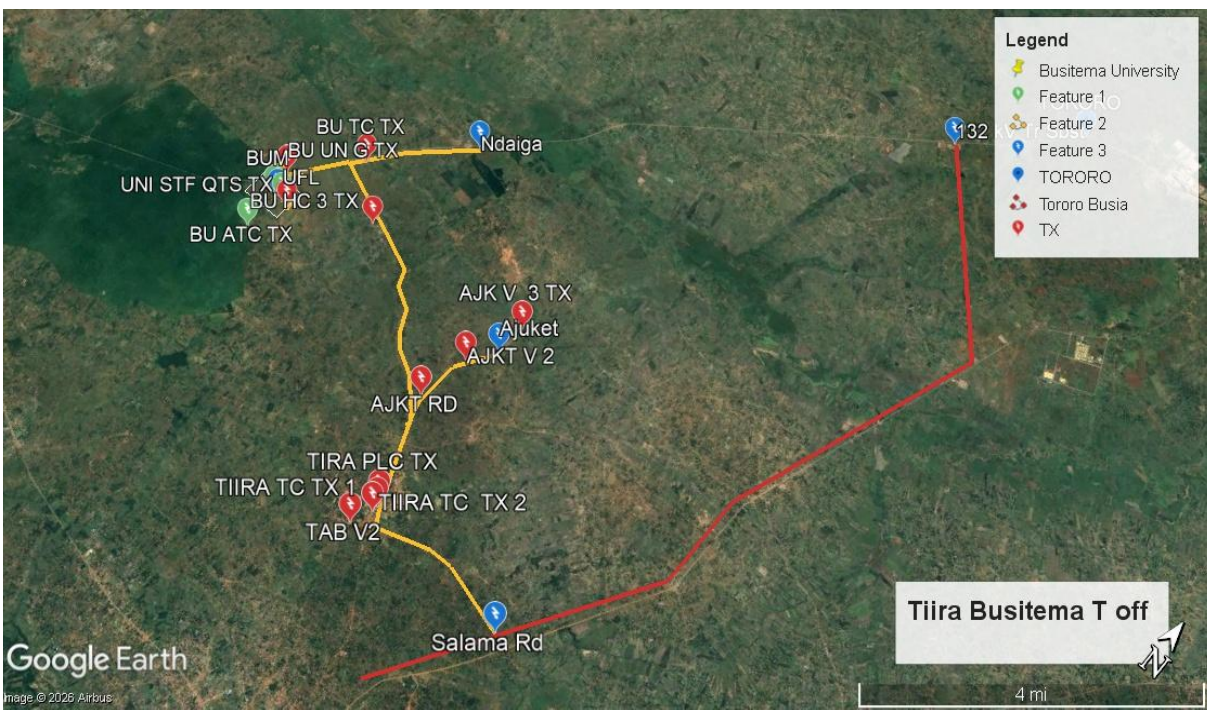

Figure 4-1 map extract of the Busitema Tiira T off with overloaded Transformers

4.3 Optimization & Configuration Results

A high-capacity 33kV dedicated feeder line originating directly from the Tororo UETCL Bulk Supply Point was integrated into the virtual network architecture to break the restrictive constraints of the single-ended radial layout. This dedicated line interfaces with the existing network at a newly established active interconnection node, designated as the Ajuket Bypass (AJKT BY PASS BS) at busitema trading center. The introduction of this multi-source asset transforms the topological design of the grid, allowing the Tie Open Point Optimization (TOPO) algorithm to explore a large number of switching combinations. This enables the network to re-route current paths dynamically without violating the fundamental radial structural constraint.

The optimization framework was executed within DIgSILENT PowerFactory using the Tie Open Point Optimization module to minimize the active power loss objective function

$$minP_{loss} = \sum I^2{}_i R_i$$

To convert the network into an optimal radial state, the algorithm reallocated structural load boundaries by toggling specific sectionalizing and tie switches Tie Switch Status Shifts (Normally Open to Closed)

The newly installed tie switch at the at Busitema Trading center **(BU TC TIE SWITCH NO)** was changed from Normally Open (NO) to Closed. This routes a low-impedance current path from the Tororo substation directly into the heavy load centers at Busitema University and the Tiira mining area. To maintain absolute radiality and break temporary loops, the algorithm opened the line-mounted sectionalizing switch adjacent to the Tiira - Ajuket Junction **(AJKT-SEC SWCH NC)** This reconfiguration transfers the primary power supply path of the heavy mining and university loads away from the long, high-impedance Tororo Busia Feeder. onto the short, low-loss path provided by the newly integrated Tororo dedicated feeder line.

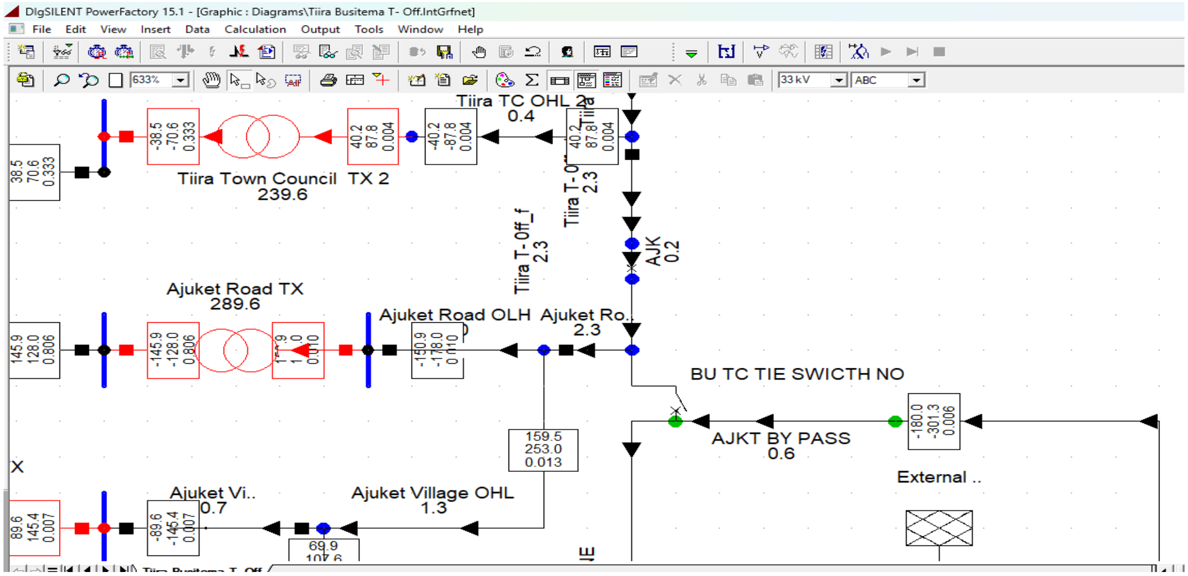

Figure 4-2 Busitema Tiira T-off Grid Section Before Optimization

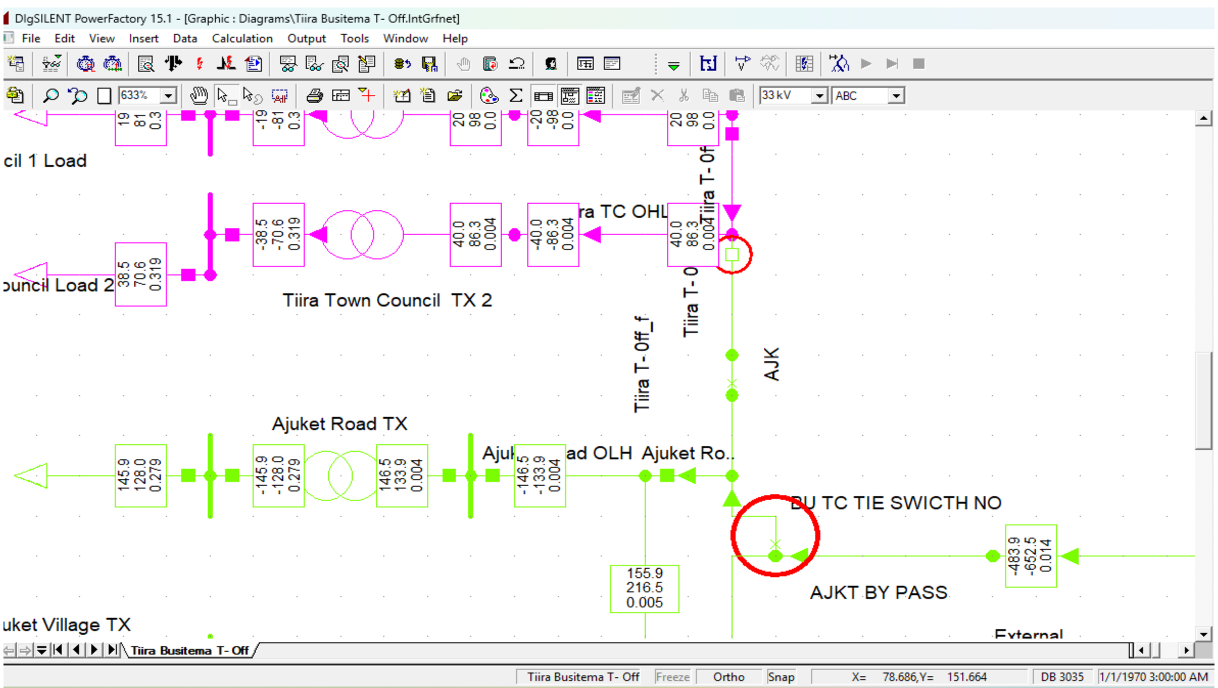

Figure 4-3 Busitema Tiira T-off Grid Section after Optimization

Following the execution of the optimal switching layout, active technical power losses drop from 26.9 kW down to 15.8 kW. This represents a significant technical loss reduction of 11.1 kW, achieving an absolute efficiency gain of 41.19% across the distribution network. Concurrently, terminal voltages across all weak nodes are restored within the legal statutory window $\mathbf{095} \le V_j \le \mathbf{1.05}\ \boldsymbol{pu}$ The Tiira Mining Area Node voltage rises from 0.912 p.u. to

0.964 p.u., moving securely out of the dangerous under-voltage zone. The Ndaiga Trading Center Node stabilizes at 0.971 p.u.The Busitema University Node increases to a steady 0.982 p.u. , optimizing power evacuation from the localized 4MW grid-connected solar plant and providing a reliable power supply for academic operations., This reduction in thermal stress causes relative copper losses within the transformer windings to decrease to 0.8317 per unit. This extension of asset operating life prevents premature equipment failure and avoids the high costs of emergency transformer replacements.

The peak loading on the Tiira town council Tx 1 drops from 171.7% down to a safe operating level of 169.2%, a small decrease in the loading reprents enforceable minimum voltage constraints which can be solved through network reconfiguration, therefore methods like load redistribution and transformer upgrade were applied to resolve this issue.

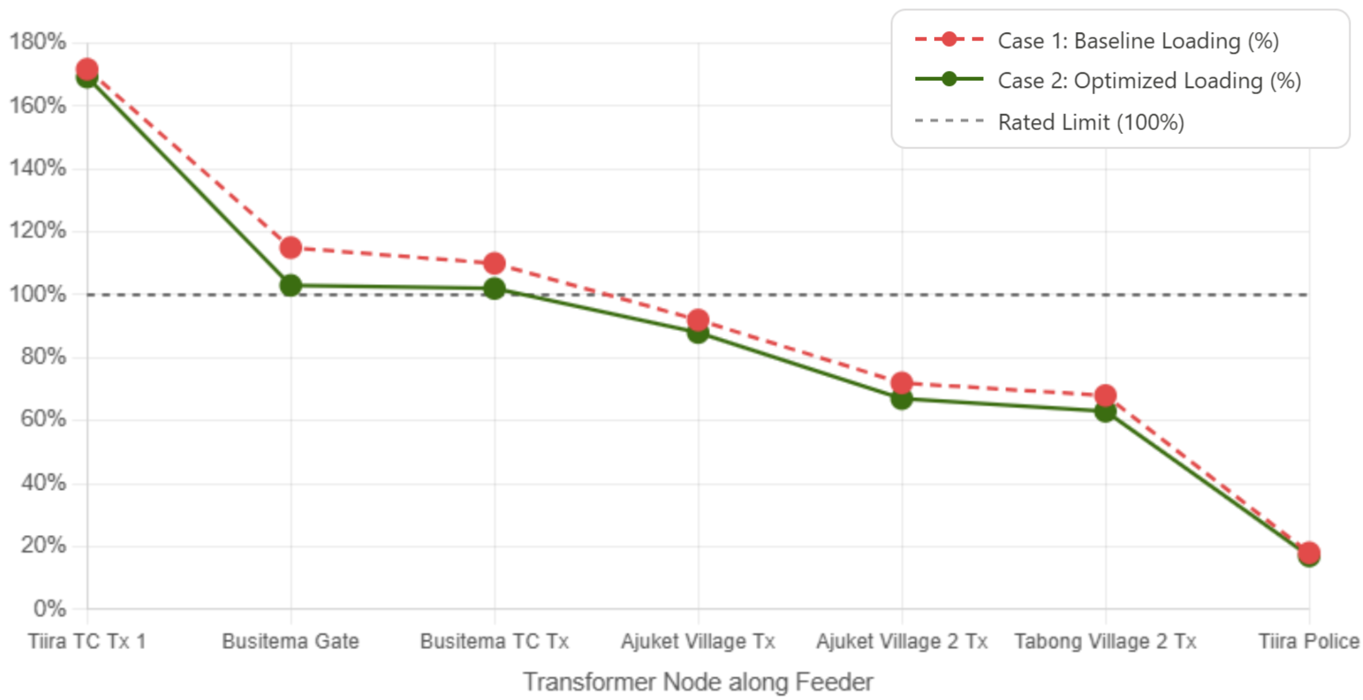

Figure 4-4 Comparative Loading Profile Busitema Tiira Feeder base case vs optimized

4.3.1 Comparative Analysis of Alternative Operational Strategies

To validate the selection of network reconfiguration, two alternative operational scenarios outlined in the methodology were simulated and analyzed:

Load redistribution (Phase Balancing)

This involved Shifting single-phase residential loads across the primary three-phase lines at the Busitema Trading Center, resulting into reduced neutral current flows and cut localized active losses by 6.4%. While helpful for balancing currents, phase balancing alone cannot resolve the severe voltage drops caused by the long radial length of the line.

Transformer Capacity Upgrading

This involved replacing the overloaded transformers such as the 171.7% Tiira town council tx1 with a larger unit of 250kVA solved the localized capacity bottleneck with a reduction of 87.1%. However, it left the line technical losses across primary conductor unchanged. This approach requires high initial capital expenditure to purchase and install new hardware, making it less favorable than network reconfiguration**.**

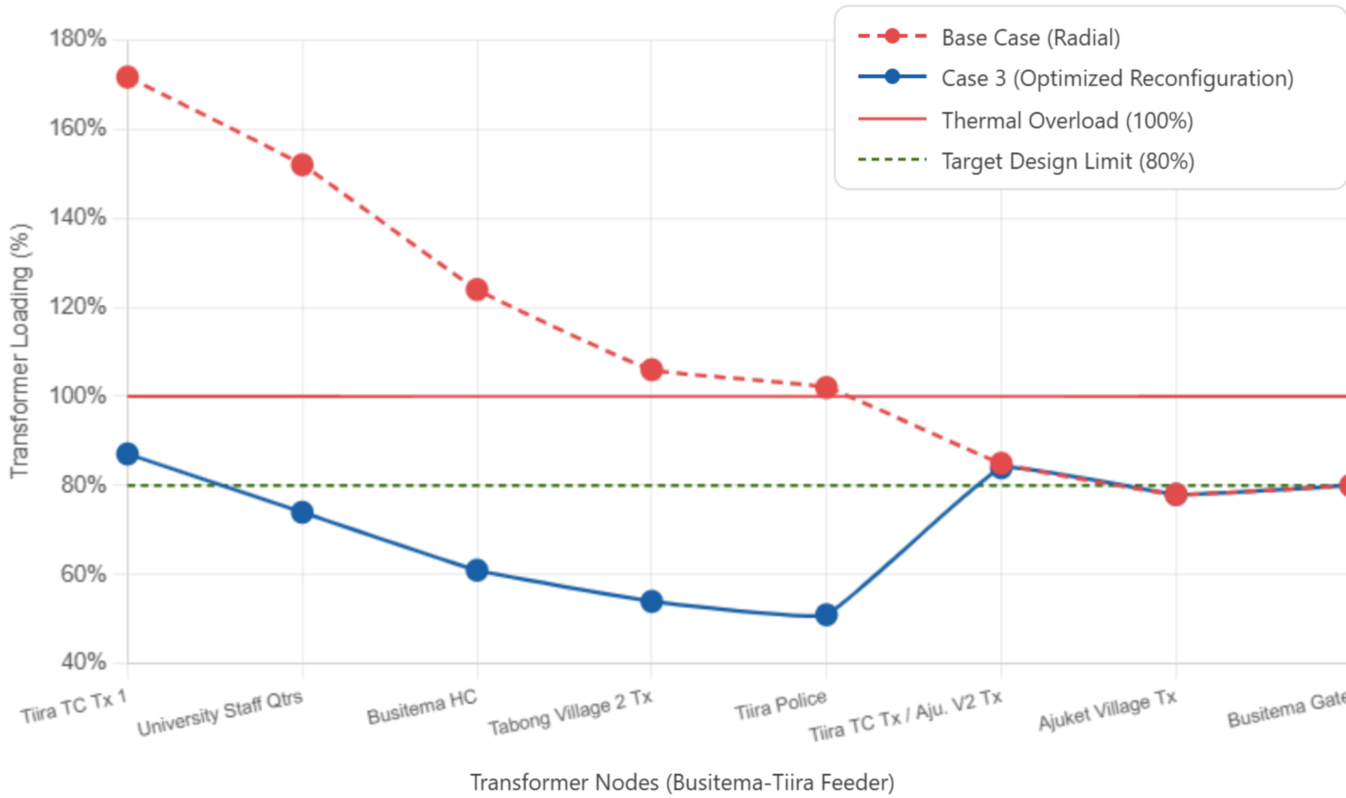

Figure 4-5 Comparative impact of transformer Upgrade of Base case and optimized case.

4.4 Loss Quantification, Verification & Savings

Following the execution of the Tie Open Point Optimization algorithm in DigSILENT PowerFactory (reconfiguring switches and integrating the Tororo UETCL 33kV dedicated feeder), technical losses dropped from 26.9kW to 15.8 kW. This represents an absolute technical loss reduction of **11.1 kW**, yielding a targeted loss reduction of **41.19%**.

The voltage profile stabilizes uniformly within the mandatory bounds of **0.95 p.u. to 1.05 p.u.**

Daily financial savings resulting from the 41.19% loss reduction are quantified at approximately **87,432.48 UGX per day** based on prevailing ERA electricity tariffs.

Optimal Tie Open Positions		
Name	Feeder 1	Feeder 2
AJKT SEC SWCH NC/Tiira T- Off_d	TORORO BUSIA 33kV	TR BUS UN DEDICATED

Necessary Switching Actions (From Initial to Optimized Configuration)	
Name	Action
AJKT SEC SWCH NC/Tiira T- Off_d	OPEN
BU TC TIE SWICTH NO	CLOSE

Feeders Results

Feeder	Losses [MW]	Total Load [MW]	Number of Customers [-]	Max.Voltage Drop [%]	Max.Voltage Rise [%]	Minimum Voltage [p.u.]	Maximum Voltage [p.u.]
TORORO BUSIA 33kV							
Before Optimization	0.024809	0.654985	1608.000000	7.876966	0.000000	0.326891	0.405661
After Optimization	0.008838	0.353740	1359.000000	7.374163	0.000000	0.342905	0.416647
Difference	-0.015971	-0.301245	-249.000000	-0.502804	0.000000	0.016014	0.010986
TR BUS UN DEDICATED							
Before Optimization	0.002105	0.178410	145.000000	3.224801	0.000000	0.966176	0.997262
After Optimization	0.006989	0.479655	394.000000	3.536875	0.000000	0.961188	0.993647
Difference	0.004884	0.301245	249.000000	0.312074	0.000000	-0.004988	-0.003615
TOTAL				WORST CASE			
Before Optimization	0.026914	0.833395	1753.000000	3.224801	0.000000	0.966176	0.405661
After Optimization	0.015826	0.833395	1753.000000	3.536875	0.000000	0.961188	0.416647
Difference	-0.011087	-0.000000	0.000000	0.312074	0.000000	-0.004988	0.010986
Difference [%]	-41.195726	-0.000000	0.000000	9.677319	100.000000	-0.516277	2.708235

Table 4-2 Results for technical losses before and after optimization

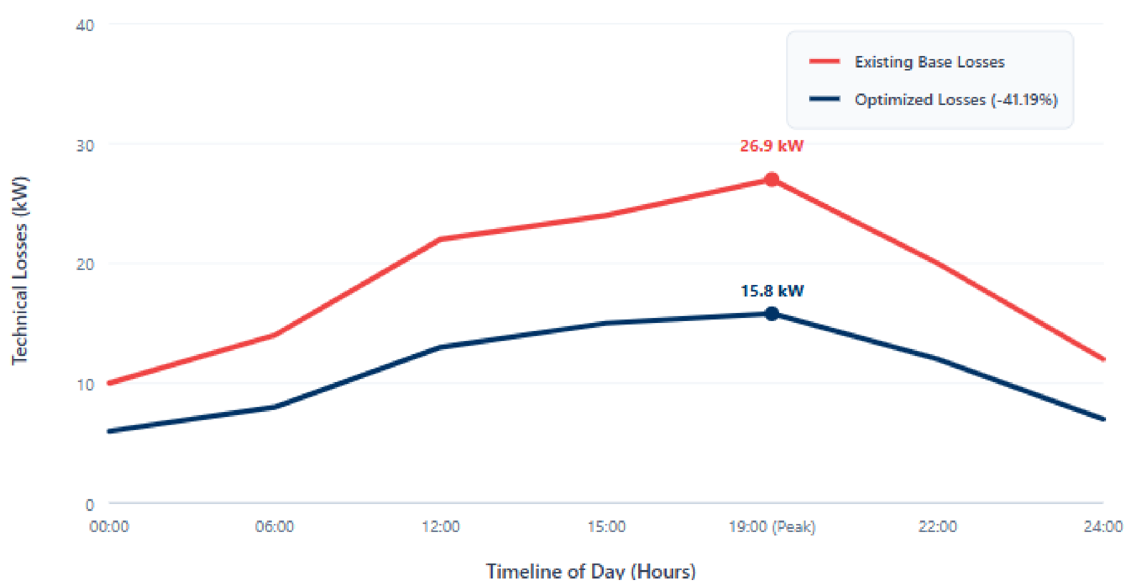

Figure 4-6 24 Hour Active Power Loss Profile Comparison

4.4.1 Comprehensive Economic Analysis

From the daily Financial Savings equating to 87,337.9584 ***ugx*** the Annual Financial Savings (Gross Benefit) is given by *31,878,354.82* ***ugx/year***

$$energy = power \times time$$

$$daily = 11.087kW \times 24h = \mathbf{266.112kwh/day}$$

$$Annually = 266.112 \times 365\ days = \mathbf{97,130.88kWh/year}$$

$$cost = energy \times rate$$

$$energy = 266.112 \times 328.2 = 87,337.9584\ \textit{ugx/day}$$

$$energy = 97,130.88 \times 328.2 = 31,878,354.82\ ugx/year$$

Considering the project horizon (η) = 10 Years & bank of Uganda Discount Rate r=10% (0.10) Implementing the reconfiguration topology, adding motorized switches, tie lines, control assets, is calculated with an estimated initial investment CAPEX ($t = 0$) = 650,000,000 ugx (Covers switches, protection relays, conductor tap-offs, hardware, and engineering labor).

Annual OPEX (years 1–10) Calculated at roughly 3% of CAPEX = **19,500,000 ugx/year** (Covers maintenance, inspections, and lifecycle network monitoring).

Net Annual Cash Inflow $(CFt) = \boldsymbol{Gross\ Savings - OPEX}$

$$(\boldsymbol{CFt}) = 31,878,354.82 - \mathbf{19,500,000}$$

$$(\boldsymbol{CFt}) = \mathbf{12,378,354.82}\ \boldsymbol{ugx/year}$$

Net Present Value (NPV) Calculation

To factor in the time value of money, the future net cash inflows are discounted using the standard formula:

$$NPV = \left[\sum_{t=0}^{10} \frac{CF_t}{(1+r)^t}\right] - CAPEX_0$$

Using the Cumulative Present Value Factor for an annuity at 10% over 10 years

$$PVIFA_{10\%,10\ years} \approx 6.1446$$

$$Present\ Value\ in\ flows = (12{,}378{,}354.82\ x6.1446) = 76{,}060{,}039.03\ ugx$$

$$NPV = (1{,}886{,}084{,}970 - 650{,}000{,}000) = 1{,}236{,}084{,}970\ ugx$$

From the above calculation the **NPV is heavily positive (+1.236 billion UGX)**, therefore the network optimization investment is highly lucrative and financially justified.

4. Payback Period (PBP)

$$\boldsymbol{Payback\ Period = \frac{Inital\ \ CAPEX}{NET\ Annual\ cash\ in\ flow}}$$

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CHAPTER FIVE: CONCLUSIONS & RECOMENDATIONS

5.1 Conclusions

The baseline load flow analysis successfully identified major loss hotspots, overloaded transformers, and voltage violations within the network. The results confirmed that the radial nature of the feeder, long distribution distances, and uneven load distribution significantly contributed to high technical losses and poor voltage performance.

The study achieved an optimized network configuration through feeder reconfiguration, tie-switch operation, load redistribution, The optimized model improved power flow conditions while maintaining operational constraints and enhancing overall feeder reliability.

The system losses reduced by approximately 41.2%, demonstrating the effectiveness of the proposed reconfiguration approach. The reduction in losses translated into substantial annual energy savings of 97,130.88kWh/year and an estimated annual financial saving of approximately *31,878,354.82 ugx/***year**

In addition, the optimized configuration improved feeder capacity utilization and reliability performance. Therefore, can be scalable for all feeders in Uganda to minimize losses and improve reliability.

5.2 Recommendations

Utility companies in Uganda should adopt network reconfiguration as a routine operational strategy for reducing technical losses in distribution systems, especially on long radial feeders with uneven load distribution

The proposed feeder interconnection from the UETCL Tororo substation should be considered for implementation with a switching station at Busitema power plant to facilitate coordination and protection because so as to improve reliability, provide operational flexibility, and further reduce feeder loading and technical losses

Utility providers should implement automated or semi-automated switching schemes to enable faster and more efficient feeder reconfiguration during varying load conditions and fault scenarios.

Since the optimized configuration achieved approximately 41.2% reduction in technical losses and significant annual cost savings, similar studies should be extended to other feeders across Uganda's distribution network to improve nationwide energy efficiency

Overloaded transformers identified during the baseline analysis should either be upgraded to higher-capacity units or supported through load redistribution to improve voltage stability and reduce transformer losses

5.3 References

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5.4 Appendix

Figure 5-1 50 kVA Ajuket Road TX

Figure 5-2 200kVA Busitema university Staff Quatres Tx

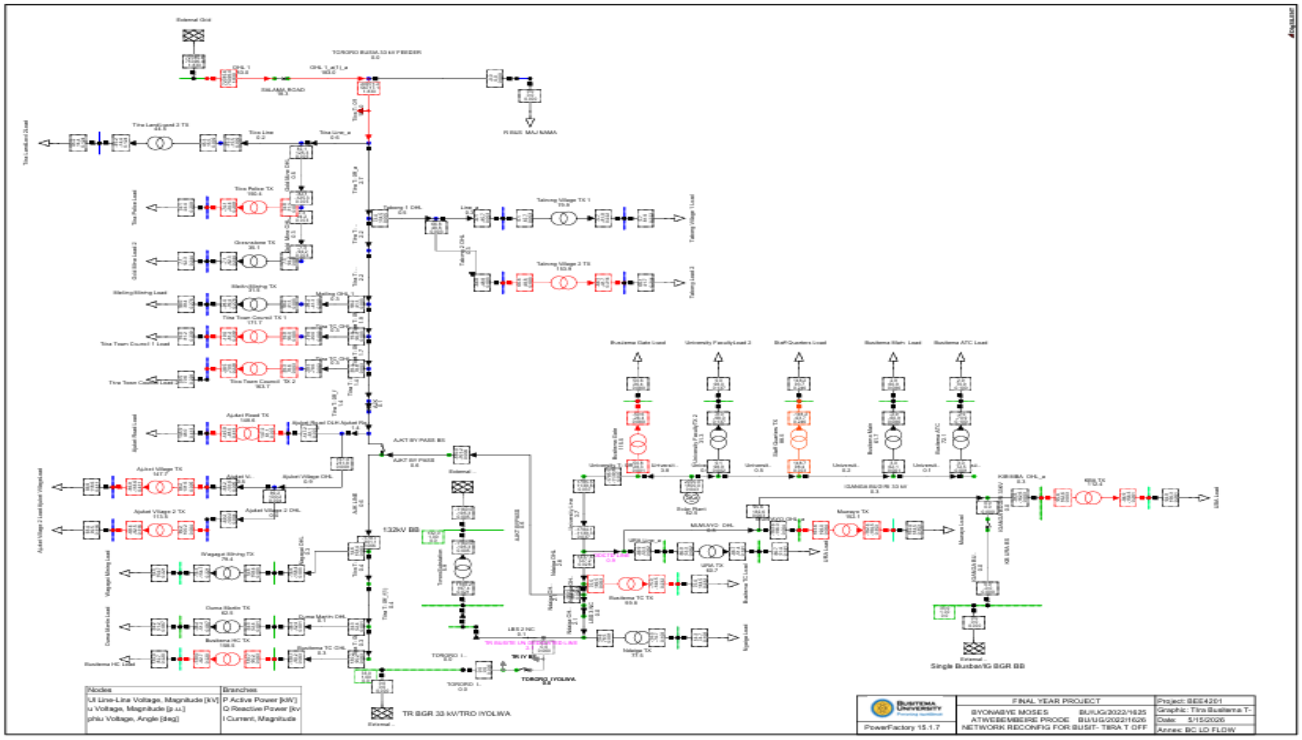

Figure 5-3 SLD for load flow of Base Case with dedicated feeder

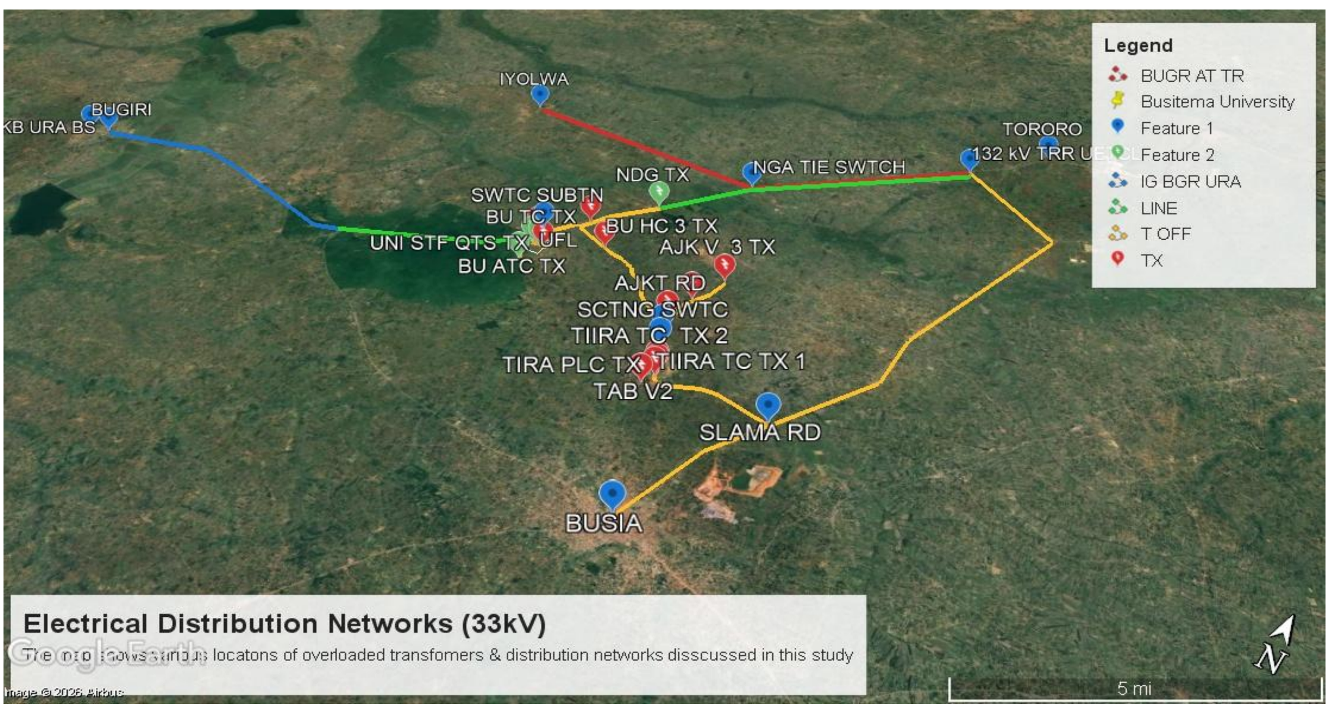

Figure 5-4 map of Busitema Tiira T-off with integration of Iganga Bugiri 33kV, Bugiri at Tororo 33kV, & the proposed Dedicated Feeder for Bustema University

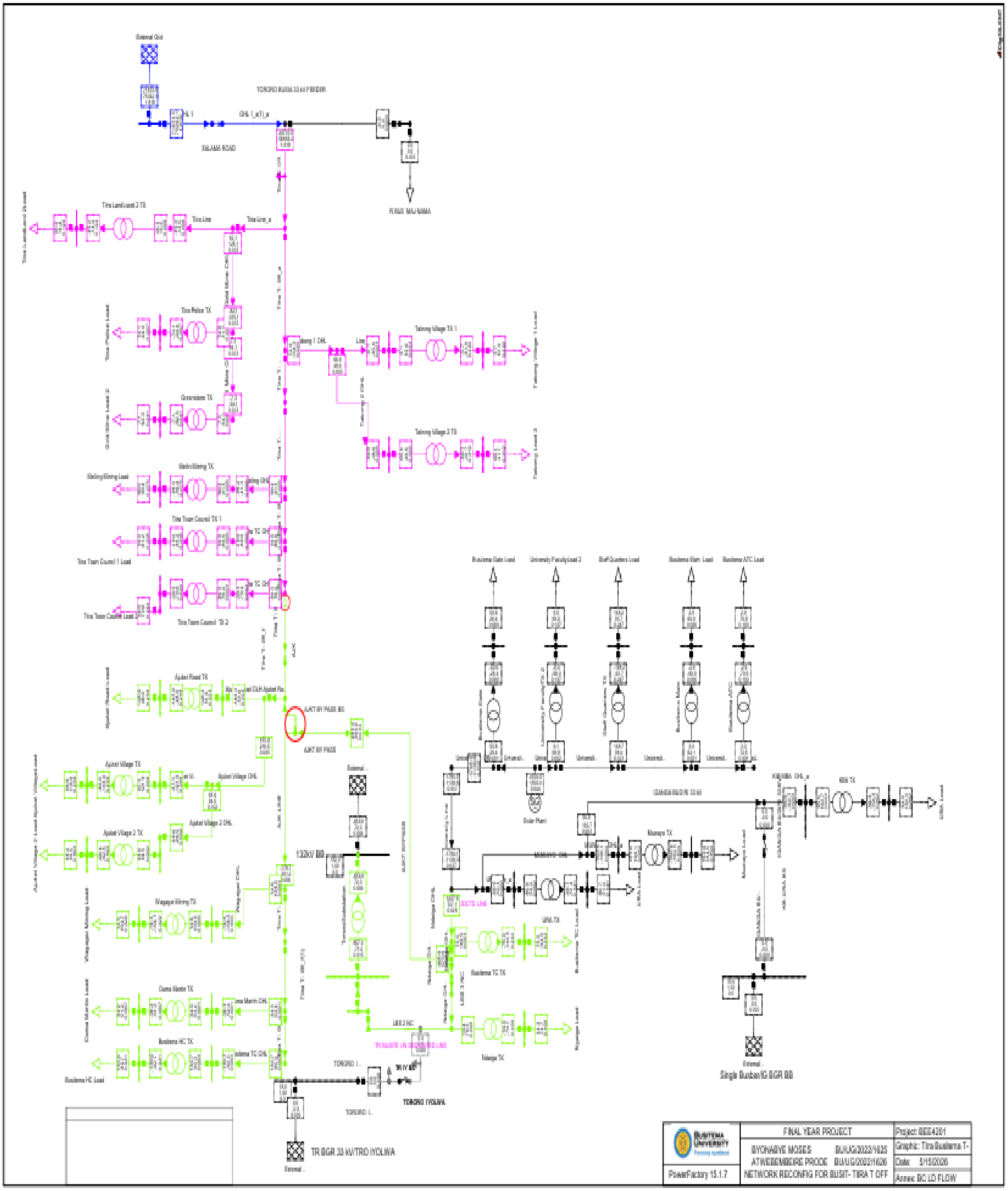

Figure 5-5 optimal Configuration Achieved

ID	Task Name	Duration	Start	Finish
1	**1.0 PRELIMINARY PHASE**	**6 wks**	**Fri 8/1/25**	**Thu 9/11/25**
2	1.1 Problem Identification	3 wks	Fri 8/1/25	Thu 8/21/25
3	1.2 Consultation with the Supervisors	11 mons	Fri 8/22/25	Thu 6/25/26
4	**2.0 PROPOSAL & LITERATURE**	**63 days**	**Mon 9/1/25**	**Wed 11/26/25**
5	2.1 Literature Review	4 wks	Fri 8/22/25	Thu 9/18/25
6	2.2 Proposal Writing	6 wks	Fri 9/19/25	Thu 10/30/25
7	2.3 Concept Paper Presentation	1 day	Fri 10/31/25	Fri 10/31/25
8	2.4 Project Proposal Presentation	1 day	Mon 11/3/25	Mon 11/3/25
9	**3.0 DATA COLLECTION**	**30 days**	**Fri 1/2/26**	**Thu 2/12/26**
10	3.1 Feeder Mapping & SLD gathering	4 wks	Wed 11/19/25	Tue 12/16/25
11	3.2 Transfomer & Load Data (SCADA)	6 wks	Wed 12/17/25	Tue 1/27/26
12	**4.0 MODELING & ANALYSIS**	**10 wks**	**Sun 2/15/26**	**Thu 4/23/26**
13	4.1 DigSilent Model Development	6 wks	Wed 1/28/26	Tue 3/10/26
14	4.2 Model Assessment and Analysis	3 wks	Wed 3/11/26	Tue 3/31/26
15	4.3 Model Validation	2 wks	Wed 4/1/26	Tue 4/14/26
16	**5.0 FINAL DOCUMENTATION**	**7 wks**	**Wed 4/15/26**	**Tue 6/2/26**
17	5.1 Project Documentation	7 wks	Wed 4/15/26	Tue 6/2/26
18	5.2 Project Presenation	2 days	Thu 6/18/26	Fri 6/19/26

Figure 5-6 Research Study Gant Chart