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# Evaluating the upgrade potential of Uganda's 132 kV transmission lines to 220 kV: Nkenda to Mbarara South as a case Study

Mwanja Grace Charles [1*], Aliyu Nuhu Shuaibu [1], Ogwal Emmanuel [1], Venkataramana Guntreddi [1]

[1] *Department of Electrical, Telecommunication and Computer Engineering, School of Engineering and Applied Sciences, Kampala International University*

*charles.mwanja@studwc.kiu.ac.ug; nuhua@kiu.ac.ug; emmanuel.ogwal@kiu.ac.ug; gvramana@kiu.ac.ug*

*Corresponding Author: Mwanja Grace Charles; charles.mwanja@studwc.kiu.ac.ug*

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## Abstract

*This study examines the feasibility of upgrading Uganda's 132 kV transmission lines to 220 kV, using the Nkenda to Mbarara South line as a case study. The primary focus is to mitigate power losses, improve system efficiency, and enhance voltage regulation. The research employs the Nominal Pi-model in MATLAB to verify line parameters, evaluate performance indicators (efficiency, power factor, and voltage regulation), and assess economic viability through a Net Present Value (NPV) analysis. Findings reveal that the upgrade would reduce power losses by 68%, increase efficiency to 98.77%, and lower voltage regulation by 7.69%. The study concludes that the upgrade is both technically and economically viable, offering long-term benefits to Uganda's energy infrastructure. Recommendations include the immediate implementation of the 220 kV upgrade and the development of policies to optimize transmission system investments.*

**Nomenclature and units**

| | | |
|---|---|---|
| $V_r$ | Receiving End Voltage | kV |
| $V_s$ | Sending End Voltage | kV |
| $I_r$ | Receiving End Current | A |
| $I_s$ | Sending End Current | A |
| $Z$ | Impedance of the Transmission line | Ω |
| $Y$ | Admittance of the Transmission Line | μS |
| $P_a$ | Active Power | kW |
| $P_f$ | Power Factor | - (dimensionless) |
| $\eta$ | Efficiency | % |
| $V_{reg}$ | Voltage Regulation | % |
| $L$ | Line Length | km |
| $f$ | Frequency of the Power Signal | Hz |
| $R$ | Resistance of the conductor | Ω/km |
| $X$ | Reactance of the conductor | Ω/km |

## 1.0 Introduction

Access to reliable and efficient electricity is a cornerstone of economic development, enhancing living standards, supporting public services, and driving industrialization (Kakumba, 2021). Uganda's electricity transmission network, managed by the Uganda Electricity Transmission Company Limited (UETCL), includes lines operating at 132 kV, 220 kV, and 400 kV (UETCL, 2021). However, much of this infrastructure, some dating back over 65 years, has become inefficient and prone to significant power losses, estimated at 7%, exceeding the acceptable threshold of 5% (Kavuma *et al*., 2021). These inefficiencies, coupled with increasing electricity demand from urbanization, population growth, and industrialization, highlight the urgent need to optimize the transmission system.

One promising approach is upgrading the voltage of transmission lines from 132 kV to 220 kV (Nor, *et al*., 2021). Such upgrades reduce current levels, thereby minimizing resistive losses, improving voltage regulation, and increasing transmission efficiency (Ahmed & Saqib, 2020). Although the benefits of voltage upgrades have been widely explored in other countries, there remains a significant research gap in Uganda regarding the technical feasibility, economic viability, and environmental implications of such projects.

This study focuses on the Nkenda to Mbarara South transmission line, a critical component of Uganda's grid, to evaluate the feasibility of upgrading from 132 kV to 220 kV. The study aims to assess the technical performance of the current infrastructure, determine the economic viability of the upgrade using a Net Present Value (NPV) analysis, and provide recommendations to inform policy and investment decisions. By addressing these objectives, the research contributes to improving the reliability and sustainability of Uganda's power transmission network.

The remaining part of the paper is organized as follows: Section II reviews existing research relevant to transmission line upgrades. Section III details the methodology employed in this study, including data collection, technical analysis, and economic evaluation. Section IV presents and discusses the results, highlighting the technical and economic feasibility of the proposed upgrade. Finally, Section V provides conclusions and recommendations for policy and future research directions.

## 2.0 Literature Review

This section reviews existing studies on the technical and economic aspects of transmission line upgrades, emphasizing their relevance to the Nkenda to Mbarara South case study. The upgrading of transmission line voltages is a widely adopted strategy to enhance power system efficiency, reduce losses, and meet growing electricity demands without extensive new infrastructure (Alvarez *et al*., 2021; Mbuli *et al*., 2019). Globally, utility companies have explored this approach to address challenges related to aging infrastructure, increasing demand, and environmental constraints (Stephen & Iglesias, 2023; Wang *et al*., 2022).

Research indicates that voltage upgrades are a cost-effective alternative to constructing new lines (Alvarez *et al.*, 2021). Upgrading reduces resistive losses, improves voltage stability, and enhances power transfer capacity (Malla *et al*., 2023; Stephen & Iglesias, 2023). Studies conducted in Malaysia and Pakistan demonstrate the feasibility of increasing voltage levels while ensuring compliance with safety and performance standards. For example, a study in Malaysia successfully upgraded a 132 kV transmission line to 275 kV by improving insulation strength and maintaining electrical clearances (Nor, *et al*., 2021). Similarly, voltage uprating in Pakistan from 500 kV to 735 kV showed significant performance gains without compromising reliability (Ahmed & Saqib, 2020).

In developed countries like Germany and Japan, advanced technologies such as insulator-supported jumper devices and multi-bundle conductors have been used to achieve efficient voltage upgrades (Ahmed *et al*., 2022; Papailiou, 2021). These innovations not only improve the technical performance of the lines but also minimize environmental and visual impacts (Stephen & Iglesias, 2023). For Uganda, these technical insights can guide the adaptation of similar approaches, considering local conditions and resource availability.

Economic viability is a crucial factor in the decision to upgrade transmission lines (Gönen *et al*., 2024). Studies often employ financial metrics such as Net Present Value (NPV), Return on Investment (ROI), and cost-benefit analyses to assess the profitability of such projects (Haque *et al*., 2020). A case study in Spain highlighted significant cost savings by upgrading a 132 kV line to 220 kV, achieving over a 30% increase in power transfer capacity at a fraction of the cost of new construction Rosendo-Macías *et al*., 2023). Similarly, projects in Bangladesh and the United States demonstrated that voltage upgrades could provide substantial long-term financial benefits, even in resource-constrained environments (Halim *et al*., 2023; Murphy, 2022).

For Uganda, where financial resources are limited, NPV analysis offers a valuable tool for evaluating the economic feasibility of proposed upgrades. By comparing projected energy savings with initial investment and operational costs, this study aims to provide a robust financial justification for upgrading the Nkenda to Mbarara South transmission line.

Despite the potential benefits, voltage upgrades pose challenges such as higher upfront costs, technical complexities, and environmental concerns (Nor, *et al.*, 2021; Sungu, 2021). Addressing these requires careful planning, stakeholder engagement, and the adoption of best practices from successful projects worldwide (Mohanbabu *et al*., 2021). The integration of modern monitoring technologies and innovative design approaches offers opportunities to mitigate risks and maximize benefits (Obumba *et al*, 2020).

While global studies provide valuable insights, there is a lack of localized research specific to Uganda's transmission network. This study fills this gap by analyzing the technical performance and economic viability of upgrading Uganda's 132 kV transmission lines, providing a tailored approach for sustainable grid development.

## 3.0 Methodology

This section outlines the methodology and framework employed to evaluate the technical and economic feasibility of upgrading the Nkenda to Mbarara South transmission line from 132 kV to 220 kV. The methodology follows a structured approach to achieve the study's objectives: assessing technical parameters, determining performance indicators, and conducting an economic analysis.

### 3.1 Study Area

The study focuses on the Nkenda to Mbarara South transmission line, a double-circuit line located in southwestern Uganda. This line spans 160 km and serves as a critical link in Uganda's electricity grid, facilitating power distribution to key industrial and urban centers.

### 3.2 Research Framework

The research framework integrates technical analysis, performance evaluation, and economic assessment, as illustrated in Figure 1. The framework involves the following steps:

1. Verification of Transmission Line Parameters:

Using the Nominal Pi-model in MATLAB, the existing line's physical and electrical characteristics were determined and validated against original design specifications.

2. Performance Evaluation:

The current performance of the 132 kV line was evaluated in terms of power factor, efficiency, and voltage regulation.

3. Economic Feasibility Assessment:

The economic viability of upgrading the transmission line was assessed using a Net Present Value (NPV) analysis, comparing projected energy savings with initial investment costs.

### 3.3 Data Collection

Data was collected over a week from the Uganda Electricity Transmission Company Limited (UETCL) headquarters and Transmission Control Station in Lugogo, Kampala. Key data points included:

i. Physical configuration (line length, conductor type, and arrangement).
ii. Electrical characteristics (resistance, reactance, impedance, and frequency).
iii. Performance metrics (receiving and sending end voltage, current, power factor, and efficiency).
iv. Economic data (equipment costs, operational expenses, and energy tariffs).

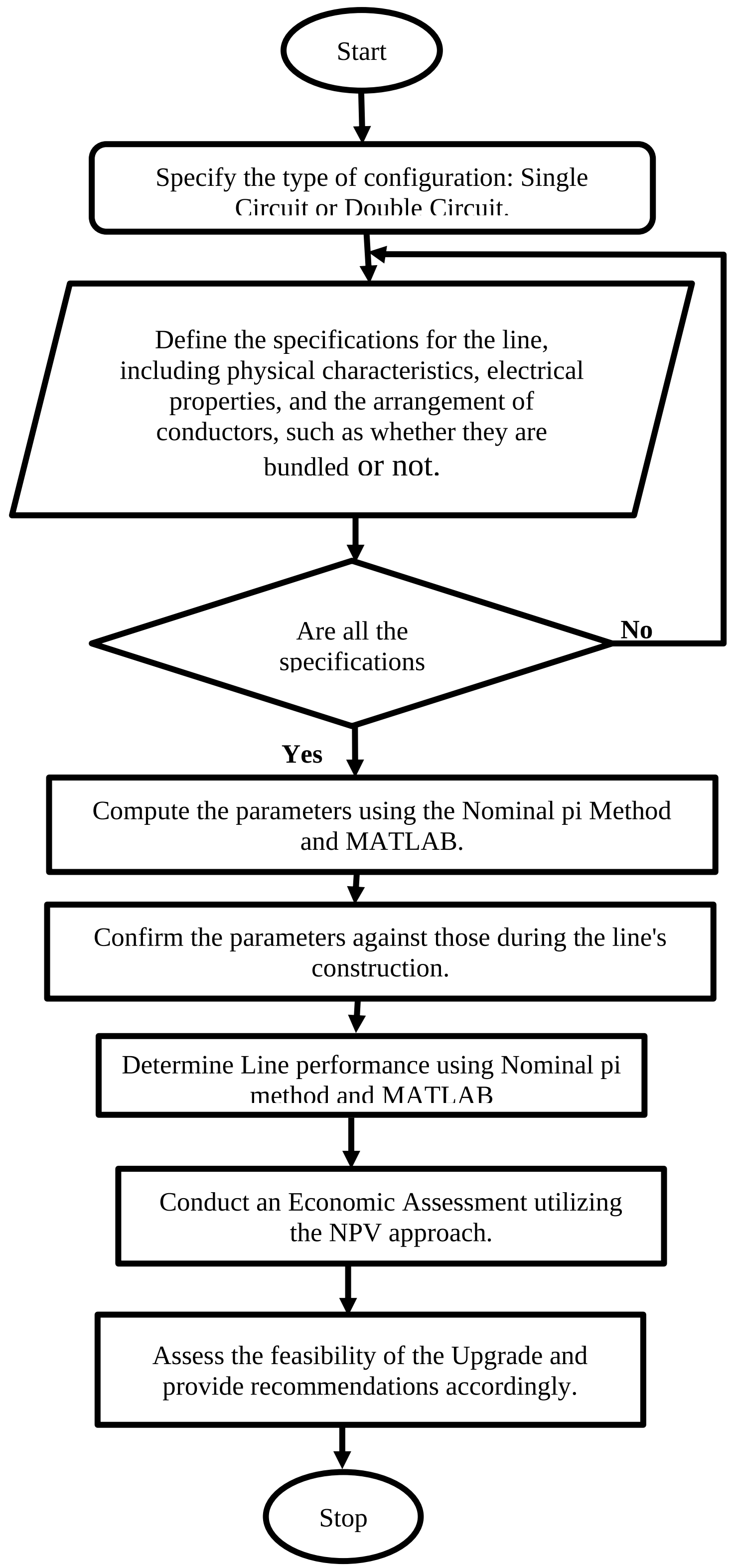

**Figure 1** Study Framework

### 3.4 Determination of Line Parameters

Line parameters were determined using MATLAB simulations based on the Nominal Pi-model (Economides *et al.*, 2021). Input data included:

i. Line length ($L$): $160\ km$.
ii. Resistance ($R$) and Reactance ($X$): Values per km of conductor.
iii. Power frequency ($f$): $50\ Hz$.

The simulation computed several critical parameters, leveraging established mathematical models to evaluate the transmission line's characteristics:

1. Impedance matrix using Maxwell's equations.

The series impedance of the transmission line was calculated using the following equations (Christopoulos, 2022):

$$Z_{ii} = R_c + j2\pi f \ln\left(\frac{2h_i}{r}\right) \quad (1)$$

$$Z_{ij} = j2\pi f \ln\left(\frac{d_{ij}}{r}\right) \quad (2)$$

where $Z_{ii}$ is the self-impedance; $Z_{ij}$ is the mutual impedance; $R_c$ is the conductor resistance (Ω/km); $f$ is the frequency of the power signal (Hz); $h_i$ is the height of the conductor above the ground (m); $d_{ij}$ is the distance between two conductors (m) and $r$ is the conductor radius (m).

2. Admittance matrix derived from capacitance calculations.

The line's admittance was computed using Maxwell's potential coefficient method (Ametani *et al*., 2020):

$$P_{ii} = \frac{1}{\varepsilon_0}\ln\left(\frac{2h_i}{r}\right) \quad (3)$$

$$P_{ij} = -\frac{1}{\varepsilon_0}\ln\left(\frac{d_{ij}}{r}\right) \quad (4)$$

where $P_{ii}$ is the self-potential coefficient; $P_{ij}$ is the mutual potential coefficient, $\varepsilon_0$ is the permittivity of free space ($8.854 \times 10^{-12}\ F/m$), $h_i$ is the height of the conductor above the ground (m); $d_{ij}$ is the distance between two conductors (m) and $r$ is the conductor radius (m)..

The potential coefficients were inverted to obtain the capacitance matrix, which was used to derive the line's admittance:

$$Y_{ph} = j2\pi f C_{ph} \quad (5)$$

Where $Y_{ph}$ is the line admittance, $C_{ph}$ is the capacitance matrix, and $f$ is the frequency of the power signal.

3. Propagation constants and characteristic impedance.

The propagation constant ($\gamma$) and characteristic impedance ($Z_c$) were derived as follows:

$$\gamma = \sqrt{ZY} \quad (6)$$

$$Z_c = \sqrt{\frac{Z}{Y}} \quad (7)$$

where $\gamma$ is the propagation constant, $Z_c$ is the characteristic impedance, $Z$ the impedance matrix and $Y$ is the admittance matrix. These parameters characterize the transmission line's behavior and determine its ability to transmit power efficiently.

### 3.5 Performance Evaluation

The performance indicators of the 132 kV line were calculated as follows:

1) Efficiency ($\eta$): Ratio of active power delivered to total power input.

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% \quad (8)$$

where $\eta$ is the efficiency, $P_{out}$ is the output power and $P_{in}$ is the input power.

2) Voltage Regulation ($V_{reg}$): Difference between sending and receiving end voltages, expressed as a percentage.

$$V_{reg} = \frac{V_s - V_r}{V_r} \times 100 \quad (9)$$

where $V_{reg}$ is the voltage regulation, $V_s$ is the sending end voltage and $V_r$ is the receiving end voltage.

3) Power factor ($P_f$): Ratio of active power to apparent power.

$$P_f = \frac{P_a}{P_s} \quad (10)$$

where $P_f$ is the power factor, $P_a$ is the active power and $P_s$ is the apparent power.

Performance was also evaluated at proposed upgrade voltages (205.73 kV and 220 kV) to assess potential improvements.

### 3.6 Economic Feasibility Analysis

The NPV method was employed to evaluate the economic feasibility of upgrading to 220 kV. The analysis involved:

1. Cost Estimation: Calculating total investment, including equipment (transformers, circuit breakers, insulators) and operational expenses.
2. Energy Savings: Calculating annual energy savings from reduced losses.
3. NPV Calculation (Gönen *et al.*, 2024):

$$NPV = \sum_{t=1}^{n} \frac{Cash\ Inflows - Cash\ Outflows}{(1+r)^t} \quad (11)$$

where NPV is the net present value, $r$ is the discount rate (11%) and $t$ is the project duration (50 years).

### 3.7 Simulation Process

The simulation of the Nkenda to Mbarara South transmission line's performance was conducted using MATLAB, a powerful computational and simulation tool. The process involved several key steps. First, input data were obtained from UETCL records, covering physical configurations, which included line length, conductor arrangement, and spacing; electrical properties (resistance, reactance, and capacitance per kilometer) and operational conditions including voltage levels, power frequency, and load characteristics. Using this data, the line's impedance and admittance matrices were calculated to describe its electrical behavior. MATLAB was then employed to implement the Nominal Pi-model, which represents the transmission line using series impedance and shunt admittance components, to simulate current, voltage, and power flows. Key performance metrics, including efficiency, voltage regulation, and power factor, were calculated for both the current 132 kV operation and the proposed 220 kV upgrade to evaluate improvements. The simulation assumed uniform line properties, constant power factor, and neglecting weather-related impacts.

## 4.0 Results and Discussions

This section presents the findings from the technical and economic evaluations of the Nkenda to Mbarara South transmission line upgrade. The results are analyzed in the context of the study's objectives, with technical performance improvements and economic feasibility discussed in detail.

### 4.1 Determination of Line Parameters

The physical and electrical parameters of the 132 kV line were determined using MATLAB simulations. Key results are summarized in Table 1.

**Table 1** Transmission Line Parameters

| **Parameter** | **Value** | **Unit** |
|---|---|---|
| Length | 160 | km |
| Resistance ($R$) | 0.1148 | Ω/km |
| Reactance ($X$) | 0.3964 | Ω/km |
| Impedance ($Z$) | 66.04 | Ω |
| Voltage ($V_r$) | 132 | kV |
| Power Factor ($P_f$) | 0.91 | - |

The results highlight the aging infrastructure's limitations, including significant impedance and suboptimal voltage regulation.

### 4.2 Line Performance Evaluation

Performance metrics for the current 132 kV operation and proposed upgrade voltages (205.73 kV and 220 kV) are detailed in Table 2.

**Table 2** Performance Metrics at Different Voltages

| **Voltage (kV)** | **Efficiency (%)** | **Voltage Regulation (%)** | **Power Factor** |
|---|---|---|---|
| 132 | 95.86 | 8.81 | 0.91 |
| 205.73 | 98.59 | 2.37 | 0.98 |
| 220 | 98.77 | 2.07 | 0.98 |

The results indicate significant improvements in all metrics at higher voltages. Efficiency increased by 3%, voltage regulation improved by 76%, and the power factor approached unity.

The improved efficiency at 220 kV demonstrates reduced power losses due to lower current levels. Enhanced voltage regulation indicates greater system stability, critical for reliable power delivery. Additionally, a higher power factor reflects better utilization of the system's capacity. Figure 2 shows that power losses decrease exponentially with higher voltages, highlighting significant operational savings. These demonstrate the benefits of upgrading to 220 kV.

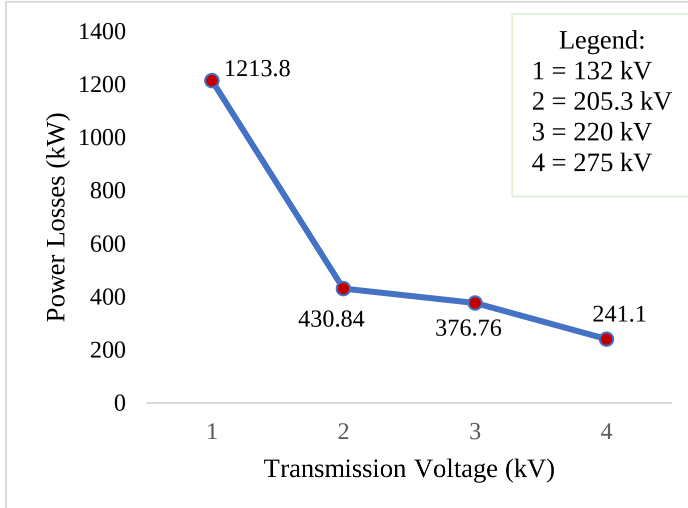


**Figure 2** Power Losses vs. Voltage

### 4.3 Economic Feasibility

The economic analysis focused on the NPV of upgrading the line to 220 kV. Key costs and savings are shown in Table 3.

**Table 3** Economic Analysis Summary

| **Description** | **Value (UGX)** |
|---|---|
| Initial Investment | 10,793,212,457 |
| Annual Energy Savings | 51,327,292,000 |
| Discount Rate ($r$) | 11% |
| NPV (50 years) | 378,754,919 |

The positive NPV indicates that the project is economically viable, providing long-term financial benefits through energy savings and reduced operational costs.

The upgrade will recover its costs within the project's lifespan, with substantial net savings. The use of standard components at 220 kV ensures cost efficiency and ease of implementation. In addition, increasing tariffs and reduced energy losses further enhance the project's financial attractiveness.

### 4.5 Technical and Economic Viability

The combined technical and economic analyses confirm that upgrading the Nkenda to Mbarara South line to 220 kV is both feasible and beneficial. The improved system performance aligns with national energy goals, addressing the challenges of aging infrastructure and increasing demand.

## 5.0 Conclusion

The study evaluated the technical and economic feasibility of upgrading the Nkenda to Mbarara South transmission line from 132 kV to 220 kV, demonstrating that the current operation is characterized by inefficiencies such as high power losses, suboptimal voltage regulation, and a lower power factor. The proposed upgrade is technically viable, with efficiency increasing from 95.86% to 98.77%, voltage regulation improving by 76%, and power losses reducing by 68%. Economically, a positive Net Present Value (UGX 378,754,919) confirms that the project offers a satisfactory return on investment. It is recommended that UETCL prioritize the upgrade with a phased implementation plan, leveraging standard 220 kV components for cost efficiency and future scalability. To ensure success, policy and investment support should be sought, and real-time monitoring systems implemented to track performance improvements. Capacity building initiatives should also be undertaken to train personnel on maintaining the upgraded infrastructure. Future research could focus on advanced simulation models to analyze long-term impacts, investigate the integration of renewable energy sources, and assess environmental and social considerations to address potential challenges in implementation.

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## Declaration of conflict of interest

The authors declare no conflict of interest in this research. All efforts have been made to ensure the integrity and impartiality of the findings presented.

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