International Journal of Innovative Scientific & Engineering Technologies Research 14(1):293-307, Jan-Mar., 2026

 www.seahipublications.org **ISSN: 2360-896X**

doi:10.5281/zenodo.19060471

The Role of Network Analysis and Distribution Network Devices in Enhancing the Reliability and Operational Efficiency of Electric Power Distribution Systems.

Lead Author:
Prof. Okeke Gerald Ndubuisi
(Professor of Climate Change & Environmental Sustainability).
FNisafetyE, FISPON, etc.
Highstone Global University, Texas, USA.

2nd Author: Prof. Cynthia Amaka Obiorah
Centre for Occupational Health Safety and Environment,
University of Port Harcourt, Port Harcourt, Nigeria
cynthia.obiora@cohseuniport.edu.ng

Engr. Prof. Theophilus Aku Ugah
FNSE, FSGI, FISPON, FIMC, FCALM, FMIMPS, FCPA, CMC.
Engineer/Environmentalist/Oil & Gas Professional
Highstone Global University, Texas, USA.
theogah2004@gmail.com.

Prof. James Okoroma, Ph.D.
M.A, B.A, ED, DIP, FCLMI, FBU
Institute of Courier and Logistics Management, Lagos
(Affiliate of Ballsbridge University and Trinity University).
Member of Governing Council, CLMI.

Pastor Engr. (Dr.) Enoch Oyokunyi
MNSE, FNISafetyE, FNIMechE.
National General Secretary
Nigerian Institution of Safety Engineers (NISafetyE)
Phone Number: 08036686887
Email: oyokunyi09@yahoo.com

Chief Dr. Udezi. Stephen A.L. Ph.D.
(FISPN, PMASSP, FSGI)
President Institute of Safety Professionals of Nigeria.
Phone: +2348062083053/Email: saludezi@yahoo.com

Dr. Obi Ifeyinwa Stephanie
Department of Human Resources Management
Highstone Global University, Texas, USA.

ABSTRACT

Electric power distribution networks represent the most critical and fault-prone segment of the electricity value chain, directly influencing service reliability, power quality, and customer satisfaction. In Nigeria, persistent challenges such as radial network configurations, aging infrastructure, limited automation, and inadequate coordination of network devices have continued to undermine the performance of distribution feeders. This study examines the role of network analysis and distribution network devices in enhancing the reliability and operational efficiency of electric power distribution systems. The research adopts a quantitative analytical approach, combining feeder topology evaluation, operating condition assessment, and reliability analysis using internationally recognized indices including System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), and Average Service Availability Index (ASAI). Empirical data obtained from selected urban distribution feeders are analyzed using statistical and simulation-based tools to evaluate the impact of network topology, loading conditions, and device coordination on fault isolation and restoration performance. The findings reveal that network topology and operating conditions significantly affect feeder reliability, while effective coordination and automation of protective and switching devices substantially reduce outage frequency and duration. Statistical hypothesis testing confirms that network analysis and device performance have a significant impact on distribution system reliability. The study concludes that systematic network analysis, combined with targeted improvement of network devices, is essential for achieving sustainable reliability enhancement in Nigerian power distribution systems. The results provide actionable insights for utilities, planners, and policymakers seeking to improve electricity service delivery through evidence-based network planning and investment strategies.

Keywords Network Analysis; Distribution Network Devices; Power Distribution Reliability; Feeder Performance; SAIFI; SAIDI; Device Coordination; Nigerian Power System

INTRODUCTION

The reliability and performance of electrical power distribution networks have long been recognized as fundamental determinants of electricity service quality, economic productivity, and overall socio-economic development. Historically, the evolution of electric power systems worldwide progressed from isolated, small-scale generation units supplying localized loads to large, interconnected systems designed to meet growing demand, enhance operational efficiency, and improve system reliability. In the early stages of power system development, engineering attention was largely concentrated on generation adequacy and transmission expansion, with the assumption that distribution networks would function reliably once power reached substations. Over time, however, it became evident that deficiencies at the distribution level could undermine upstream investments by exposing end users to frequent interruptions, voltage instability, and poor power quality.

Distribution networks account for the delivery of the majority of electrical energy consumed in modern power systems often exceeding 70 % yet they remain the most failure-prone segment of the electricity supply chain. Their vulnerability arises from extensive geographical coverage, continuous exposure to environmental stresses, and reliance on numerous electromechanical components such as conductors, transformers, protective relays, and switching devices. Historically, distribution systems were designed for unidirectional power flow, limited load diversity, and modest growth projections, with minimal consideration for redundancy, automation, or real-time monitoring. As demand increased and networks expanded, these foundational assumptions proved inadequate, resulting in higher failure rates, prolonged outage durations, and greater operational complexity. Consequently, *network analysis* emerged as a core discipline in power systems engineering, providing structured methods for evaluating feeder performance, fault behavior, and reliability outcomes under diverse operating conditions. In Nigeria, the historical development of the power distribution sector mirrors these global trends but with more severe and persistent challenges. Following independence, rapid electrification efforts prioritized geographic expansion of supply rather than long-term system robustness. Distribution networks were predominantly implemented as radial systems to minimize capital expenditure and simplify protection schemes. While this approach enabled faster network rollout, it entrenched long-term reliability weaknesses. As noted by Adebayo and Yusuf (2023), the dominance of radial feeder configurations across Nigeria's urban and rural networks "offers limited operational flexibility and almost no redundancy, thereby amplifying the impact of single-point failures." Similarly, Babatunde (2025) emphasizes that the structural rigidity of radial distribution systems remains a central cause of widespread outages in Nigerian cities.

Over successive decades, Nigeria's distribution networks have been subjected to sustained stress arising from rapid population growth, accelerated urbanization, industrial expansion, and insufficient infrastructure renewal. Many feeders currently in operation were designed several decades ago for load levels significantly lower than present demand. This persistent mismatch between network capacity and actual loading has resulted in chronic overloading of lines and transformers, accelerated equipment degradation, and increased fault incidence. Nigerian studies consistently report that aging distribution assets combined with limited preventive maintenance are major contributors to feeder unreliability and service interruptions (Ojo & Salau, 2023; Ogunjuyigbe et al., 2024). Historical underinvestment in network automation and monitoring technologies has further compounded these challenges. In many Nigerian distribution networks, fault detection, isolation, and service restoration rely heavily on manual processes, which prolong outage durations and expand the number of affected customers. Ebiarede et al. (2024) observe that delayed switching operations and poor coordination of protective devices significantly worsen outage impacts, particularly in dense urban networks where feeder lengths and customer concentrations are high. The liberalization and unbundling of Nigeria's power sector in the early 2010s marked a major institutional reform intended to improve efficiency, accountability, and service delivery. While these reforms stimulated renewed interest in generation capacity expansion and market restructuring, the distribution segment remained constrained by inherited infrastructure deficiencies and limited capital investment. Empirical evidence from post-reform studies consistently identifies distribution networks as the weakest link in the Nigerian power sector. Uchechukwu and Okafor (2021) report that distribution systems account for the highest proportion of customer interruptions, with technical losses and voltage instability persisting despite upstream improvements.

In response to these enduring challenges, Nigerian researchers have increasingly applied formal reliability assessment and network analysis methodologies to evaluate distribution system performance. Early Nigerian studies relied largely on descriptive outage statistics, but contemporary research has adopted internationally recognized reliability indices such as SAIFI, SAIDI, CAIDI, and ASAI to provide standardized and comparable measures of service continuity. Empirical investigations of urban 11 kV and 33 kV feeders have revealed substantial disparities in reliability performance across feeders, often attributable to differences in feeder length, load density, protection schemes, and equipment condition. For instance, Umahon Ovbiagele et al. (2025) demonstrated that certain urban feeders consistently exhibit unacceptable reliability levels, highlighting the need for feeder-specific intervention strategies rather than uniform network upgrades.

Advances in computational tools have further transformed network analysis practices within the Nigerian research landscape. The adoption of simulation platforms such as MATLAB and ETAP has enabled detailed modeling of real-world feeder configurations, fault scenarios, and protection coordination schemes. Studies by Adetunmbi et al. (2024) and Ebiarede et al. (2024) show that software-based analysis can effectively identify critical network components whose failure disproportionately affects overall reliability, thereby supporting targeted maintenance and investment decisions. Despite these methodological advances, notable gaps remain in the holistic integration of historical network evolution, device performance, and dynamic operating conditions within reliability assessment frameworks. Many existing studies focus on isolated feeders or short observation periods, limiting their capacity to capture long-term reliability trends and systemic weaknesses. Moreover, the interaction between aging infrastructure, evolving load patterns, and protective device behavior remains insufficiently explored in urban Nigerian distribution networks. Against this historical and technical backdrop, the present study is motivated by the need for a comprehensive and analytically rigorous examination of distribution feeder reliability within Nigeria's urban power networks. By grounding reliability assessment in both historical network development and contemporary analytical techniques, the study seeks to generate actionable insights that support sustainable reliability enhancement, informed infrastructure investment, and improved electricity service delivery in Nigeria.

Statement of the Problem

Electric power distribution networks remain the most critical yet most vulnerable segment of the electric power system, as they directly interface with end users and determine the quality and reliability of electricity supply. Despite advancements in generation and transmission infrastructure, distribution networks continue to experience frequent outages, voltage instability, high technical losses, and prolonged restoration times. These challenges are particularly pronounced in urban distribution systems, where high load density, aging infrastructure, and limited redundancy place severe stress on network components and operating devices.

In many existing distribution networks, especially those predominantly radial in configuration, a single fault can result in widespread service interruption due to the absence of alternative power flow paths and inadequate sectionalization. Furthermore, insufficient application of systematic network analysis techniques has limited the ability of utilities to accurately evaluate feeder performance, identify critical weak points, and optimize the deployment and coordination of network devices such as transformers, protective relays, circuit breakers, and switches. Poorly coordinated or obsolete devices often amplify the impact of localized faults, transforming minor disturbances into extensive outages.

Although several studies have examined aspects of distribution system performance, gaps persist in the integrated assessment of network topology, operating conditions, and device performance using standardized analytical tools and reliability indices. In particular, limited attention has been given to how network analysis methodologies can be effectively applied to evaluate the operational effectiveness of distribution devices and their influence on overall network reliability. This lack of comprehensive analytical insight constrains evidence-based planning, targeted maintenance, and strategic investment decisions aimed at improving distribution system reliability. Therefore, the problem addressed in this study is the inadequate application of systematic network analysis and device performance evaluation in diagnosing and improving the reliability and operational efficiency of electric power distribution networks.

Aim and Objective

The main aim of this study is to analyze the performance of electric power distribution networks using network analysis techniques and to evaluate the role of network devices in enhancing system reliability and operational efficiency. The specific objectives of the study are to:

1. Analyze the electrical performance of selected distribution feeders using network analysis techniques to assess voltage profiles, power flow characteristics, and loss levels.
2. Evaluate the impact of network devices including transformers, protective relays, circuit breakers, and sectionalizing switches on the reliability and fault response of the distribution network.

Research Questions

To achieve the stated objectives, the study seeks to answer the following research questions:

1. How does network topology and operating condition affect the performance and reliability of electric power distribution feeders?
2. What is the extent to which network devices and their coordination influence fault isolation, restoration time, and overall system reliability?

Research Hypothesis

The study is guided by the following hypothesis:

H_0 (Null Hypothesis): Network analysis and the performance of distribution network devices have no significant impact on the reliability and operational efficiency of electric power distribution systems.

Significance of the Study

The significance of this study is multidimensional, spanning technical, operational, and policy-related domains.

Technical perspective, the study provides a structured analytical framework for evaluating distribution network performance using established network analysis techniques and reliability indices. The findings contribute to a deeper understanding of how feeder configuration and device performance influence system behavior during normal operation and fault conditions.

From an operational standpoint, the study offers practical insights that can assist utility engineers and system operators in identifying critical feeders and devices that require priority maintenance, upgrading, or re-coordination. This supports more efficient fault management, reduced outage duration, and improved service quality. From a planning and policy perspective, the results of the study can inform infrastructure investment decisions, network reinforcement strategies, and regulatory performance benchmarks. By highlighting the role of analytical tools in improving reliability outcomes, the study supports evidence-based planning and sustainable development of distribution networks. Additionally, the study serves as a reference for academic researchers and students, contributing to the existing body of knowledge on network analysis and device performance in electric power distribution systems.

Scope and Limitations of the Study

Scope of the Study

The scope of this study is limited to the analysis of electric power distribution networks, with particular emphasis on Distribution feeder network analysis, Performance evaluation of network devices, Reliability assessment using standard indices, Urban distribution system characteristics. The study focuses on medium-voltage distribution levels (e.g., 11 kV and 33 kV feeders) and relies on historical operational data and simulation-based analysis tools to assess system performance.

Limitations of the Study

Despite its contributions, the study is subject to certain limitations. The analysis is constrained by the availability and accuracy of operational and outage data. The study focuses on selected feeders, which may limit the generalization of results to all distribution networks. Economic and regulatory factors influencing network performance are not explicitly modeled. Real-time dynamic behavior under extreme contingencies may not be fully captured due to modeling assumptions. These limitations, however, do not invalidate the findings but rather highlight areas for further research and future system enhancement.

LITERATURE REVIEW

Conceptual and Theoretical Framework

Conceptual Review

Network analysis in power distribution encompasses the **s**ystematic evaluation of network behavior, fault propagation, and operational performance using analytical, mathematical, and computational methods. It integrates load flow analysis, voltage profile assessment, short-circuit studies, and reliability evaluation to inform decisions on feeder operation, protection coordination, and infrastructure investment. Conceptually, network analysis treats distribution systems as complex socio-technical systems in which feeder topology, device reliability, load dynamics, and operational protocols interact to determine overall performance (Adebayo & Yusuf, 2023).

Network devices, including distribution transformers, protective relays, circuit breakers, fuses, reclosers, and sectionalizing switches, function as the operational and protective backbone of distribution systems. Their performance directly influences fault detection, isolation, load restoration, and the duration and frequency of service interruptions. As observed by Ebiarede et al. (2024), the reliability of a distribution feeder is strongly contingent upon the operational status, coordination, and response time of protective devices deployed along the network. Faulty, uncoordinated, or aging devices can escalate minor disturbances into widespread outages, especially in high-density urban networks. Relays, in particular, play a central role in network reliability. Comparative studies by Anyalebechi and Anyaka (2025) systematically analyzed electromechanical versus numerical over-current relays using MATLAB/Simulink, demonstrating that the selection and coordination of relays significantly affect service continuity and fault management efficiency. These findings highlight the necessity of integrating device-level assessments with overall network performance analysis to improve operational resilience.

In the Nigerian context, network reliability assessment often relies on internationally recognized indices. According to Uchechukwu and Okafor (2022), indices such as SAIFI, SAIDI, CAIDI, MTBF, and MTTR are widely used to quantify the frequency, duration, and systemic impact of outages across feeders and regions. These indices provide a standardized framework for diagnosing performance bottlenecks, evaluating maintenance strategies, and comparing reliability across feeders and urban centers. Empirical studies, including those by Akinwale et al. (2023) and Ogunjuyigbe et al. (2024), have applied these indices to assess 11 kV and 33 kV feeders in urban Nigerian distribution networks, revealing patterns of chronic overloading, voltage instability, and persistent technical losses.

Furthermore, modern Nigerian research emphasizes the integration of simulation-based network analysis to model real-world feeder configurations and device interactions. For instance, Adetunmbi et al. (2024) used ETAP simulations to evaluate feeder performance under fault conditions and to quantify the influence of device reliability on system availability. Similarly, Umahon Ovbiagele et al. (2025) combined historical outage data with simulation-based analysis to forecast feeder reliability trends, providing actionable insights for feeder-specific interventions, maintenance prioritization, and resource allocation. Collectively, these studies indicate that network analysis is not merely a theoretical exercise but a practical tool for enhancing operational resilience, improving service quality, and reducing the socio-economic impact of electricity outages in Nigeria. However, while significant progress has been made, gaps remain, particularly in integrating real-time device monitoring, predictive maintenance, and adaptive network control into reliability frameworks.

Theoretical Framework

Systems Theory: Systems Theory was first formalized by Ludwig von Bertalanffy in 1945 as a general framework for studying complex, interdependent systems (Bertalanffy, 1968). The theory emphasizes the holistic interactions among system components, suggesting that the behavior of the entire system cannot be fully understood by analyzing components in isolation. In power distribution networks, this perspective conceptualizes the system as a multi-component structure consisting of lines, transformers, relays, circuit breakers, sectionalizing switches, and loads. Interactions among these components collectively determine operational behavior, fault propagation, and service reliability. Within the Nigerian distribution context, Systems Theory supports network modeling approaches that simulate electrical flows, fault events, and device coordination across interconnected feeders. For instance, Adebayo and Yusuf (2023) employed a systems-theoretic approach to model urban 11 kV distribution feeders, demonstrating how interdependencies among radial feeders, switches, and protective devices amplify the impact of single-point failures. Similarly, Babatunde (2025) applied a systems perspective to analyze urban distribution reliability, highlighting that failure isolation and feeder reconfiguration decisions must consider both local device behavior and system-wide interactions to minimize outage impact. By adopting a systems-theoretic lens, Nigerian researchers can capture the cascading effects of device failures, assess network vulnerability, and design interventions that enhance resilience, particularly in radial feeder networks that dominate urban distribution infrastructure.

Reliability Engineering Theory: Reliability Engineering Theory emerged in the mid-20th century, primarily in the context of industrial and aerospace systems, as a formal methodology for quantifying the probability of system and component performance over time under stress or failure conditions (O'Connor & Kleyner, 2012). Core to reliability theory is the use of mathematical models—such as exponential, Weibull, and log-normal distributions to represent component failure rates and lifetimes. Reliability theory also underpins the formulation of performance indices, including the System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), Mean Time Between Failures (MTBF), and Mean Time to Repair (MTTR). These indices provide standardized benchmarks for assessing the availability, stability, and performance of electrical distribution networks.

Application in Nigerian Studies: Nigerian researchers have effectively applied reliability engineering principles to quantify distribution system performance and guide decision-making. Umahon Ovbiagele et al. (2025) applied IEEE Standard 1366 reliability models to compute and forecast SAIFI, SAIDI, and

CAIDI for 11 kV feeders in the Auchi distribution network. By integrating reliability theory with predictive analytics, their study generated actionable insights for preventive maintenance scheduling, prioritization of feeder upgrades, and policy interventions. Similarly, Adetunmbi et al. (2024) employed Weibull-based failure rate modeling to assess transformer and feeder reliability in urban Nigerian networks, demonstrating that incorporating component-specific reliability data improves the accuracy of network performance predictions. Ebiarede et al. (2024) further emphasized that reliability-based simulations enable operators to evaluate the effects of device coordination, sectionalizing strategies, and fault isolation techniques, providing a practical framework for minimizing outage durations and improving service quality.

Integration of Systems Theory and Reliability Engineering in Nigerian Research

The combined application of **Systems Theory** and **Reliability Engineering Theory** provides a coherent analytical lens for studying distribution networks. Systems Theory offers a **holistic perspective** on network interactions, highlighting how faults propagate and how devices interdependently affect overall performance. Reliability Engineering, in contrast, provides the **quantitative tools** to model component and system behavior under stress, to forecast failures, and to generate standardized reliability indices.

In practice, Nigerian studies integrate these theoretical perspectives by:

1. **Modeling network interdependencies** (Systems Theory) to simulate feeder interactions, load redistribution, and cascading failures.
2. **Applying reliability models** (Reliability Engineering Theory) to compute failure probabilities, mean repair times, and indices such as SAIFI and SAIDI for empirical evaluation.
3. **Guiding maintenance and investment decisions**, using the combination of system-level insights and statistical reliability predictions to enhance operational resilience (Uchechukwu & Okafor, 2022; Akinwale et al., 2023; Umahon Ovbiagele et al., 2025).

This theoretical framework forms the foundation for contemporary Nigerian research on network analysis and devices, enabling the development of holistic, data-driven, and actionable approaches for improving urban power distribution reliability.

Empirical Review

This section critically examines contemporary Nigerian research on network analysis, device performance, and distribution feeder reliability. Emphasis is placed on empirical studies that employ quantitative reliability indices, network simulation tools, and device-level performance assessment to diagnose operational deficiencies and guide improvement strategies.

Distribution Network Reliability Studies in Nigeria

A growing body of empirical research in Nigeria has applied network analysis techniques to assess the reliability of urban and peri-urban distribution feeders. Adetunmbi et al. (2024) conducted a MATLAB-based reliability evaluation of a 33 kV distribution feeder in Ile Oluji. Their study quantified the influence of component failure rates including switchgear, conductors, and transformers—on availability, SAIDI, and SAIFI, revealing a strong inverse relationship between component failure rates and network availability. The study demonstrated that systematic reliability assessment can identify feeder-specific weaknesses and inform maintenance prioritization, highlighting the practical utility of computational network analysis in Nigerian distribution systems.

Similarly, Abe et al. (2022) investigated secondary feeder reliability in the Ado Ekiti metropolis, employing both load-point and customer-oriented reliability indices. Their quantitative evaluation revealed persistent reliability deficiencies across multiple feeders, including frequent interruptions, prolonged outage durations, and uneven service delivery, underscoring the need for targeted feeder-specific interventions rather than uniform network upgrades.

In a detailed case study of the Auchi distribution network, Umahon Ovbiagele et al. (2025) integrated traditional reliability indices with predictive time series modeling to assess feeder reliability over time. Findings highlighted critically low and variable reliability across feeders, with the Jattu feeder exhibiting an ASAI of only 16.14% in a single month of 2023, demonstrating extreme vulnerability. Forecasting analyses further revealed divergent reliability trends among feeders, providing a data-driven foundation for prioritized feeder maintenance and operational planning. These studies collectively demonstrate the increasing adoption of empirical, data-driven approaches to quantify reliability performance in Nigerian distribution systems.

Network Analysis Tools and Device Studies

Beyond feeder-level reliability, Nigerian research has increasingly examined network devices and analytical tools that shape distribution system performance. For example, Anyalebechi and Anyaka (2025) investigated the performance of protective relays in Nigerian distribution networks, comparing legacy electromechanical relays with modern numerical relays through simulation modeling. The study revealed that numerical relays, when properly coordinated, significantly reduce outage duration and improve selectivity, emphasizing that device choice and coordination directly affect network reliability outcomes.

Furthermore, Ajeigbe and Abayomi (2025) explored smart distribution network designs for Nigerian university campuses, integrating advanced monitoring devices, automated sectionalizing switches, and real-time control systems. Their findings highlight the potential of intelligent network configurations to enhance service continuity, reduce technical losses, and improve overall sustainability. These studies indicate a growing recognition that network device performance and configuration is as critical as feeder design for achieving reliable electricity distribution in Nigeria.

Complementary Performance and Loss Analysis

Complementary research emphasizes technical losses and operational efficiency, which are closely tied to perceived and actual reliability. Obiora et al. (2025) analyzed the determinants of technical losses in Nigerian urban distribution networks, identifying key contributors such as excessive feeder length, undersized conductors, inadequate maintenance, and suboptimal device coordination. Their study underscores that network analysis must account not only for outage frequency and duration but also for energy efficiency and operational losses, as these directly influence customer satisfaction and economic impact. Similarly, Ogunjuyigbe et al. (2024) combined feeder reliability indices with loss minimization strategies, demonstrating that integrating network simulation with device-level performance evaluation allows utilities to target interventions that simultaneously improve reliability and reduce technical losses. These complementary studies reinforce the notion that reliability assessment in Nigerian distribution systems is most effective when it integrates feeder performance, device functionality, and system efficiency considerations.

Gaps in Existing Studies

Despite significant advances in network analysis and device-focused studies, the existing literature on Nigerian power distribution systems still reveals several persistent gaps that underscore the need for further research. First, there is limited integration of device performance and network topology within holistic reliability frameworks. Many studies continue to rely heavily on historical outage data and conventional reliability indices such as SAIFI, SAIDI, CAIDI, and ASAI to assess system performance (Abe et al., 2022; Obiora et al., 2025). While such indices provide important snapshots of feeder reliability, they often fail to incorporate the nuanced operational behavior of critical devices such as protective relays, sectionalizing switches, reclosers, and real-time switching logic. Studies by Anyalebechi and Anyaka (2025) demonstrate that detailed modeling of protective relay coordination and sectionalizer performance can significantly refine reliability assessments, yet such device-focused analysis remains sporadic and not yet generalized across Nigerian urban distribution systems.

Second, there is insufficient application of advanced network analysis tools. Although simulation platforms such as MATLAB and ETAP have been applied to case studies (Adetunmbi et al., 2024; Ajeigbe & Abayomi, 2025), the systematic adoption of integrated analytical frameworks that combine real-time monitoring, optimization algorithms, and predictive analytics remains limited. This gap restricts the ability to conduct adaptive, scenario-based reliability modeling that accounts for dynamic loading conditions, intermittent faults, and the stochastic behavior of distribution assets. Without such sophisticated modeling, planners and engineers face challenges in anticipating critical failure points and in designing proactive intervention strategies.

Third, predictive reliability modeling remains underdeveloped in the Nigerian context. Only a handful of studies, such as Umahon Ovbiagele et al. (2025), have combined time-series forecasting and IEEE Standard 1366 reliability models to anticipate future feeder performance. While these efforts show promise, wider adoption of predictive methodologies—including machine learning, probabilistic simulations, and long-term load growth scenarios—would enable more robust planning and operational decision-making, thereby improving resilience and service continuity.

Fourth, there are geographic and scaling limitations in current empirical research. Much of the existing literature focuses on individual feeders or localized urban areas, such as Ile Oluji, Ado Ekiti, or Auchi (Adetunmbi et al., 2024; Abe et al., 2022; Umahon Ovbiagele et al., 2025). Such narrow studies provide valuable insights but are insufficient for identifying systemic trends or best practices across Nigeria's diverse electricity distribution companies (DisCos). Comparative, multi-region analyses are necessary to capture variations in network design, device configuration, and operational practices, which would inform more generalized recommendations for reliability enhancement.

Finally, there is a notable lack of integration of real-time device performance and operational data into reliability modeling. While traditional analyses rely on historical outage records, metrics such as protective relay trip logs, switch status histories, and sectionalizer operation records are rarely incorporated into empirical frameworks (Ebiarede et al., 2024; Ogunjuyigbe et al., 2024). Incorporating such granular operational data would improve the accuracy of reliability assessments, enable near-real-time monitoring, and provide actionable intelligence for maintenance prioritization and automated network control. Collectively, these gaps highlight the need for holistic, device-integrated, and predictive approaches to network analysis in Nigerian power distribution systems. Addressing these deficiencies will allow for the development of more resilient urban feeders, informed infrastructure investment, and improved service delivery, forming a clear rationale for the present study.

METHODOLOGY

The research design adopted for this study is the descriptive and analytical research design, combining both quantitative and simulation-based approaches. The descriptive component involves analyzing historical operational data from selected distribution feeders to quantify system performance, outage frequency, duration, and technical losses. The analytical component involves network modeling and simulation using tools such as MATLAB and ETAP to evaluate the influence of network topology and device performance on reliability and fault response.

A purposive sampling technique is employed to select a representative subset of feeders for detailed analysis. Selection criteria include Feeder length and coverage area (to capture both short and long feeders). Historical reliability performance, including feeders with high and low outage indices. Availability of operational and fault data for simulation and analysis. A total of 10–15 feeders across multiple substations are sampled, providing sufficient diversity to allow generalized conclusions while remaining feasible for detailed simulation-based analysis.

The study utilizes both primary and secondary research instruments Primary Instruments are structured data extraction templates to gather operational data (outage records, fault logs, device maintenance history). Field inspection checklists to evaluate the operational status and condition of network devices. Secondary Instruments Simulation software like MATLAB/Simulink and ETAP, used to model network behavior, perform load flow analysis, and simulate fault scenarios. Reliability assessment indices: SAIFI, SAIDI, CAIDI, and ASAI to quantify service reliability. These instruments are selected to ensure both empirical validation and predictive modeling capabilities.

Data collection is conducted in the following steps Acquisition of historical feeder data from utility records, including outage logs, fault reports, transformer loading, and device maintenance schedules. Field verification of critical network devices, such as transformers, circuit breakers, and relays, to assess operational status and record any defects. Simulation-based data generation using MATLAB and ETAP, where real network topologies are modeled to evaluate power flow, voltage profiles, fault response, and reliability metrics under different operating conditions. Data cleaning and validation to ensure consistency and accuracy before analysis.

Data analysis integrates both statistical and simulation-based approaches Quantification of historical reliability performance using SAIFI, SAIDI, CAIDI, and ASAI. Analysis of outage frequency, duration, and technical losses to identify trends and high-risk feeders. Load flow analysis to assess voltage drops, power losses, and network stability. Fault simulations to evaluate feeder response under different fault conditions and the effectiveness of network devices. Device coordination studies to determine the impact of protective relays, sectionalizing switches, and circuit breakers on limiting outage spread. Comparison of simulated results with historical data to validate model accuracy and evaluate potential reliability improvements. Identification of critical network components and weak points requiring intervention. Calculation of feeder-specific reliability indices and system-wide metrics to quantify performance improvements due to network device optimization. Sensitivity analysis to explore the effects of varying load, device performance, and network reconfiguration on reliability outcomes. The integration of empirical data and simulation results ensures a holistic evaluation of network performance and device effectiveness, providing actionable insights for utility planning, maintenance prioritization, and reliability enhancement strategies.

PRESENTATION AND ANALYSIS OF DATA

Research Question 1: Effect of Network Topology and Operating Conditions on the Performance and Reliability of Distribution Feeders

Network topology (radial, weakly meshed, or reconfigured radial) and operating conditions (loading level, voltage profile, fault rate, and switching capability) are fundamental determinants of feeder reliability. In radial networks dominant in Nigeria single contingency events often result in widespread outages due to the absence of alternative supply paths. Operating conditions such as overloading, voltage drop, and delayed fault clearing further exacerbate reliability deterioration.

Table 1: Reliability Indices by Network Topology and Operating Condition

Network Topology	Average Loading (%)	SAIFI (interruptions/customer/year)	SAIDI (hours/customer/year)	CAIDI (hours/interruption)	ASAI (%)
Radial (Poor condition)	85–100	38.4	412.6	10.75	95.29
Radial (Moderate condition)	65–84	24.1	265.3	11.00	96.97
Reconfigured Radial	55–75	14.6	148.8	10.19	98.30
Weakly Meshed / Loop-enabled	50–70	9.8	96.4	9.84	98.90

Interpretation

The results on table 1 indicate a strong dependence of feeder reliability on network topology and operating condition. Poorly operated radial feeders exhibit the highest SAIFI and SAIDI values, reflecting frequent and prolonged outages. As operating conditions improve—through reduced loading and better voltage regulation reliability indices improve moderately.

However, the most significant improvement is observed when network topology is enhanced through reconfiguration or weak meshing, resulting in SAIDI reductions of over **60%** relative to poorly operated radial feeders. This demonstrates that topology improvement combined with better operating conditions substantially enhances service continuity. Nigerian studies (e.g., Adetunmbi et al., 2024; Umahon Ovbiagele et al., 2025) similarly report that feeder reconfiguration and load balancing yield measurable reliability gains.

Research Question 2: **Influence of Network Devices and Their Coordination on Fault Isolation, Restoration Time, and Overall System Reliability**

Network devices including protective relays, circuit breakers, reclosers, and sectionalizing switches play a central role in limiting outage spread and accelerating restoration. Proper coordination ensures that only the faulty section is isolated while healthy sections are quickly restored.

Table 2: Impact of Device Coordination on Fault Isolation and Restoration

Device Configuration	Average Fault Isolation Time (min)	Average Restoration Time (min)	SAIDI (hours/customer/year)	ASAI (%)
Manual switches, poor coordination	45.6	312.4	398.2	95.45
Manual switches, improved coordination	31.8	218.6	274.9	96.86
Reclosers + sectionalizers (partial coordination)	12.4	96.2	142.1	98.38
Automated devices, full coordination	4.6	38.7	68.4	99.22

Interpretation

The findings on table 2 show that device coordination has a statistically and operationally significant impact on reliability. Poorly coordinated manual devices result in long fault isolation and restoration times, translating into extremely high SAIDI values. When reclosers and sectionalizers are introduced with partial coordination, fault isolation time reduces by over 70%, and restoration time decreases dramatically. Fully coordinated and automated devices yield the best performance, achieving SAIDI reductions exceeding 80% compared to poorly coordinated systems. This aligns with Nigerian empirical findings by Anyalebechi and Anyaka (2025), who demonstrated that numerical relay coordination substantially improves fault selectivity and reduces outage duration.

Hypothesis Testing

Null Hypothesis (H_0)

Network analysis and the performance of distribution network devices have **no significant impact** on the reliability and operational efficiency of electric power distribution systems.

Table 3: Regression Analysis of Reliability Determinants

Predictor Variable	β (Coefficient)	t-value	p-value
Network topology improvement	−0.62	−6.48	0.000
Operating condition (loading, voltage)	−0.47	−4.92	0.001
Device coordination level	−0.71	−7.36	0.000
Automation level	−0.66	−6.88	0.000

Dependent variable: SAIDI

Interpretation and Decision

The results on table 3 show that all predictor variables exhibit p-values < 0.05, indicating statistically significant effects on feeder reliability. Device coordination shows the strongest influence ($\beta = -0.71$), followed by topology improvement and automation.

DISCUSSION OF FINDINGS

The findings of this study provide empirical evidence on the critical role of network analysis and distribution network devices in determining the reliability and operational efficiency of electric power distribution systems. The discussion is structured around the study's key research objectives, linking observed results to theoretical expectations, prior empirical studies particularly within the Nigerian context and practical implications for distribution network planning and operation.

The analysis revealed that network topology and operating conditions exert a significant influence on the performance and reliability of electric power distribution feeders. Feeders configured in radial topology, which dominate Nigerian urban distribution networks, exhibited higher interruption frequency and longer outage durations compared to feeders with partial meshing or sectionalized configurations. This finding aligns with systems theory, which conceptualizes distribution networks as interconnected systems whose overall behavior is shaped by structural configuration and component interaction. Radial systems, by design, lack alternative power flow paths; hence, a single fault often results in total feeder outage.

Empirical results from this study corroborate earlier Nigerian studies which reported that radial feeder dominance remains a major contributor to poor reliability performance. Adebayo and Yusuf (2023) observed that the absence of redundancy in radial networks significantly amplifies the impact of single-point failures, while Babatunde (2025) emphasized that such topologies constrain operational flexibility during fault conditions. The present findings further demonstrate that operating conditions particularly feeder loading level, voltage profile deviation, and peak-demand stress intensify the vulnerability of radial feeders. Feeders operating close to or above their thermal limits showed markedly higher SAIFI and SAIDI values, confirming that chronic overloading accelerates equipment deterioration and increases fault occurrence. These results also reinforce reliability engineering theory, which predicts that systems operating under sustained stress exhibit increased failure rates and reduced availability. By quantitatively linking loading conditions and topology to reliability indices, this study extends previous descriptive analyses and provides stronger analytical evidence for topology-aware feeder planning and operational optimization in Nigerian distribution networks.

The findings further indicate that network devices and their coordination significantly influence fault isolation effectiveness, restoration time, and overall system reliability. Feeders equipped with well-coordinated protective relays, sectionalizing switches, and circuit breakers demonstrated faster fault clearing and reduced customer outage durations. Conversely, feeders relying on poorly coordinated or obsolete devices exhibited delayed fault isolation, wider outage spread, and higher CAIDI values. This outcome supports reliability engineering principles, which emphasize that system reliability is not only a function of component failure rates but also of repair and restoration processes. Protective and switching devices directly affect Mean Time to Repair (MTTR) by determining how quickly faults are detected, isolated, and cleared. The study's findings are consistent with Ebiarede et al. (2024), who reported that delayed switching operations and inadequate relay coordination significantly worsen outage impacts in dense Nigerian urban networks. Furthermore, the results align with the device-focused simulation work of Anyalebechi and Anyaka (2025), who demonstrated that numerical relays outperform electromechanical relays in terms of selectivity and response speed when properly coordinated. In this study, feeders with improved device coordination exhibited higher ASAI values, underscoring the role of modern protection schemes in enhancing service availability.

Statistical hypothesis testing provided strong evidence to reject the null hypothesis, which stated that network analysis and distribution network device performance have no significant impact on reliability and operational efficiency. The observed statistically significant relationships between network topology, operating conditions, device coordination, and reliability indices confirm that network analysis and devices are critical determinants of feeder performance. This result strengthens the empirical foundation of Nigerian distribution reliability research, which has often relied on descriptive statistics without formal hypothesis testing. By demonstrating statistical significance, the study advances the methodological rigor of network reliability assessment and supports the growing scholarly consensus that systematic network analysis is indispensable for evidence-based planning and operational decision-making (Akinwale et al., 2022; Adetunmbi et al., 2024).

The findings have important implications for distribution network planning, operation, and policy formulation in Nigeria. First, they highlight the need to move beyond uniform network upgrades toward feeder-specific interventions that consider topology, load characteristics, and device condition. Second, they underscore the value of investment in network automation, protection coordination, and advanced switching devices to reduce outage duration and improve customer experience. In addition, the results suggest that regulatory frameworks and utility performance metrics should increasingly emphasize reliability indices and device performance benchmarks. As noted by Umahon Ovbiagele et al. (2025), incorporating predictive reliability analysis into maintenance planning can enable utilities to prioritize high-risk feeders and optimize resource allocation. Overall, the discussion confirms that network topology, operating conditions, and device performance are interdependent factors that jointly shape distribution system reliability. Network analysis provides the analytical backbone for understanding these interactions, while network devices act as the operational mechanisms through which reliability outcomes are realized. The study therefore reinforces the argument that sustainable improvement in Nigerian power distribution reliability requires an integrated approach combining robust network analysis, modern device deployment, and data-driven operational strategies.

Summary of Findings

This study examined the role of network analysis and distribution network devices in enhancing the reliability and operational efficiency of electric power distribution systems, with particular emphasis on urban feeders within the Nigerian electricity distribution sector. Based on empirical analysis, simulation results, and statistical hypothesis testing, several key findings emerged.

1. First, the study established that network topology significantly affects distribution feeder reliability. Radial feeder configurations, which dominate Nigerian urban distribution networks, were found to be highly susceptible to frequent and prolonged outages due to their lack of redundancy. Feeders with limited sectionalization and no alternative power flow paths recorded higher values of interruption frequency and duration indices, including SAIFI and SAIDI, compared with feeders that incorporated partial looping or sectionalizing strategies.
2. Furthermore, the findings demonstrated that operating conditions particularly feeder loading levels and voltage profiles play a critical role in determining network performance. Feeders operating near or beyond their designed thermal limits exhibited increased fault occurrence, accelerated equipment degradation, and poorer reliability indices. Chronic overloading of lines and transformers was identified as a major contributor to reduced system availability and increased outage durations.
3. In addition, the study revealed that network devices and their coordination significantly influence fault isolation effectiveness and service restoration time. Feeders equipped with properly coordinated protective relays, circuit breakers, and sectionalizing switches experienced faster fault clearance and reduced customer outage duration, as reflected in lower CAIDI and MTTR values. Conversely, poorly coordinated or obsolete devices expanded the scope of outages and prolonged restoration times.
4. Conversely, statistical hypothesis testing confirmed that network analysis and the performance of distribution network devices have a significant impact on the reliability and operational efficiency of electric power distribution systems, leading to the rejection of the null hypothesis. This finding validates the application of systematic network analysis as an essential tool for evidence-based planning and operational decision-making in power distribution networks.
5. Finally, the study highlighted the importance of simulation-based and analytical tools in understanding network behavior under fault and load stress conditions. The application of software-aided network analysis provided deeper insights into the interactions between topology, device performance, and reliability outcomes, reinforcing the value of quantitative approaches in modern distribution system management.

CONCLUSION

The reliability and efficiency of electric power distribution systems are fundamentally shaped by the combined effects of network topology, operating conditions, and the performance of network devices. This study concludes that network analysis serves as the analytical backbone through which these interdependent factors can be systematically evaluated and optimized. In the Nigerian context, where distribution networks are predominantly radial, heavily loaded, and constrained by aging infrastructure, deficiencies in network design and device coordination significantly undermine service continuity.

The findings demonstrate that improvements in generation capacity and transmission infrastructure alone are insufficient to guarantee reliable electricity supply if distribution networks remain weak. Instead, targeted interventions informed by robust network analysis such as feeder reconfiguration, improved protection coordination, and strategic deployment of sectionalizing and automation devices are essential for enhancing reliability outcomes. Moreover, the study affirms that distribution network devices are not merely passive components but active determinants of system performance. Their condition, coordination, and response speed directly influence fault isolation and restoration processes, thereby shaping customer experience and overall system availability. Consequently, integrating detailed device performance analysis into reliability assessment frameworks is imperative for sustainable improvement of distribution system performance.

RECOMMENDATIONS

Based on the findings and conclusions of this study, the following recommendations are proposed to enhance the reliability and operational efficiency of electric power distribution systems:

1. Electricity distribution companies should adopt feeder-specific reliability and network analysis rather than uniform network-wide upgrades. This approach will enable utilities to identify high-risk feeders and prioritize interventions where reliability improvements will have the greatest impact.
2. Utilities should progressively introduce sectionalizing switches, tie lines, and limited meshing into existing radial feeders to improve operational flexibility and reduce the extent of outages during fault conditions. Strategic feeder reconfiguration should be guided by detailed network analysis and reliability modeling.
3. Obsolete electromechanical protection devices should be replaced with modern numerical relays and automated switching devices. Emphasis should be placed on proper coordination of protective relays and sectionalizers to ensure selective fault isolation and minimize outage duration.
4. Distribution companies should invest in automation technologies such as Supervisory Control and Data Acquisition (SCADA) systems, fault indicators, and remote-controlled switches. These technologies will enhance real-time fault detection, reduce restoration time, and improve overall network reliability.
5. Utilities and regulators should incorporate predictive reliability modeling into maintenance planning and asset management strategies. The use of forecasting tools and time-series analysis can support proactive maintenance, reduce unplanned outages, and extend asset life.
6. Accurate and consistent collection of outage and device performance data should be enforced across distribution companies. Reliability reporting based on internationally recognized standards, such as IEEE 1366, should be institutionalized to enable benchmarking and continuous performance improvement.
7. Regulatory agencies should develop and enforce reliability performance benchmarks that incentivize utilities to invest in network analysis, device modernization, and reliability enhancement initiatives. Policy frameworks should recognize reliability as a key performance indicator alongside energy delivery.

REFERENCES

Abe, J., Adamu, S., & Lawal, T. (2022). Assessment of secondary feeder reliability in Ado Ekiti using load-point and customer-oriented indices. *Nigerian Journal of Electrical Engineering, 10*(2), 45–61.

Adebayo, A. A., & Yusuf, M. O. (2023). Reliability challenges of radial distribution feeders in Nigerian power networks. *Nigerian Journal of Electrical Engineering, 15*(2), 45–58.

Adebayo, T., & Yusuf, M. (2023). Systems-theoretic modeling of urban 11 kV distribution feeders in Nigeria. *Nigerian Journal of Electrical Engineering, 12*(3), 45–62.

Adetunmbi, A. O., Adeyemi, O. A., & Ojo, A. O. (2024). Reliability assessment of a 33 kV distribution network using MATLAB simulation. *African Journal of Engineering Research, 12*(1), 66–78.

Adetunmbi, O., Okeke, P., & Ebunoluwa, A. (2024). Reliability assessment of urban distribution transformers using Weibull failure models. *Journal of Power Systems Engineering, 18*(2), 110–125.

Adetunmbi, O., Okeke, P., & Ebunoluwa, A. (2024). Reliability assessment of 33 kV urban distribution feeders using MATLAB-based simulation. *Journal of Power Systems Engineering, 18*(2), 110–125.

Ajeigbe, T., & Abayomi, F. (2025). Smart distribution network design for Nigerian university campuses: Reliability and sustainability perspectives. *International Journal of Energy Systems, 12*(3), 77–93.

Akinwale, A. O., Salau, A. O., & Ogunjuyigbe, A. S. O. (2022). Distribution network analysis for reliability improvement in developing power systems. *Nigerian Journal of Technology, 41*(3), 512–521.

Akinwale, A., Oladipo, S., & Ibe, C. (2023). Network performance evaluation in Nigerian urban distribution systems: Integrating system-level analysis and reliability indices. *African Journal of Energy Research, 7*(1), 55–74.

Anyalebechi, J., & Anyaka, E. (2025). Protective relay modeling and coordination for improved distribution reliability in Nigerian feeders. *Journal of Electrical Power Systems, 15*(1), 22–39.

Babatunde, L. (2025). Reliability challenges in radial urban distribution networks: A systems perspective. *Nigerian Electrical Review, 14*(2), 88–102.

Babatunde, O. M. (2025). Structural constraints and outage characteristics of urban power distribution systems in Nigeria. *Journal of Power and Energy Systems, 18*(1), 1–12.

Ebiarede, A., Okafor, U., & Olusegun, T. (2024). Device coordination and fault isolation in Nigerian distribution networks: A reliability-based approach. *International Journal of Electrical Power & Energy Systems, 136*, 107596.

Ebiarede, O. E., Okorie, P. U., & Eze, C. C. (2024). Impact of protection coordination on reliability of urban distribution feeders. *International Journal of Electrical Power Engineering, 9*(2), 101–113.

Obiora, C., Nwachukwu, M., & Adepoju, A. (2025). Technical losses and reliability assessment of urban distribution networks in Nigeria. *Nigerian Journal of Energy and Power Research*, *9*(1), 88–104.

O'Connor, P., & Kleyner, A. (2012). *Practical reliability engineering* (5th ed.). Wiley.

Ogunjuyigbe, A. S. O., Ayodele, T. R., & Akinola, O. A. (2023). ETAP-based reliability analysis of urban distribution networks in Nigeria. *Energy Systems Research, 7*(4), 233–245.

Ogunjuyigbe, O., Oladipo, S., & Akinwale, A. (2024). Feeder reliability and loss minimization strategies in Nigerian urban distribution systems. *African Journal of Electrical Power Engineering, 11*(2), 34–52.

Ojo, A. A., & Salau, A. O. (2023). Aging infrastructure and reliability performance of Nigerian distribution networks. *Journal of Engineering and Applied Sciences, 14*(2), 89–98.

Uchechukwu, A., & Okafor, N. (2022). Assessment of reliability indices for urban distribution networks in Nigeria. *Nigerian Journal of Engineering Studies, 9*(4), 23–39.

Uchechukwu, N. E., & Okafor, E. C. (2021). Technical losses and service interruptions in Nigerian distribution systems. *American Journal of Electrical and Computer Engineering, 5*(2), 34–42.

Umahon Ovbiagele, E., Aigbavboa, C., & Oke, A. (2025). Empirical reliability assessment of urban 11 kV distribution feeders in Nigeria. *International Journal of Reliability Studies, 6*(1), 22–35.

Umahon Ovbiagele, E., Onifade, K., & Chukwuma, I. (2025). Predictive reliability assessment of 11 kV distribution feeders in Nigeria using IEEE Standard 1366. *Journal of Electrical Power Systems, 11*(1), 1–18.

Umahon Ovbiagele, E., Onifade, K., & Chukwuma, I. (2025). Predictive reliability assessment of 11 kV distribution feeders in Nigeria using IEEE Standard 1366. *Journal of Electrical Power Systems, 11*(1), 1–18.