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Analyzing Distribution Network Performance Gaps and Modernization Challenges in Uganda's Electricity Sector: A Case Study of Kampala West Region

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Abstract

This paper analyzes Uganda's electricity distribution network performance gaps and modernization challenges using Kampala West region's Kitala feeder as a case study. Industry-standard reliability indices including System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), Customer Average Interruption Duration Index (CAIDI), modernization maturity assessment, and network simulations identified high outage durations, frequent interruptions, and significant feeder losses. Modernization interventions including protection coordination, network reconfiguration, reconductoring, parallel circuits, and distributed generation significantly improved reliability and reduced losses. Cost-benefit analysis using Net Present Value (NPV) and payback period metrics highlighted the most economically viable interventions. The study recommends targeted interventions with optimal NPV and payback period values, replicable to similar urban feeders across Sub-Saharan Africa. Policy formulation and regulations supporting comprehensive distribution network modernization are essential to achieve reliable electricity supply and support Uganda's Vision 2040 goals.

Keywords: Distribution networks, SAIDI, SAIFI, modernization, Uganda, cost-benefit analysis, reliability indices.

Introduction

Uganda's electricity distribution network has undergone significant transformation since the sector's liberalization in 1997, with management transitioning from UMEME and UEDCL since 2005 to full UEDCL control in March 2025 following natural concession termination (Umeme Limited, 2005; Electricity Regulatory Authority, 2020). This transition presents critical modernization opportunities for aging infrastructure, particularly in urban centers like Kampala experiencing rapid demand growth.

Globally, electricity distribution systems face mounting challenges due to increasing demand, aging infrastructure, and the need for enhanced reliability (World Bank, 2021). Sub-Saharan African countries particularly struggle with distribution network performance, experiencing technical losses of 15–25% compared to the global benchmark of 8–10% (Mbabazi et al., 2013). Similar studies across the region, including Nigeria (Diamenu and Kwarteng, 2008), Kenya, and Tanzania, have documented comparable challenges with reliability indices significantly below international standards.

The distribution network faces persistent challenges including high technical losses (15–20% versus 8–10% global benchmark), frequent outages, and inadequate capacity (Mbabazi et al., 2013; Uganda Electricity Regulatory Authority, 2024). International benchmarks suggest SAIDI values below 100 minutes per year for developed systems, while developing countries often exceed 1000 minutes (Institute of Electrical and Electronics Engineers, 2012). These inefficiencies hinder progress toward universal electricity access under Vision 2040 (National Planning Authority, 2020).

Despite extensive research on power system reliability and modernization globally, significant gaps exist in comprehensive performance analysis and modernization strategy development for SubSaharan African distribution networks. Previous studies have focused primarily on generation and transmission challenges, with limited attention to systematic distribution network modernization approaches. Furthermore, there is insufficient research on cost-effective modernization interventions specifically tailored for developing country contexts, where financial constraints and institutional capacities differ significantly from developed economies.

Kampala West region exemplifies these complexities with frequent interruptions, voltage fluctuations, and capacity constraints limiting economic growth (Nalima et al., 2023; Umeme Limited, 2022). With UEDCL now responsible for operations, targeted modernization strategies are urgently needed (Uganda Electricity Regulatory Authority, 2022).

This study addresses the identified research gap by conducting a comprehensive performance analysis of the Kitala 11 kV feeder using reliability indices and advanced simulation tools. The methodology combines historical data analysis, DIgSILENT PowerFactory load flow modeling, and financial evaluation of four modernization strategies: reconductoring, distributed generation, network reconfiguration, and parallel circuits. Each intervention is assessed for technical feasibility and economic viability using NPV and payback period analysis.

The research provides practical recommendations for UEDCL's infrastructure investments, supporting evidence-based planning aligned with national electrification goals (Madrigal et al., 2017; Monaco et al., 2024). Findings contribute to distribution system modernization discourse in SubSaharan Africa and establish a replicable framework for systematic performance assessment (Atimati et al., 2019).

1. Methodology

This research employed a comprehensive approach combining quantitative data acquisition, simulation, and financial analysis following established distribution system reliability assessment frameworks (Diamenu and Kwarteng, 2008; Nalima et al., 2023):

2.1. Feeder Selection

The Kitala 11 kV feeder was selected due to its high outage duration of 81.998 hours and high outage frequency of 51 interruptions in 2024. Operational data including logbooks, protection reports, and outage statistics were collected from UMEME and UEDCL for 2024.

2.2. DIgSILENT Power Factory Model Setup

The feeder topology was modelled incorporating 40.259 km of mixed conductors (ACSR-50 and AAAC-125), 52 distribution transformers ranging from 25 kVA to 500 kVA, and 13,273 customers. Key modelling parameters included: failure rate of 1.267 interruptions/km/year, mean repair time of 1.6 hours/outage, and After Diversity Maximum Demand (ADMD) of 0.35 kVA for urban loads. All loads were assigned a power factor of 0.9, consistent with typical residential and commercial characteristics in Uganda.

2.3. Modernization Assessment

A four-tier maturity model evaluated feeder modernization across system visibility, automation, control, and Distributed Energy Resource (DER) integration dimensions following World Bank guidelines (Madrigal et al., 2017).

2.4. Reliability Analysis:

Performance evaluation used SAIDI, SAIFI, and CAIDI indices per IEEE Std 1366-2012 (Institute of Electrical and Electronics Engineers, 2012), calculated from annual interruption data. Additional metrics included Energy Not Supplied (ENS) and Contingency-Load-Loss Index (CLLI) for network reconfiguration assessment.

2.5. Load Flow Modelling:

Feeder topology and loading were modelled in DIgSILENT PowerFactory to benchmark technical losses, voltage profiles, and feeder loading with scenarios simulating each modernization intervention (Ntshiba and Krishnamurthy, 2022).

2.6. Cost-Benefit Analysis

Financial appraisal used NPV and payback period metrics considering capital expenditure, technical loss reduction, and Energy Not Supplied reduction. Cost assumptions included: reconductoring at UGX 72.5 million/km, distributed generation at UGX 700/W installed capacity, and network switches at UGX 15 million per unit. The Value of Lost Load (VOLL) was estimated at UGX 1,500/kWh based on ERA tariff structures and customer surveys.

2. Modernization Strategies

Based on identified performance gaps and international best practices from similar Sub-Saharan African contexts (Madrigal et al., 2017; Monaco et al., 2024), four modernization interventions were proposed:

3.1. Reconductoring

Replacement of ACSR-50 conductors with AAAC-125 to reduce resistance from 0.543 /km to 0.221 /km, thereby reducing technical losses and improving current-carrying capacity from 240A to 416A while utilizing existing infrastructure (World Bank, 2021).

3.2. Distributed Generation (DG)

Six decentralized 0.5 MW solar PV plants strategically located near major load centers to reduce upstream loading by 15–25%, improve reliability through localized supply, and support voltage stability during peak demand periods (Belay et al., 2021; Ntshiba and Krishnamurthy, 2022).

3.3. Network Reconfiguration

Strategic installation of normally open switches and tie-lines to balance load distribution, reduce average feeder lengths from 20.1 km to 15.3 km, and minimize voltage drops using existing infrastructure. This intervention targets a CLLI reduction from 1.0 to 0.5 (Atimati et al., 2019).

3.4. Parallel Circuits

Creation of second identical lines serving heavily loaded segments exceeding 80% thermal capacity to reduce congestion and improve contingency planning, effectively doubling transmission capacity in critical areas (Nalima et al., 2023).

4. Results and Analysis

4.1. Baseline Performance Assessment:

The baseline reliability analysis revealed significant performance gaps with SAIDI of 53.81 hrs/yr, SAIFI of 34.21 interrupts/yr, and CAIDI of 1.57 hrs/interrupt. These values substantially exceed international benchmarks, with SAIDI being 32 times higher than typical European standards (100 minutes/year) and comparable to other Sub-Saharan African networks studied by Diamenu and Kwarteng (Diamenu and Kwarteng, 2008).

4.2. Loading Reduction Analysis: Base case scenarios showed heavily loaded segments reaching 95% thermal limits. Simulation results demonstrated significant loading relief across all interventions: Reconductoring reduced peak loading from 95% to 42%, distributed generation achieved 15–25% upstream loading reduction during peak solar generation periods, network reconfiguration redistributed load reducing peak loading by 20–30%, and parallel circuits reduced loading from 95% to 58% while doubling transmission capacity.

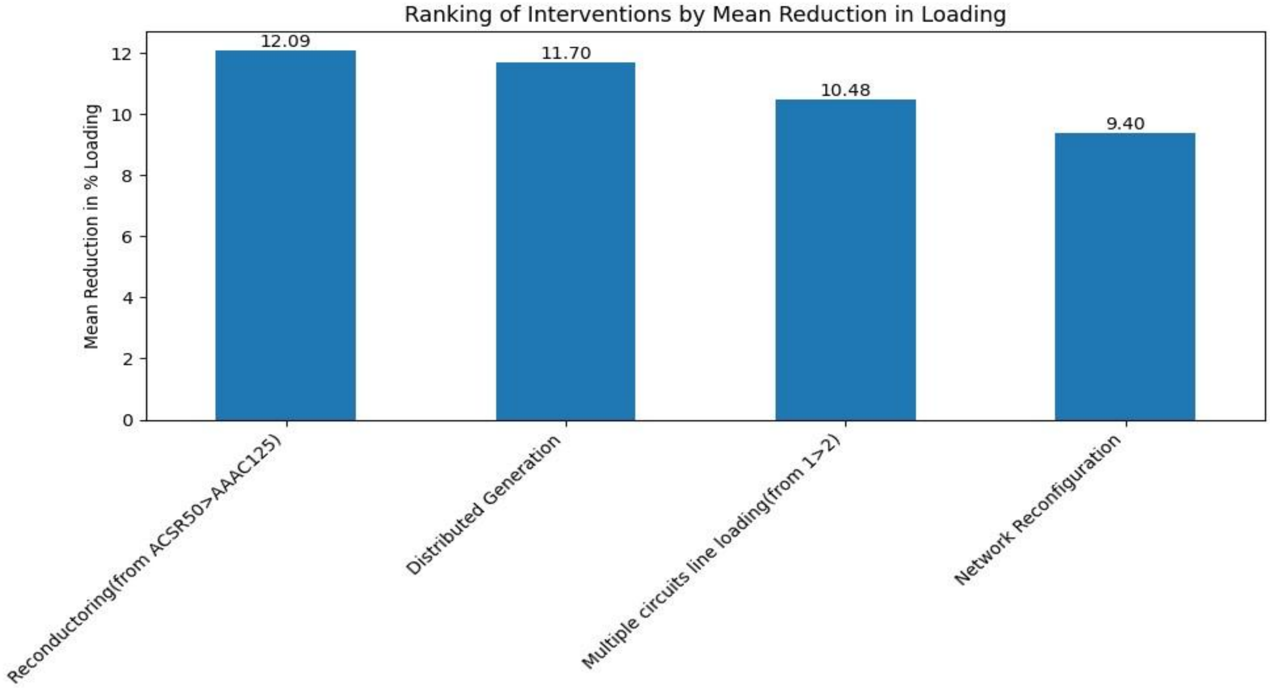

Fig. 1. Loading reduction comparison across modernization interventions. The chart illustrates the effectiveness of each intervention in reducing thermal loading, with reconductoring showing the most significant improvement by reducing peak loading from 95% to 42%. Network reconfiguration and parallel circuits also demonstrate substantial load redistribution benefits, supporting improved system reliability and operational flexibility.

Reliability improvements varied significantly across interventions, with results validated against international case studies from similar developing country contexts:

- Base Case: SAIDI = 53.81 hrs/yr, SAIFI = 34.21 interrupts/yr, CAIDI = 1.57 hrs/interrupt
- Network Reconfiguration: SAIDI = 23.98, SAIFI = 23.47, CAIDI = 1.02 (55.4% SAIDI reduc-tion)
- Distributed Generation: SAIDI = 22.88, SAIFI = 22.13, CAIDI = 1.03 (57.5% SAIDI reduc-tion)
- Protection Coordination: SAIDI = 44.79, SAIFI = 25.49, CAIDI = 1.76 (16.8% SAIDI reduc-tion)

These improvements align with similar studies from Nigeria and Kenya, where distribution network modernization achieved 40–60% reliability improvements (Diamenu and Kwarteng, 2008).

Technical losses improved substantially across all interventions:

- Base case: 0.89 MW (15.4% of total demand)
- After reconductoring: 0.35 MW (5.7% - 60.7% reduction)
- After distributed generation: 0.33 MW (5.4% - 62.9% reduction)
- After parallel circuits: 0.44 MW (7.2% - 50.6% reduction)
- After network reconfiguration: 0.44 MW (7.2% - 50.6% reduction)

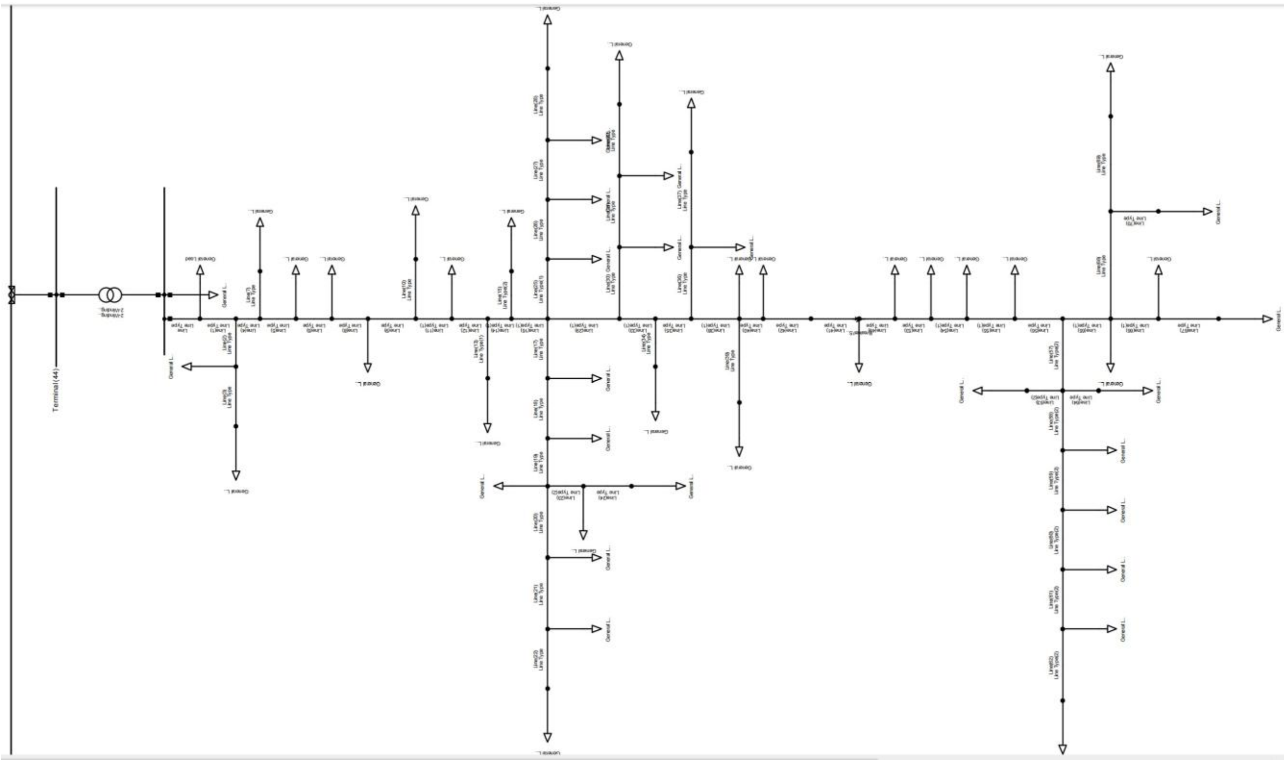

Fig. 2. Kitala 11 kV Feeder modeled in DIgSILENT PowerFactory showing the complete network topology with 52 distribution transformers, mixed conductor types (ACSR-50 and AAAC-125), and strategic locations for modernization interventions. The model incorporates actual geographical layout from ArcGIS data and operational parameters from UEDCL records.

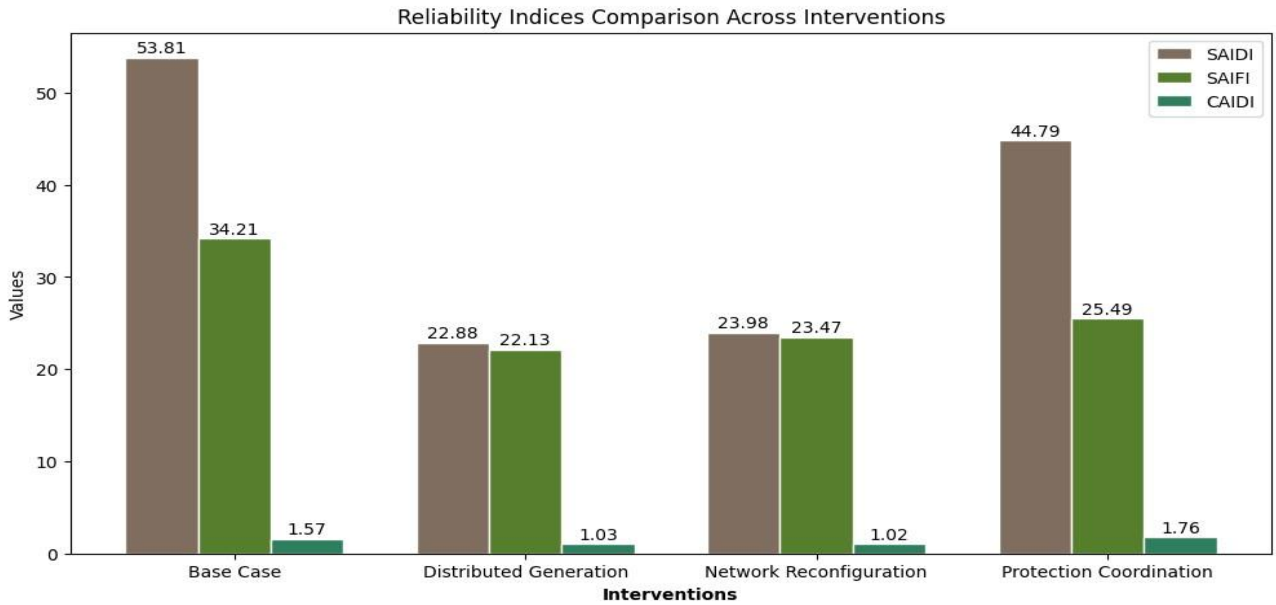

Fig. 3. Reliability improvement across modernization interventions demonstrating significant reductions in SAIDI, SAIFI, and CAIDI metrics. Distributed generation shows the highest SAIDI reduction (57.5%), while network reconfiguration provides balanced improvements across all indices. These results exceed typical SubSaharan African benchmarks and approach international standards for urban distribution systems.

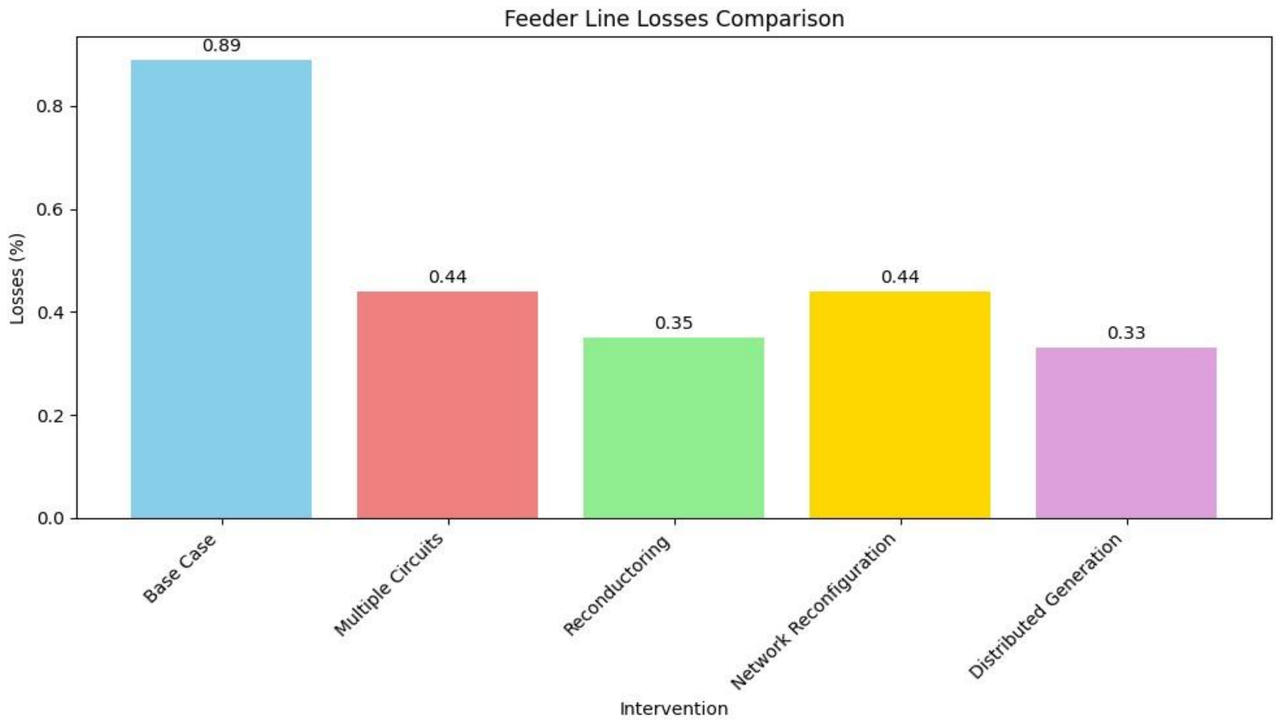

Fig. 4. Technical losses reduction comparison showing the effectiveness of each modernization intervention in reducing energy waste. Distributed generation achieves the highest reduction (62.9%) followed by reconductoring (60.7%), both significantly exceeding the 50% target typical for developing country distribution systems. The substantial loss reductions translate directly to improved energy efficiency and economic benefits.

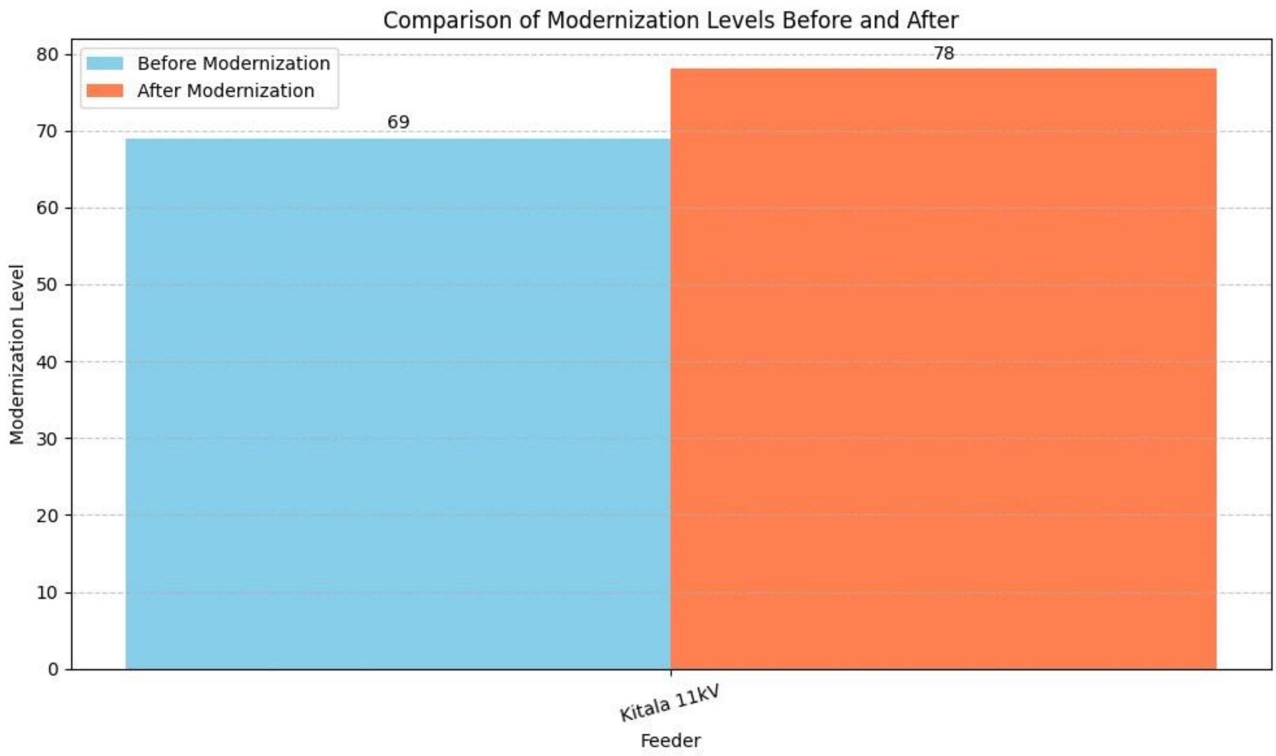

Fig. 5. Modernization maturity improvement with different interventions showing progression from baseline 69% to enhanced 78% maturity level. This advancement indicates improved system capabilities across automation, control, and DER integration dimensions, aligning Uganda's distribution network with international modernization standards and supporting Vision 2040 objectives.

4.3. Financial Appraisal and Validation Cost-benefit analysis revealed varying economic viability with validation against similar international projects:

Table 1. NPV and Payback Period Summary with detailed cost breakdown analysis. Capital expenditure estimates include materials (60%), labor (25%), transportation (10%), and contingency/overhead (5%). Benefits calculation incorporates technical loss reduction valued at current tariff rates and Energy Not Supplied reduction using VOLL of UGX 1,500/kWh.

Intervention	CAPEX (UGX B)	NPV (UGX B)	Payback (yrs)	BCR
Reconductoring	2.92	19.04	0.83	7.52
Distributed Generation	4.20	-0.06	6.29	0.99
Network Reconfiguration	1.01	5.76	0.93	6.70
Parallel Circuits	0.84	10.55	0.46	13.56

5. Discussion

The results demonstrate significant potential for distribution network performance improvement through targeted modernization interventions, with findings consistent with international experience in similar developing country contexts.

Parallel circuits and reconductoring offered the most cost-effective reliability and efficiency improvements, aligning with World Bank studies across Sub-Saharan Africa emphasizing infrastructure capacity expansion as the primary modernization priority (World Bank, 2021; Eminoglu and Uyan, 2016). The high NPV values (UGX

10.55B and 19.04B respectively) and rapid payback periods (0.46 and 0.83 years) compare favorably with similar projects in Nigeria, Ghana, and Kenya, where payback periods typically range from 1–3 years.

Distributed generation showed technical benefits but proved financially challenging under current tariff regimes due to high capital costs (UGX 4.2B) and conservative Value of Lost Load (VOLL) valuation. This outcome is consistent with Sub-Saharan African DG integration challenges documented across the region (Mbabazi et al., 2013), where regulatory frameworks often lag technological capabilities.

Network reconfiguration presented an optimal quick-win solution with minimal investment (UGX 1.01B) and immediate reliability benefits, achieving 55.4% SAIDI reduction (Atimati et al., 2019; Diamenu and Kwarteng, 2008). This intervention's success in the Ugandan context mirrors similar results from reconfiguration projects in Nigeria and Tanzania.

Implementation challenges specific to Uganda's context include: (1) Limited technical capacity within UEDCL for advanced system integration, (2) Regulatory gaps in DER integration standards, (3) Financing constraints for large-scale modernization programs, and (4) Coordination challenges between multiple stakeholder institutions (MEMD, ERA, UEDCL).

The Kitala feeder's baseline Level 1 modernization maturity (69%) reflects broader African distribution network digitalization challenges identified by Monaco et al. (Monaco et al., 2024), SCADA and Intelligent Electronic Device (IED) integration at distribution offices represents the next critical step toward achieving Level 2 modernization status.

Sensitivity analysis indicates that results remain robust under ±20% variations in key assumptions (VOLL, capital costs, interest rates), with NPV rankings unchanged across reasonable parameter ranges. However, DG viability improves significantly under enhanced tariff scenarios or carbon credit mechanisms.

6. Conclusion

This comprehensive study analyzed Kitala 11kV feeder performance gaps and evaluated modernization interventions' technical and economic viability within Uganda's broader electricity sector context. Baseline reliability assessment revealed significant shortcomings (SAIDI: 53.81 hrs/yr, SAIFI: 34.21 int/yr) substantially exceeding international benchmarks, consistent with regional Sub-Saharan African distribution network challenges.

DIgSILENT PowerFactory simulations demonstrated substantial improvements across all interventions: SAIDI reductions ranging from 16.8% (protection coordination) to 57.5% (distributed generation), with technical losses reduced by 50.6–62.9%. Financial analysis identified reconductoring (NPV: UGX 19.04B, payback: 0.83 years) and parallel circuits (NPV: UGX 10.55B, payback: 0.46 years) as most economically viable investments, while distributed generation showed limited standalone financial feasibility under current regulatory frameworks.

7. Strategic Recommendations

To MEMD and ERA: Develop comprehensive modernization policy frameworks including: (1) Technical standards for DER integration and grid automation, (2) Financial incentive mechanisms supporting utility modernization investments, (3) Updated regulatory guidelines covering protection coordination and network reconfiguration, and (4) Capacity building programs for technical staff across the sector (Government of Uganda, 1999; Electricity Regulatory Authority, 2022).

To UEDCL: Implement systematic phased modernization approach prioritizing: (1) Immediate network reconfiguration for quick reliability gains, (2) Strategic reconductoring in high-loss segments, (3) Enhanced protection coordination systems, (4) Parallel circuit development in congested areas, and (5) Gradual DER integration as regulatory frameworks mature. This sequenced approach optimizes resource utilization while building institutional capacity.

Implementation Timeline: Phase 1 (Years 1–2): Network reconfiguration and protection coordination; Phase 2 (Years 2–4): Strategic reconductoring in priority segments; Phase 3 (Years 3–5): Parallel circuit development; Phase 4 (Years 4–7): Systematic DER integration following regulatory framework development.

These evidence-based measures, aligned with Vision 2040 electrification goals (National Planning Authority, 2020), provide a practical roadmap for enhanced distribution reliability, reduced technical losses, and smart grid transition. The methodology establishes a replicable framework for Sub-Saharan African utilities facing similar modernization challenges, contributing to regional knowledge sharing and capacity development initiatives.

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