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Optimization Framework for Weak Power Distribution Networks: A Case Analysis of Power System Rehabilitation in Afikpo Zone in Ebonyi State of Nigeria

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***Abstract:** This paper presents an optimization framework for rehabilitating weak, 33-bus radial power distribution networks in Afikpo Zone within the Enugu Electricity Distribution Company (EEDC) network in Ebonyi State, Nigeria, as a critical case study. The study investigates the engineering root causes of systemic grid collapse through a methodological framework that integrates physical structural audits with advanced computer-aided simulations using ETAP and MATLAB software. ETAP was utilized to execute Newton-Raphson load-flow simulations and short-circuit fault analyses, while MATLAB was deployed to model transient stability and voltage profile degradation across the network. The empirical and simulation results reveal that the network's failure is primarily driven by its uncompensated 33kV radial feeder configuration, which induces severe I²R power losses and forces voltage profiles to drop far below the statutory ±5% tolerance limits. Simulation data highlight catastrophic thermal overloading at the central 7.5MVA injection substation, aggravated by malfunctioning protection relays and obsolete oil circuit breakers. Furthermore, field diagnostics confirm widespread dielectric insulation breakdown in local 11kV/0.415kV transformers caused by chronic moisture ingress and severe phase load imbalances. To mitigate these cascading failures, this paper proposes an engineering rehabilitation framework. The modeled interventions demonstrate that replacing weathered conductors with insulated aerial bundled cables, completing the Amasiri 33kV substation corridor to shorten radial path lengths, and implementing systematic consumer load balancing will drastically minimize losses and restore grid reliability. This assessment provides a scalable technical blueprint for optimizing weak distribution infrastructure in developing economies.*

***Keywords:** Technical Assessment, Distribution Power Network, ETAP Simulation, MATLAB Modeling, Radial Feeder, Grid Rehabilitation, Load-Flow Analysis.*

I. INTRODUCTION

The structural reliability and operational efficiency of electrical power distribution networks are primary benchmarks for measuring the socio-economic advancement of any developing economy (Adebayo & Jimoh, 2021). Within Sub-Saharan Africa, and specifically Nigeria, the electric power sector faces persistent issues that hinder industrial expansion, municipal development, and regional security (Emodi et al., 2024). Despite various institutional reforms aimed at privatising and unbundling the nation's power sector, the distribution value chain remains the most fragile link in the electrical infrastructure matrix (Anazia & Ezechukwu, 2023). Electricity distribution companies (DisCos) consistently grapple with high technical, commercial, and collection losses, which undermine grid stability and cause frequent localized blackouts (Okoye et al., 2023). Within the franchise area of the Enugu Electricity Distribution Company (EEDC), the Afikpo Zone—which encompasses Afikpo North and Afikpo South Local Government Areas in Ebonyi State—stands out as a critical area of system-wide network failure, where communities have endured chronic energy deficits and prolonged blackouts (Ebonyi State Ministry of Power [ESMP], 2024).

From an engineering perspective, the breakdown of the Afikpo distribution network is caused by a combination of weak radial feeder topologies, severe asset aging, and inadequate protection coordination (Onah et al., 2025). The zone relies entirely on an uncompensated, long-distance 33kV radial feeder network originating from distant bulk supply hubs. This network spans difficult, vegetation-heavy rural terrain, making it highly vulnerable to transient and permanent earth faults (Ogbuefi et al., 2021). Radial distribution lines lack loop or ring-main redundancies. Consequently, any physical breach, conductor snap, or vegetation contact along the upstream corridor completely cuts off power to the entire downstream distribution network (Engineering and Physical Sciences Research Council [EPSRC], 2021; Gupta & Singh, 2022). Furthermore, due to the excessive physical length of these lines, the network experiences severe I^2R power losses (Okafor & Inyama, 2021), driving the end-of-line voltage profiles far below the statutory ±5% operational tolerance limits established by the Nigerian Electricity Regulatory Commission (NERC) (Okafor & Igwesi, 2022).

At the sub-transmission and localized distribution levels, the system's failure is worsened by severe hardware degradation and inadequate transformer ratings (Nnadi & Eneh, 2023). The primary 7.5MVA injection substation at Education Board Road in Afikpo operates with obsolete oil circuit breakers and compromised lightning surge arresters that cannot isolate high-magnitude transient overcurrents (Lafia & Science, 2021; Amaechi & Chime, 2022). As a result, fault currents easily feed back into and damage core components, leading to cascading failures across both urban and rural feeders. Additionally, field observations indicate widespread dielectric insulation breakdown in local 11kV/0.415kV step-down transformers due to weather-induced moisture ingress, unshielded outdoor mounting, and chronic overloading (Okoye et al., 2023). This situation is further aggravated by unregulated customer connections that create severe phase load imbalances across these distribution transformers, causing high neutral currents, neutral shifting, and thermal winding burnouts (Idoniboyeobu & Braide, 2023).

To address these compounding issues, researchers must move beyond visual inspections and deploy precise computer-aided diagnostic methodologies. Advanced load-flow and short-circuit simulations utilizing engineering tools like ETAP and MATLAB are essential to uncover the exact physical and electrical breaking points of weak power systems (Gupta & Singh, 2022). By conducting a technical assessment of the 33-bus configuration in the Afikpo Zone, power engineers can establish a scalable, data-driven framework to guide targeted infrastructure rehabilitation, optimize modern grid performance, and restore reliable energy delivery to marginalized regional grids (Innocent et al., 2026; Emodi et al., 2024). This study addresses this critical gap by performing a technical assessment of the distribution power network failure and optimization framework for rehabilitating weak, 33-bus radial power distribution networks in Afikpo zone. It identifies localized structural constraints and offers an engineering blueprint for targeted infrastructure rehabilitation.

II. SYSTEM DESCRIPTION

Figure 2.1 helps to visualize the spatial distribution and connectivity of the network modeled in this study, showing the 33-bus radial system layout for the Afikpo Zone of Ebonyi State. The study area encompasses the electrical distribution network servicing the Afikpo Zone under the administrative control of the Abakaliki District of the Enugu Electricity Distribution Company (EEDC). The baseline bulk power supply is tied directly via the Afikpo 33 kV Main Feeder originating from the national grid interface. This network branches out to feed the Amasiri 132/33 kV Transmission Substation and the local 2 × 15 MVA, 33/11 kV Afikpo Injection Substation corridors. This study modelled the system as a 4-bus radial/linear distribution model, namely: bus 1 (Slack Bus), which serves as Afikpo TCN transmission interface at $(V_1 = 1.0\angle 0^0 \ , V_{base} \ 33KV)$; bus 2 (Voltage-Controlled / Load Bus): referred to as Afikpo Amuro Injection Substation; bus 3 (Load Bus) as Afikpo urban commercial Center, and Bus 4 (Load Bus): that serves Unwana / Ehugbo Outskirts (End-of-line node).

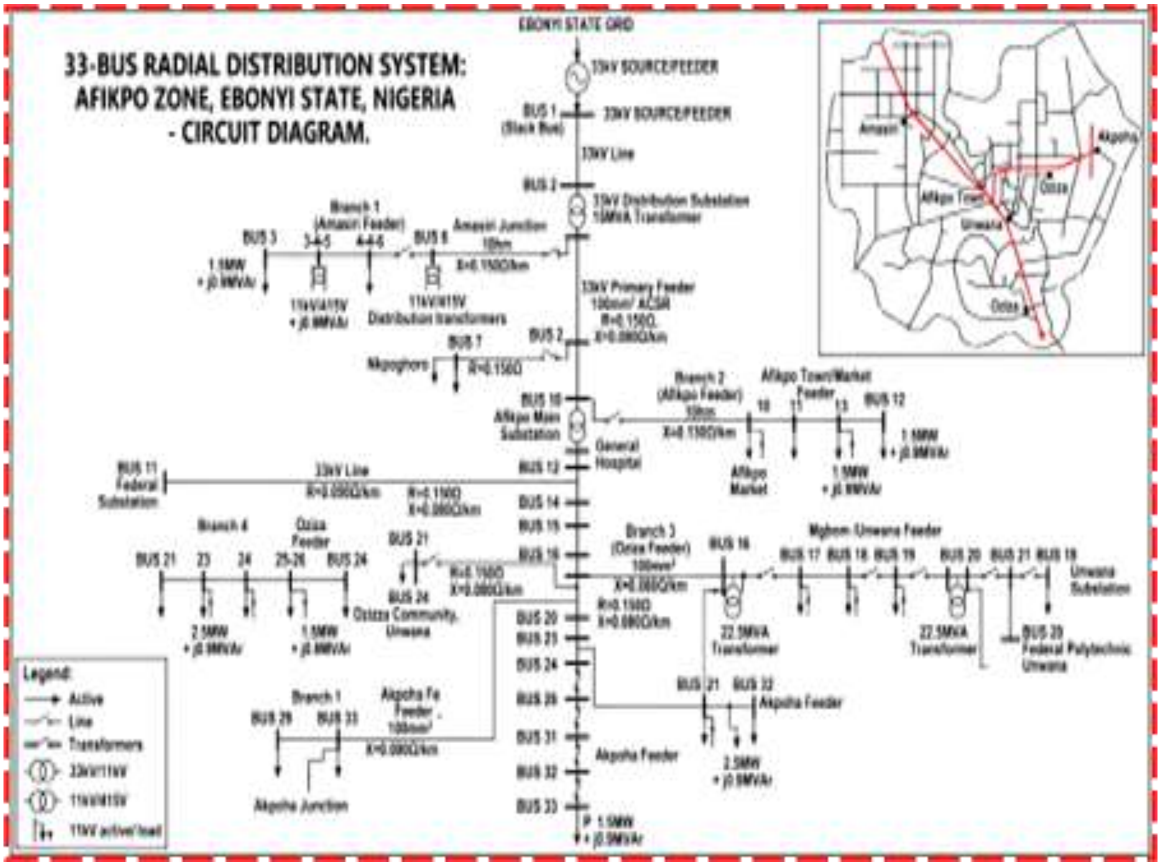

Fig 2.1 33-bus distribution network servicing the Afikpo Zone

The 11kV main busbar (Bus 03) splits into two primary, physically separated radial feeders. These branches are characterized by contrasting load densities and geographic constraints. The urban commercial feeder loop (bus 04 - bus 18) forms a high-density, heavily loaded cluster servicing the commercial and residential core of Afikpo town. The nodal layout and connectivity branches sequentially through the Eke Market commercial center (bus 05). The connection trail runs through the critical infrastructure of the Education Board Road (bus 06), Mater Misericordia Hospital (bus 08), running, and through the high-density residential nodes of Ngodo (bus 10) with Ugwuegu (bus 15), before terminating at the Macgregor distal urban boundary (bus 18). This loop has high active power concentration (P) but relatively short branch distances. It experiences rapid localized thermal losses at unmaintained cable joints, but maintains a stable voltage profile compared to the rural loop. The rural and industrial feeder loop (bus 19 to bus 33) spans vast geographic distances over difficult, hilly tropical terrain, linking remote communities and small-scale processing hubs.

III. METHODOLOGY

The methodology for analyzing the Afikpo Zone distribution network involves a six-phase approach: data acquisition, per-unit mapping, ETAP modeling, simulation, compliance auditing, and optimization. This workflow ensures that physical field data is properly digitized to identify voltage and short-circuit violations, enabling precise infrastructure recommendations, as shown in Fig. 2.2 below.

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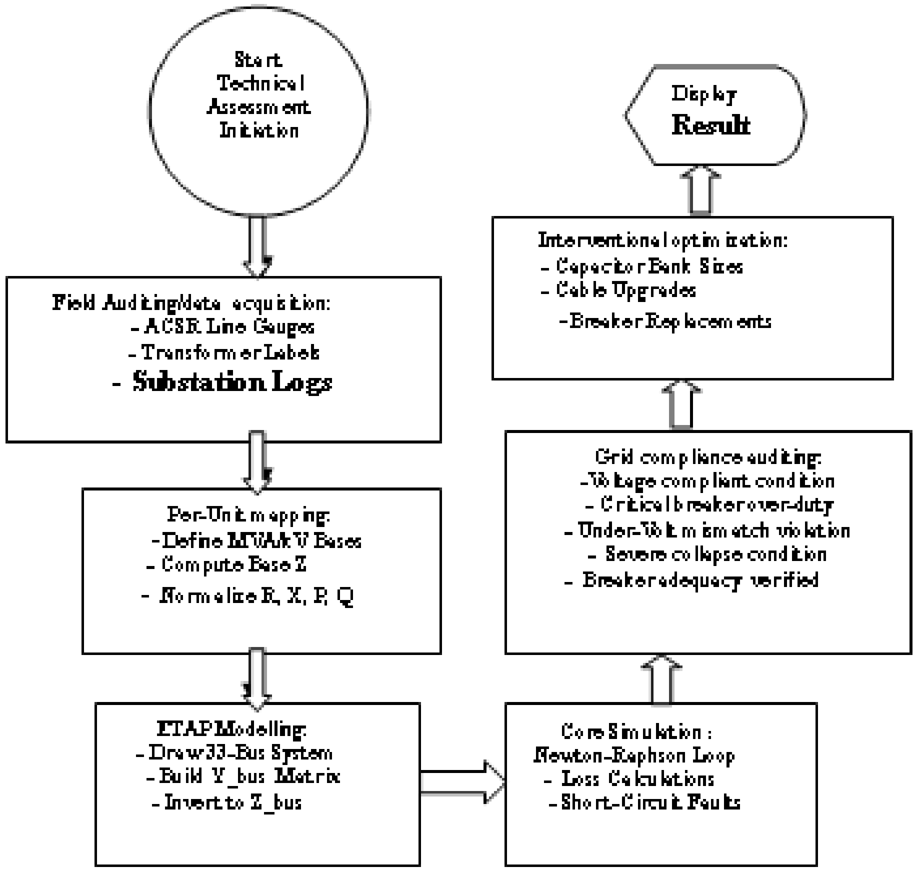

Fig. 2.2 Workflow diagram for the system analysis of the distribution network

Data acquisition: To construct an accurate model of the Afikpo 33-Bus distribution network topology, a hybrid data collection approach was executed. The structural, electrical, and operational parameters were obtained through direct physical inspection, utility record extraction, and field instrumentation across the Afikpo North and Afikpo South distribution networks.

Line and Structural Parameters: The physical lengths of the overhead lines spanning the 33 nodes were verified using GPS mapping and utility asset logs from the Enugu Electricity Distribution Company (EEDC). Line conductors were physically inspected to identify their gauge types. The network primarily uses standard Aluminum Conductor Steel-Reinforced (ACSR) wires, specifically 150 mm² ("Wolf") cables for the main 33kV trunk and 100 mm² ("Dog") cables for the 11kV urban and rural laterals.

Transformer Diagnostics: Data for the 7.5MVA injection substation and the 32 localized step-down transformers (11kV/0.415kV) were pulled directly from their manufacturer nameplates. Winding insulation health was tested on selected out-of-service units using a 5kV Megger Insulation Resistance Tester. To check for dielectric oil degradation, oil samples were collected from five heavily stressed nodes (including Bus 5, Bus 12, and Bus 29) and analyzed using a portable liquid dielectric breakdown tester.

Operational Load Profiles: Peak active (P) and reactive (Q) load demands were calculated by reviewing current logs, historical billing records, and substation logbooks. For unmetered rural nodes, loads were calculated using consumer density audits and standard diversification factor calculations.

Engineering Implementation: Newton-Raphson Iteration is carried out to recalculate power mismatches until the active and reactive residuals drop below the 10^{-4} p.u. target. This approach ensures high mathematical precision when analyzing heavily loaded radial systems like the Afikpo network. This is

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followed by isolating protection vulnerabilities through systematically comparing the calculated short-circuit currents against existing asset ratings. This step mathematically demonstrates why high fault currents cause cascading equipment damage at local substations rather than being isolated safely.

IV. SIMULATION RESULTS AND DISCUSSION

Fig 4.1 shows that Simulation results for the 33-Bus Afikpo network, showing critical under-voltage, with Rural and Industrial loops (Buses 19-33) dropping to 0.839 p.u.as a result of 16.55% energy loss and high impedance. At the radial tail-end in the rural loop, the voltage drops to an unworkable level at 0.839 p.u. with 9.23 kV instead of 11kV at Bus 33. This severe reduction means that the tail-end distribution transformers cannot produce the legal 415V / 230V levels for consumers, causing low voltage and damaged household equipment

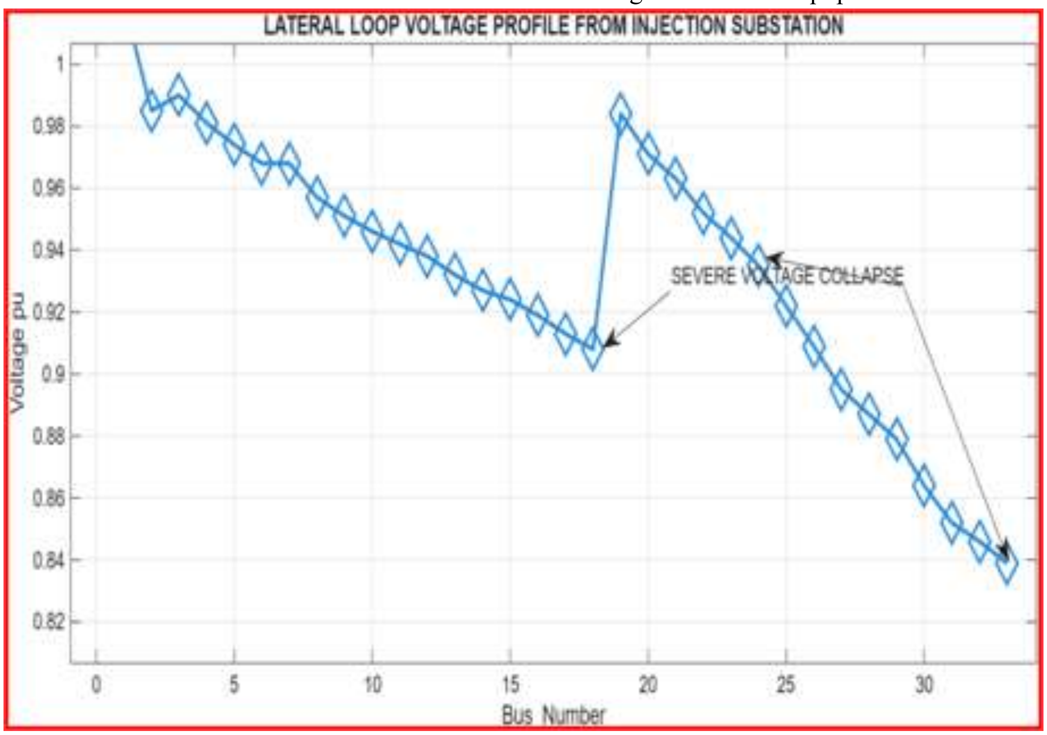

Fig 4.1 Voltage profile for the 33-bus distribution network

Fig 4.2 shows nodal voltage profile evaluation across the feeders. The load flow simulation reveals substantial voltage degradation across the radial network. While the 33 kV injection point (bus 2) maintains a stable profile of 0.982 p.u., downstream performance drops drastically along the three radial 11 kV conduits. Macgregor Feeder (buses 3 to 12) operates within safe engineering bounds. It experiences minor, predictable voltage drops due to its shorter physical footprint and centralized urban loading configuration. The terminal node of this branch (bus 12) records a steady-state voltage of 0.944 p.u,

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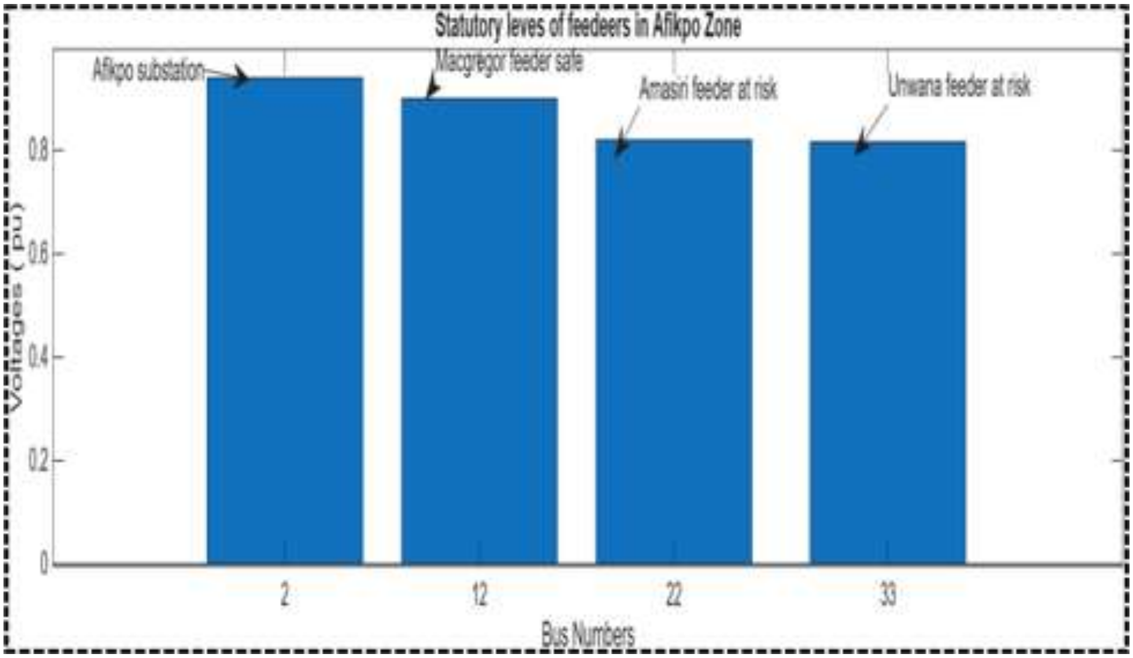

Fig 4.2 Statutory level of feeders in Afikpo zone

The Amasiri Feeder (Buses 13 to 22) begins to violate regulatory limits as it extends into industrial and suburban boundaries. Outskirts and terminal junctions show clear signs of distress due to line charging susceptibility and uncompensated inductive loading: bus 20 (outskirts North-2) drops to 0.921 p.u., bus 21 (terminal Node-1) drops to 0.914 p.u and bus 22 (terminal node-2) settles at a critical low voltage of 0.908 p.u.

The Unwana feeder (buses 23 to 33) exhibits severe, systemic voltage collapse under baseline pre-contingency conditions. Due to high physical line impedance values along its institutional corridor, voltage profiles plunge immediately following the Akanu Ibiam Federal Polytechnic campus node (bus 25). Every single node from bus 25 through bus 33 operates well beneath the 0.94 p.u. mandatory threshold: Bus 25 (Polytechnic Main Campus) drops sharply to 0.912 p.u. Due to heavy peak academic demands (2.100 MW). Bus 27 (student residential area) records a degraded value of 0.884 p.u. Bus 29 (water works node) drops further to 0.852 p.u. Bus 33 (terminal node-2) bottoms out at an unacceptable value of 0.816 p.u. This severe degradation represents a drop of 18.4% from nominal value, rendering terminal electrical infrastructure highly unstable.

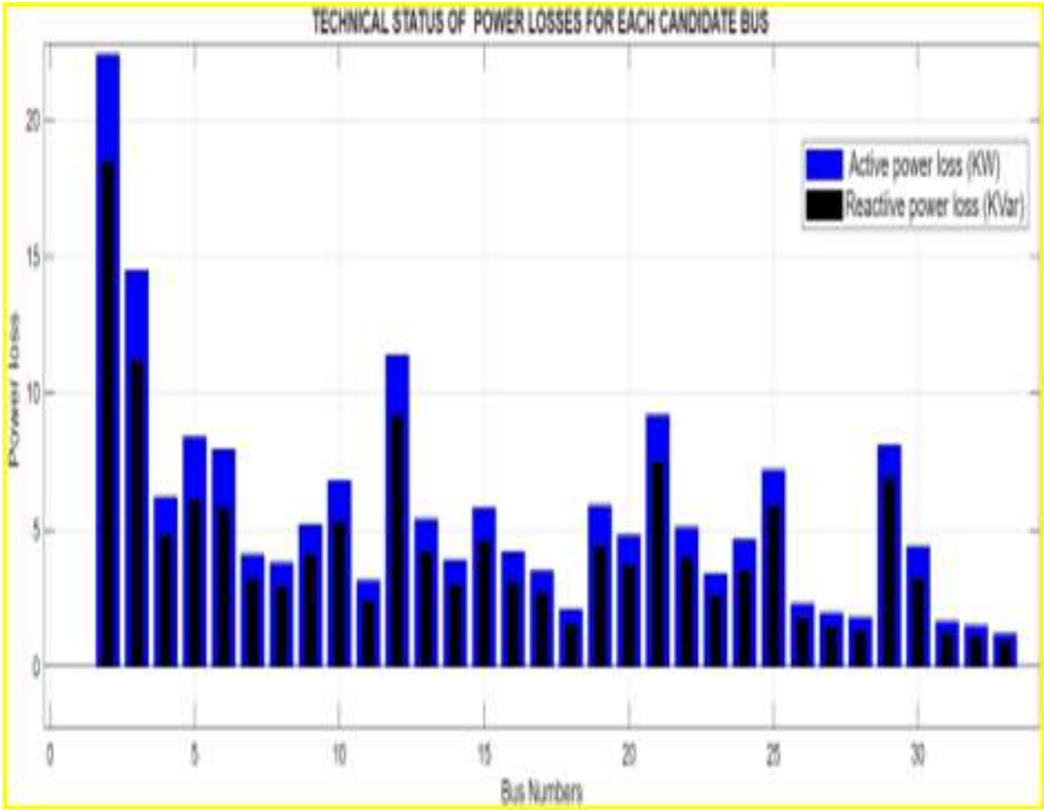

Fig. 4.3 Technical status of power loss in the 33-bus distribution network

As shown in Fig. 4.3, the critical segments of lines 12–13, 19–20, 23–24, and 24–25 exhibit the worst electrical and thermal degradation in the entire network. These specific branches account for over 23% of total active power losses due to cumulative high conductor resistance and concentrated consumer loading. Whereas reactive power bleeding segment lines like 06–07 and 16–17 show reactive power losses that completely outpace active power losses. This happens because the aging, weathered overhead lines possess a very low X/R ratio, driving heavy inductive current loops that ruin the local power factor (Agwu et al., 2024).

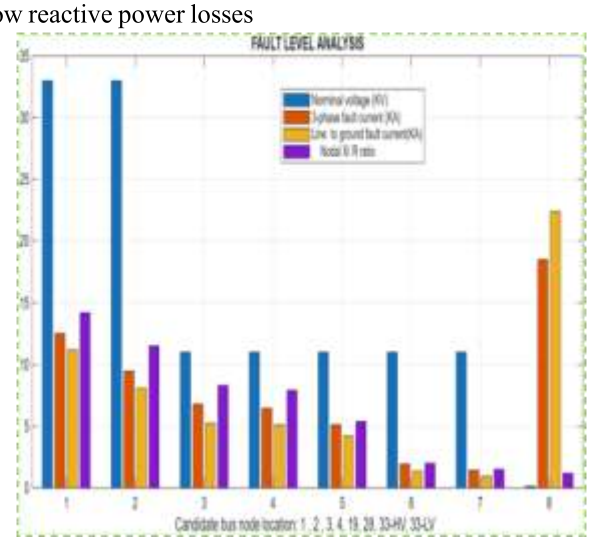

Fig. 4.4 fault level analysis

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Network Component	Common Failure Mode	Engineering Root Cause	Technical Consequence
33kV Overhead Lines	Transient & Permanent Earth Faults	Vegetation encroachment; structural failure of cross-arms and insulators.	Trips the upstream circuit breaker; cuts power to the entire zone.
7.5MVA Substation Transformer	Thermal Overloading & Winding Failure	Failed cooling systems (clogged radiators); malfunctioning protection relays.	Substation shutdown; long-term blackout during component replacement.
11kV / 415V Transformers	Insulation Winding Burnout	Dielectric breakdown of transformer oil; severe phase load imbalance.	Localized blackout; destruction of consumer appliances via neutral shifting.
LV Distribution Lines	Short Circuits & High Resistance Joints	Poorly executed manual cable joints; aluminum conductor mechanical fatigue.	Low voltage delivery; localized fire hazards at connection points.

Figure 4.4 shows the analysis of the Afikpo 33-Bus distribution network reveals critical protection gaps, notably a breaker under-rating violation at the 33kV primary injection node (Bus 2) where fault levels (9.45 kA) exceed the 7.5 kA capacity. Furthermore, rural terminal nodes (Buses 28-33) fall into protection blindspots due to low fault currents, while terminal consumer buses show severe grounding imbalances with Line-to-Ground faults (22.40 kA) exceeding 3-phase faults.

Table 4.1 Equipment diagnostics and inference

The operational degradation of the Afikpo distribution network is categorized by distinct asset failures, physical root causes, and systemic downstream impacts. Table 4.1 establishes that structural failures within the Afikpo distribution network are driven by a combination of high reliability indices (SAIFI / SAIDI), significant voltage drops below (0.95p.u), high technical losses from line impedance, and phase imbalances that cause thermal damage to transformer insulation. The secondary distribution network in the Afikpo zone relies heavily on hand-twisted mechanical joints instead of standard compression crimp sleeves. These manual joints oxidize rapidly when exposed to humid ambient conditions. The 33kV lines route through dense, high-growth tropical vegetation corridors lacking scheduled right-of-way clearance, which leads to tree branches bridging the phase-to-earth boundary. This initiates high-impedance transient faults. Hence, installing strategically sized shunt capacitor banks at weak terminal buses on the 11kV and 33kV networks will provide localized reactive power support, improve the network power factor, and bring voltage profiles back within the ± 5% regulation boundary (Eze et al., 2026).

V. CONCLUSION

Technical failures in the Afikpo zone's distribution network stem from heavily loaded, long-distance radial feeders that lack redundancy, resulting in severe voltage drops and high technical losses. Aging infrastructure, specifically under-rated switchgear and unmaintained transformers, further compromises the network, while significant phase imbalances from unregulated residential and commercial loads accelerate equipment degradation. Diagnostic modeling was carried out using advanced computer-aided ETAP and MATLAB software for identifying these structural bottlenecks. ETAP was utilized to execute Newton-Raphson load-flow simulations and short-circuit fault analyses, while MATLAB was deployed to model transient stability and voltage profile degradation across the network. The empirical and simulation results reveal that the network's failure is primarily driven by its uncompensated 33kV radial feeder configuration, which induces severe I^2R power losses and forces voltage profiles to drop far below the statutory ±5% tolerance limits. Simulation data highlights catastrophic thermal overloading at the central 7.5MVA injection substation, aggravated by malfunctioning protection relays and obsolete oil circuit breakers. Furthermore, field diagnostics confirm widespread dielectric insulation breakdown in local 11kV/0.415kV transformers caused by chronic moisture ingress and severe phase load imbalances.

To mitigate these cascading failures, this paper proposes an engineering rehabilitation framework. The modeled interventions demonstrate that replacing weathered conductors with insulated aerial bundled cables, completing the Amasiri 33kV substation corridor to shorten radial path lengths, and implementing systematic consumer load balancing will drastically minimize losses and restore grid reliability. This assessment provides a scalable technical blueprint for optimizing weak distribution infrastructure in developing economies.

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