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Criticality Assessment and Reliability-Centered Maintenance Planning of Distribution Substation Components in Nigeria

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Abstract
This study presents a criticality assessment and reliability-centered maintenance (RCM) framework for improving the operational performance of distribution substation assets within the Ikorodu Distribution Network. Historical outage records were analyzed to evaluate component failure rates, outage durations, availability, and annual outage contributions. Criticality ranking was performed using reliability indices and outage impact assessments. Results indicate that transformers, fuses, and outgoing feeders are the most critical assets, contributing significantly to system interruptions and customer dissatisfaction. A reliability-centered maintenance strategy is proposed to optimize maintenance resources, reduce equipment failures, and improve system availability. The findings provide practical guidance for distribution utilities seeking to enhance network reliability and asset management practices.
Keywords: *Reliability-Centered Maintenance, Asset Criticality, Distribution Substation, Failure Rate, Availability, Power System Reliability.*

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I. Introduction

Electric power distribution systems constitute the final stage in the delivery of electricity from generation sources to end-users and play a crucial role in ensuring reliable and continuous power supply. The reliability of distribution networks has become increasingly important due to the growing dependence of modern societies on electricity for residential, commercial, industrial, and technological applications. Interruptions in electricity supply can result in significant economic losses, reduced industrial productivity, equipment damage, and customer dissatisfaction (Brown, 2009; Gonen, 2014).

Distribution substations are among the most critical facilities within power distribution systems because they serve as the interface between transmission and distribution networks. These substations comprise various interconnected components, including transformers, switchgear, circuit breakers, busbars, feeders, relays, and surge arresters, whose operational performance directly affects the reliability and availability of electricity supply. Failure of any critical component may lead to service interruptions, increased maintenance costs, and deterioration of overall system performance (Billinton& Allan, 1996).

In many developing countries, particularly Nigeria, maintaining reliable electricity supply remains a major challenge due to aging infrastructure, inadequate maintenance practices, increasing load demand, equipment overloading, vandalism, and insufficient investment in network expansion. These challenges often result in frequent equipment failures, prolonged outages, and poor quality of service. According to the Nigerian Electricity Regulatory Commission (NERC), distribution networks account for a significant proportion of customer interruptions experienced within the Nigerian Electricity Supply Industry (NERC, 2024). Consequently, there is a growing need for effective asset management strategies that can enhance equipment performance and improve system reliability.

Reliability assessment has emerged as an important tool for evaluating the operational performance of power system components and identifying assets that contribute significantly to system failures. Reliability indices such as failure rate (λ), Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR), availability, and unavailability provide quantitative measures for assessing equipment performance and maintenance effectiveness (Ebeling, 2019). These indices assist utility operators in identifying weak components, prioritizing maintenance activities, and allocating resources more efficiently.

Traditional maintenance approaches, such as corrective and time-based preventive maintenance, are often inadequate for modern power systems because they may result in excessive maintenance costs or unexpected equipment failures. Reliability-Centered Maintenance (RCM) has therefore gained considerable attention as an effective maintenance strategy that focuses on preserving system functions through risk-based and condition-oriented maintenance practices. RCM enables utilities to prioritize maintenance efforts based on equipment criticality and reliability performance, thereby improving operational efficiency and reducing outage occurrences (Moubray, 2018; Kumar et al., 2021).

Asset criticality assessment is a key component of reliability-centered maintenance because it provides a systematic framework for ranking equipment according to its impact on system reliability, safety, operational performance, and customer service. Criticality analysis combines factors such as failure frequency, outage duration, availability, repair time, and customer impact to identify assets requiring immediate attention. Several studies have demonstrated that criticality-based maintenance planning can significantly improve system availability while reducing maintenance expenditure and operational risks (Saha, Purvins, &Halgamuge, 2021; Mousa, El-Sehiemy, & Abd-Elaziz, 2021).

Recent advancements in reliability engineering have further enhanced the application of data-driven approaches for maintenance optimization and asset management. Li, Wang, Shahidehpour, and Su (2022) demonstrated the effectiveness of data-driven reliability assessment techniques in improving the performance of modern distribution systems, while Zhang, Chen, and Liu (2023) highlighted the role of artificial intelligence in predictive maintenance and reliability management. Despite these developments, there remains limited research focusing on component-level criticality assessment and reliability-centered maintenance planning for Nigerian distribution substations.

This study therefore presents a criticality assessment and reliability-centered maintenance framework for major distribution substation components within the Ikorodu Distribution Network. Historical outage records are utilized to evaluate component failure rates, MTBF, MTTR, availability, and outage contributions. The study further develops a criticality ranking of substation assets and proposes maintenance strategies aimed at improving system reliability and operational performance.

The objectives of the study are to:

1. Evaluate the reliability characteristics of major distribution substation components.
2. Determine failure rates, MTBF, MTTR, and availability indices for each component.
3. Rank components according to their criticality and contribution to system interruptions.
4. Develop a reliability-centered maintenance framework for maintenance prioritization.
5. Provide recommendations for improving asset management and reliability performance within Nigerian distribution networks.

The findings of this study are expected to support utility operators, maintenance engineers, regulators, and policymakers in implementing effective maintenance strategies and enhancing the reliability of electricity distribution systems.

II. Literature Review

2.1 Overview of Power System Reliability

Power system reliability refers to the ability of an electric power system to continuously provide adequate electricity to consumers while maintaining acceptable standards of quality and service continuity. Reliability assessment has become an essential aspect of power system planning, operation, and maintenance because it enables utilities to quantify system performance and identify factors contributing to service interruptions.

Reliability in electric power systems is generally categorized into adequacy and security. Adequacy refers to the availability of sufficient facilities to meet consumer demand under normal operating conditions, while security relates to the system's ability to withstand disturbances arising from faults, equipment failures, and unforeseen operating conditions. Distribution systems are particularly important in reliability studies because they account for a significant proportion of customer interruptions experienced in power networks.

Reliability assessment techniques commonly employ parameters such as failure rate, Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR), availability, unavailability, outage duration, and outage frequency. These indicators provide quantitative measures of equipment performance and are widely used for maintenance planning and asset management.

2.2 Reliability Assessment of Distribution Networks

Distribution networks are exposed to numerous operational and environmental factors that affect their reliability performance. Equipment aging, overloading, insulation deterioration, adverse weather conditions, vegetation interference, and protection system malfunctions are among the major causes of failures in distribution systems.

Several studies have shown that distribution substations contribute significantly to power supply interruptions because failures of critical equipment often affect large groups of consumers. Reliability evaluation of distribution systems therefore plays an important role in identifying weak components and improving service continuity.

Recent research has focused on the use of statistical reliability models, reliability indices, and data-driven analytical techniques to evaluate distribution network performance. Modern reliability studies increasingly integrate operational data with advanced computational methods to support maintenance decision-making and improve network performance.

Furthermore, the growing penetration of distributed energy resources and smart-grid technologies has increased the need for more sophisticated reliability assessment techniques capable of addressing evolving network complexities.

2.3 Reliability-Centered Maintenance

Maintenance is a critical activity aimed at preserving the operational functionality and reliability of electrical equipment. Traditional maintenance approaches generally fall into three categories: corrective maintenance, preventive maintenance, and predictive maintenance.

Corrective maintenance is performed after equipment failure has occurred and focuses on restoring the asset to operational condition. Although this approach requires minimal planning, it often results in prolonged outages and increased maintenance costs.

Preventive maintenance involves scheduled inspections and servicing activities intended to reduce the probability of equipment failure. While preventive maintenance improves reliability, it may result in unnecessary maintenance interventions when equipment remains in satisfactory condition.

Predictive maintenance utilizes equipment condition information and monitoring technologies to determine maintenance requirements before failures occur. This approach improves maintenance efficiency and reduces downtime.

Reliability-Centered Maintenance (RCM) extends these maintenance strategies by focusing on preserving system functions and prioritizing maintenance activities based on equipment reliability characteristics and operational significance. RCM provides a structured framework for determining the most appropriate maintenance actions required to ensure reliable system performance.

The implementation of RCM has been widely recognized as an effective means of reducing outage frequency, minimizing maintenance costs, improving equipment availability, and extending asset life.

2.4 Asset Criticality Assessment

Asset criticality assessment is an important component of reliability-centered maintenance. It involves the evaluation and ranking of equipment according to its impact on system reliability, operational performance, safety, environmental consequences, and customer service.

Criticality analysis enables utilities to identify assets whose failures have the greatest effect on network operation. Components with high failure frequency, long repair times, significant outage impacts, or extensive customer interruption consequences are generally classified as highly critical assets.

Several methods have been proposed for equipment criticality assessment, including risk-based approaches, reliability indices, failure mode analysis, and multi-criteria decision-making techniques. These methods assist utilities in allocating maintenance resources effectively and prioritizing asset replacement programs.

The adoption of criticality-based maintenance planning has been shown to improve operational efficiency and optimize maintenance expenditures while enhancing service reliability.

2.5 Reliability Indices for Asset Evaluation

Reliability indices provide quantitative measures for evaluating equipment and system performance. The most commonly used component reliability indices include failure rate (λ), MTBF, MTTR, availability, and unavailability.

Failure rate measures the frequency with which a component experiences failure during a specified period of operation. MTBF indicates the average operating duration between successive failures and is commonly used to assess equipment reliability.

MTTR represents the average time required to repair and restore failed equipment to service. Components with lower MTTR values are generally easier and less costly to maintain.

Availability combines both reliability and maintainability characteristics and represents the probability that a component is operational when required. High availability is typically associated with low failure rates and short repair durations.

These indices are widely used in reliability engineering because they provide objective measures for comparing component performance and identifying maintenance priorities.

2.6 Reliability of Distribution Substation Components
Distribution substations consist of several interconnected components whose reliability directly affects electricity supply continuity. Among these components, transformers are generally regarded as the most critical assets due to their high replacement cost and significant impact on customer supply.
Switchgear, circuit breakers, and protection relays play essential roles in fault isolation and system protection. Failures of these devices can compromise network security and increase outage durations.
Outgoing feeders and supply lines are also major contributors to customer interruptions because they connect substations to load centers and consumers. Environmental conditions, conductor deterioration, and vegetation encroachment frequently contribute to feeder failures.
Fuses and switches provide protection and operational flexibility within distribution networks. Although these devices are relatively inexpensive, frequent failures can significantly affect service reliability.
Reliability studies have consistently shown that transformers, feeders, and protective devices account for a substantial proportion of distribution system outages and therefore require priority attention in maintenance planning.

2.7 Research Gap
Although numerous studies have evaluated distribution system reliability using outage statistics and reliability indices, many of these investigations focus primarily on system performance assessment without adequately addressing maintenance prioritization and asset criticality.
Furthermore, limited studies have examined component-level reliability characteristics of Nigerian distribution substations using failure rate, MTBF, MTTR, availability, and criticality ranking techniques. Existing studies often emphasize customer-oriented reliability indices while providing little information regarding maintenance optimization and asset management strategies.
Consequently, there is a need for a comprehensive study that integrates reliability assessment, criticality analysis, and reliability-centered maintenance planning to support effective decision-making in Nigerian distribution networks.
This study addresses this gap by evaluating the reliability performance of major distribution substation components, establishing criticality rankings, and developing a reliability-centered maintenance framework for improving system reliability and asset management effectiveness.

III. Methodology, Reliability Theory and Modeling, Study Area and Data Collection
3.1 Methodology
This study adopted a quantitative reliability assessment approach to evaluate the operational performance and criticality of major distribution substation components within the Ikorodu Distribution Network. Historical outage and maintenance records were analyzed to determine the reliability characteristics of individual components and their contributions to system interruptions.
The methodology consisted of the following stages:
1. Collection of historical outage and maintenance data from the distribution substation.
2. Classification of outage events according to component type.
3. Determination of component failure frequencies and outage durations.
4. Calculation of reliability indices including failure rate, Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR), availability, and unavailability.
5. Evaluation of annual outage contributions of individual components.
6. Criticality ranking of substation assets based on reliability performance indicators.
7. Development of a Reliability-Centered Maintenance (RCM) framework for maintenance prioritization.

The adopted methodology provides a systematic approach for identifying critical assets and establishing maintenance strategies capable of improving overall system reliability.

3.2 Reliability Theory and Modeling
Reliability theory provides mathematical models for evaluating the probability that a system or component performs its intended function satisfactorily for a specified period under stated operating conditions.
In power distribution systems, reliability analysis focuses on determining the likelihood of component failures, restoration performance, and system availability. The major reliability parameters utilized in this study include failure rate, MTBF, MTTR, availability, and unavailability.

3.2.1 Failure Rate Model
Failure rate (λ) is a measure of the frequency with which a component experiences failure during operation. It is expressedas;

$$(\lambda)=\frac{Nf}{T} \qquad 3.1$$

where:bλ = Failure rate (failures/year), Nf = Number of failures recorded, T = Total operating time.

A high failure rate indicates poor reliability performance and increased likelihood of service interruptions.

3.2.2 Mean Time Between Failures (MTBF)

MTBF represents the average duration for which a component operates successfully before experiencing failure. It is an important indicator of equipment reliability.

$$MTBF=\frac{1}{\lambda} \qquad 3.2$$

Where:MTBF = Mean Time Between Failures (hours or years), λ = Failure rate.

Higher MTBF values indicate more reliable equipment.

3.2.3 Mean Time To Repair (MTTR)

MTTR measures the average time required to restore a failed component to normal operation.

$$MTTR=\frac{Tr}{Nf} \qquad 3.3$$

Where:MTTR = Mean Time To Repair, Tr = Total repair duration, Nf = Number of failures.

Components with lower MTTR values are generally easier to maintain and restore.

3.2.4 Availability Model

Availability is defined as the probability that a component is operational when required for service.

$$A=\frac{MTBF}{MTBF+MTTR} \qquad 3.4$$

Where:A = Availability, MTBF = Mean Time Between Failures, MTTR = Mean Time To Repair.

High availability indicates improved reliability and reduced service interruptions.

3.2.5 Unavailability Model

Unavailability represents the proportion of time during which a component is unable to perform its intended function.

$$U=1-A \qquad 3.5$$

Where:U = Unavailability, A = Availability.

Unavailability is used to estimate outage contributions and system performance deficiencies.

3.2.6 Asset Criticality Modeling

To prioritize maintenance activities, components were ranked according to their contribution to system interruptions based on: 1. Failure frequency, 2. Outage duration, 3. Availability performance, 4. Annual outage contribution and 5. Operational importance.

Components exhibiting high failure rates, long repair durations, and significant outage impacts were classified as highly critical assets.

3.3 Study Area

The study was conducted on the Ikorodu Distribution Network operated by Ikeja Electric in Ikorodu. The network forms an important part of the electricity distribution infrastructure serving residential, commercial, and industrial consumers within the Ikorodu axis and surrounding communities.

The distribution substation receives electrical energy from the upstream transmission network and distributes power through several outgoing feeders to various load centers. The substation comprises critical equipment such as power transformers, switchgear, circuit breakers, busbars, protection relays, fuses, switches, surge arresters, and feeder circuits.

Like many distribution networks in developing economies, the Ikorodu distribution system experiences operational challenges including equipment aging, increasing load demand, transformer overloading, feeder faults, environmental disturbances, and maintenance constraints. These factors make the network suitable for reliability and criticality assessment studies.

The findings obtained from this study are expected to contribute toward improving maintenance planning, asset management practices, and service reliability within the distribution network.

3.4 Data Collection

The reliability analysis was based on historical operational and outage records obtained from the Ikorodu distribution substation. The data covered a twelve-month operational period and included information on equipment failures, outage durations, repair activities, and maintenance interventions.

The collected data comprised:

1. Number of failures recorded for each component.
2. Duration of outages associated with each failure event.
3. Equipment repair and restoration times.
4. Maintenance records.
5. Operational reports.
6. Equipment performance logs.

The major components considered in the analysis include: 1. Power transformers, 2. Switchgear, 3. Incoming supply lines, 4. Busbars, 5. Circuit breakers, 6. Fuses, 7. Switches, 8. Outgoing feeders, 9. Overcurrent relays, 10. Earth-fault relays and 11. Surge arresters.

3.5 Data Analysis Procedure

The collected outage data were organized and categorized according to component type. Statistical analysis was performed to determine failure frequencies and outage durations for each equipment category.

The reliability indices were subsequently computed using the established mathematical models. Component performance was evaluated based on: 1. Failure rate (λ), 2. MTBF, 3. MTTR, 4. Availability, 5. Unavailability and Annual outage contribution.

Comparative charts and graphical analyses were used to visualize component performance and identify critical assets within the network.

The results obtained formed the basis for component criticality ranking and the development of reliability-centered maintenance recommendations aimed at enhancing system performance and reducing service interruptions.

IV. Results and Discussion

Table 1. Summary of Outage Frequency and Duration on Switches

Month	No. of failures	Outage Time (Hours)	Total Hour	Failure Rate (λ)
January	0	0	744	0
February	0	0	696	0
March	1	3	744	0.0013
April	0	0	720	0
May	0	0	744	0
June	0	0	720	0
July	0	0	744	0
August	0	0	744	0
September	1	6	720	0.0014
October	0	0	744	0
November	2	7	720	0.0028
December	0	0	744	0

Table 2. Summary of Outage Frequency and Duration on Outgoing Feeder(0.415kV)

Month	No. of failures	Outage Time (Hours)	Total Hour	Failure Rate (λ)
January	3	26	744	0.0040
February	7	19	696	0.0101
March	2	9	744	0.0027
April	3	16	720	0.0042
May	6	11	744	0.0081
June	2	8	720	0.0028
July	2	16	744	0.0027
August	1	3	744	0.0013
September	4	10	720	0.0056
October	1	15	744	0.0013
November	5	12	720	0.0069
December	3	14	744	0.0040

Table 3. Summary of Outage Frequency and Duration on OvercurrentRelay

Month	No. of failures	Outage Time (Hours)	Total Hour	Failure Rate (λ)
January	0	0	744	0
February	1	2	696	0.0014
March	0	0	744	0
April	1	0.5	720	0.0014
May	0	0	744	0
June	0	0	720	0
July	0	0	744	0
August	0	0	744	0
September	0	0	720	0
October	0	0	744	0
November	0	0	720	0
December	0	0	744	0

Table 4.: Summary of Outage Frequency and Duration on Earth Fault Relay

Month	No. of failures	Outage Time (Hours)	Total Hour	Failure Rate (λ)
January	0	0	744	0
February	0	0	696	0
March	0	0	744	0
April	0	0	720	0
May	0	0	744	0
June	0	0	720	0
July	0	0	744	0
August	0	0	744	0
September	0	0	720	0
October	1	2	744	0.0013
November	0	0	720	0
December	0	0	744	0

Table 5.: Summary of Outage Frequency and Duration on Surge Arrester

Month	No. of failures	Outage Time (Hours)	Total Hour	Failure Rate (λ)
January	0	0	744	0
February	0	0	696	0
March	0	0	744	0
April	0	0	720	0
May	0	0	744	0
June	0	0	720	0
July	0	0	744	0
August	0	0	744	0
September	0	0	720	0
October	0	0	744	0
November	0	0	720	0
December	0	0	744	0

Table 6.: Basic Reliability Indices on Each Component

Component	Failure Rate (f/yr) Λ	Average Outage Time (Hours)	Annual Outage Time (Hours)
Transformer	0.0031	38.1667	0.1181
Switch gear	0.0044	6.4167	0.0280
Supply line (Incoming)	0.0022	5.8333	0.0126
Bus bars	0.00046322	1.6667	0.00077203
Circuit Breakers	0.00068324	2.0833	0.0014
Fuses	0.0061	15.1667	0.0927
Switches	0.00045923	1.3333	0.00061231
Outgoing feeder	0.0045	13.2500	0.0593
Overcurrent relay	0.00023547	0.2083	0.000049057
Earth fault relay	0.00011201	0.1667	0.000018668
Surge Arrester	0	0	0

4.1 Failure Rate Evaluation

Figure 1: Failure Rate Analysis

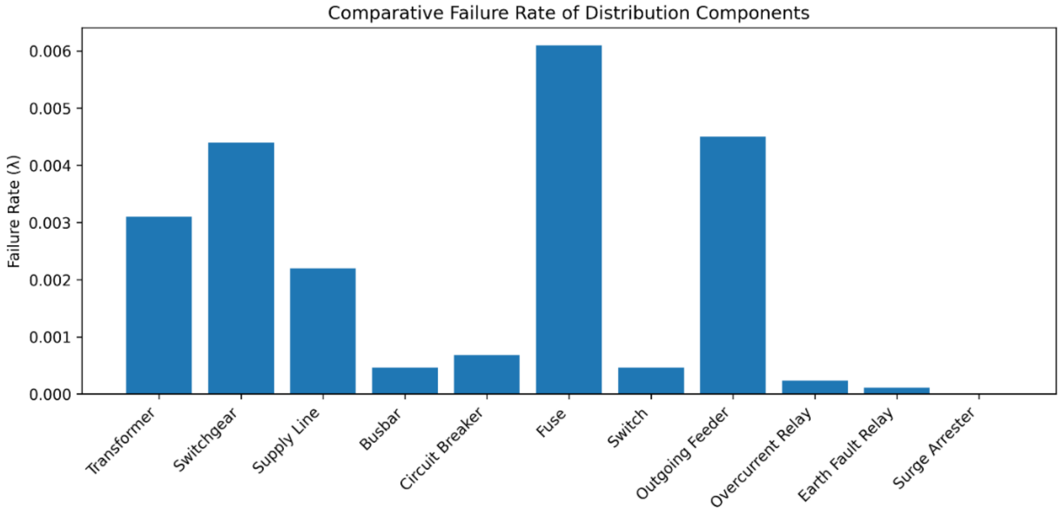

Figure 1 presents the failure rate comparison of the distribution substation components. The result shows that the fuse recorded the highest failure rate (0.0061 failures/year), indicating that it experienced the highest frequency of operational interruptions. This can be attributed to its protective function, where repeated responses to overloads and fault currents result in frequent operations.

The outgoing feeder (0.0045 failures/year) and switchgear (0.0044 failures/year) also recorded high failure rates, suggesting increased exposure to network disturbances, switching operations, environmental conditions, and loading variations.

The transformer recorded a failure rate of 0.0031 failures/year. Although lower than the fuse failure rate, transformer faults have greater system impact because they affect a large number of customers and require longer restoration periods.Components such as busbars, switches, protection relays, and surge arresters exhibited very low failure rates, demonstrating better reliability performance.

The reliability assessment commenced with the evaluation of component failure rates to determine the frequency of equipment failures within the distribution substation. Failure rate serves as an important indicator of equipment reliability because it quantifies the likelihood of component failure during operation.

The results revealed significant variations in failure rates among the studied components. The fuse recorded the highest failure rate of 0.0061 failures/year, followed by the outgoing feeder (0.0045 failures/year) and switchgear (0.0044 failures/year). The transformer exhibited a failure rate of 0.0031 failures/year, while the supply line recorded 0.0022 failures/year.

The high failure rate observed for fuses indicates frequent protection operations resulting from overload conditions, short circuits, and feeder faults. Similarly, the relatively high failure rates of outgoing feeders and switchgear suggest increased exposure to operational stresses and environmental influences.

The lower failure rates recorded for circuit breakers, busbars, switches, overcurrent relays, earth-fault relays, and surge arresters indicate comparatively better operational performance. Notably, surge arresters recorded no failures throughout the study period, demonstrating excellent reliability characteristics.
The results suggest that reliability improvement efforts should focus primarily on components exhibiting high failure frequencies, particularly fuses, outgoing feeders, switchgear, and transformers.

4.2 Analysis of Mean Time Between Failures (MTBF)

Figure 2: MTBF Analysis

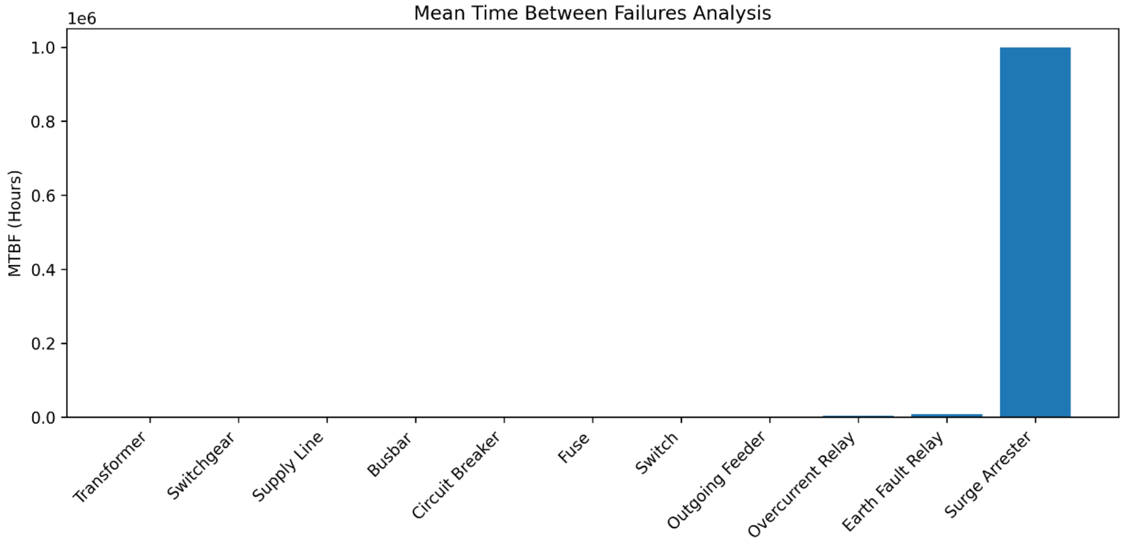

Figure 2 illustrates the Mean Time Between Failures(MTBF) provides a measure of equipment reliability by indicating the average operating duration between successive failures. Components with higher MTBF values are generally more reliable because they experience fewer failures over time.
The analysis showed that surge arresters possessed the highest MTBF due to the absence of recorded failures during the study period. Earth-fault relays, overcurrent relays, switches, and busbars also exhibited relatively high MTBF values owing to their low failure frequencies.
Conversely, fuses recorded the lowest MTBF because of their high failure rate. Outgoing feeders and switchgear also exhibited comparatively lower MTBF values, reflecting their susceptibility to operational disturbances and environmental effects.
The transformer demonstrated a moderate MTBF value. Although transformer failures occurred less frequently than fuse failures, the consequences of transformer outages were significantly more severe due to their impact on multiple consumers and the complexity of repair activities.
These findings indicate that components with low MTBF values require increased maintenance attention and condition monitoring to minimize service interruptions.

4.3 Analysis of Mean Time To Repair (MTTR)

Figure 3: MTTR Analysis

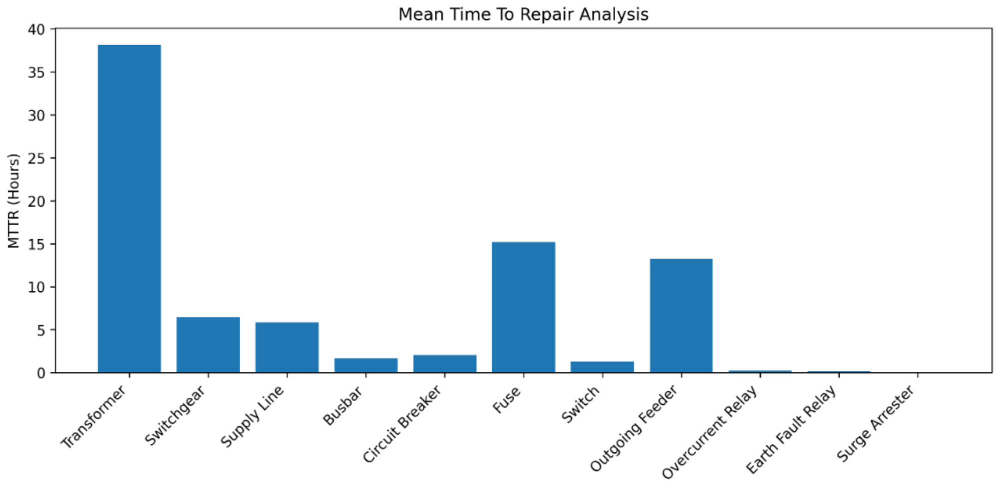

Figure 3 presents the Mean Time To Repair (MTTR) of the distribution components. The MTTR analysis evaluated the maintainability of substation components by determining the average duration required to restore failed equipment to normal operation.
The results showed that transformers recorded the highest MTTR value, with an average outage duration of approximately 38.17 hours per failure. This prolonged repair time is attributable to the complexity of transformer maintenance, fault diagnosis, equipment replacement, and commissioning procedures.
Fuses recorded the second highest average outage duration of approximately 15.17 hours, while outgoing feeders recorded an average repair duration of about 13.25 hours. These values suggest that faults associated with protection systems and feeder networks require substantial restoration efforts.
Switchgear and supply lines recorded average repair durations of approximately 6.42 hours and 5.83 hours respectively, indicating moderate maintenance requirements.
Circuit breakers, busbars, switches, overcurrent relays, and earth-fault relays exhibited relatively low MTTR values due to their simpler maintenance procedures and ease of replacement.
The results demonstrate that reducing repair durations for transformers, feeders, and protection devices can significantly improve overall network availability.

4.4 Availability Analysis

Figure 4: Availability Assessment

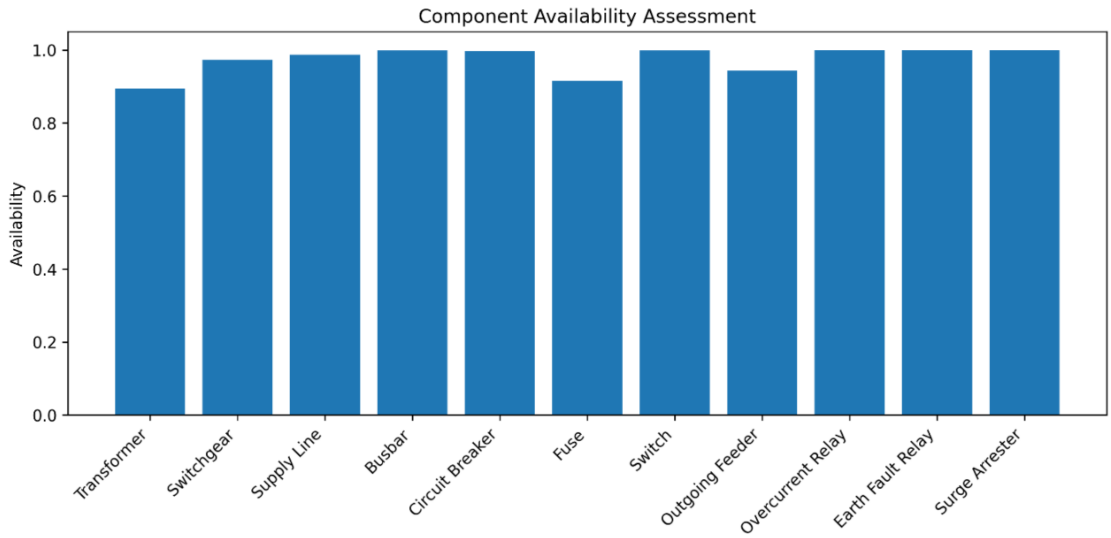

Figure 4 shows the availability performance of the distribution components. Availability analysis was conducted to determine the operational readiness of individual substation components. Availability combines both reliability and maintainability characteristics and represents the probability that a component is operational when required.
Most components recorded high availability values, indicating satisfactory operational performance. However, differences exist due to variations in failure frequency and repair duration. The analysis revealed generally high availability values for all studied components. However, significant differences were observed in their contributions to annual outage time.
Transformers recorded the highest annual outage contribution of 0.1181 hours/year, followed by fuses with 0.0927 hours/year and outgoing feeders with 0.0593 hours/year. These components were therefore identified as the primary contributors to system unavailability.
Switchgear contributed 0.0280 hours/year, while supply lines contributed 0.0126 hours/year. Other components recorded relatively insignificant outage contributions due to their low failure frequencies and shorter repair durations.
The findings indicate that availability improvement initiatives should focus on reducing outage durations associated with transformers, feeders, and protective devices.

4.5Annual Outage Contribution

Figure 5: Annual Outage Contribution

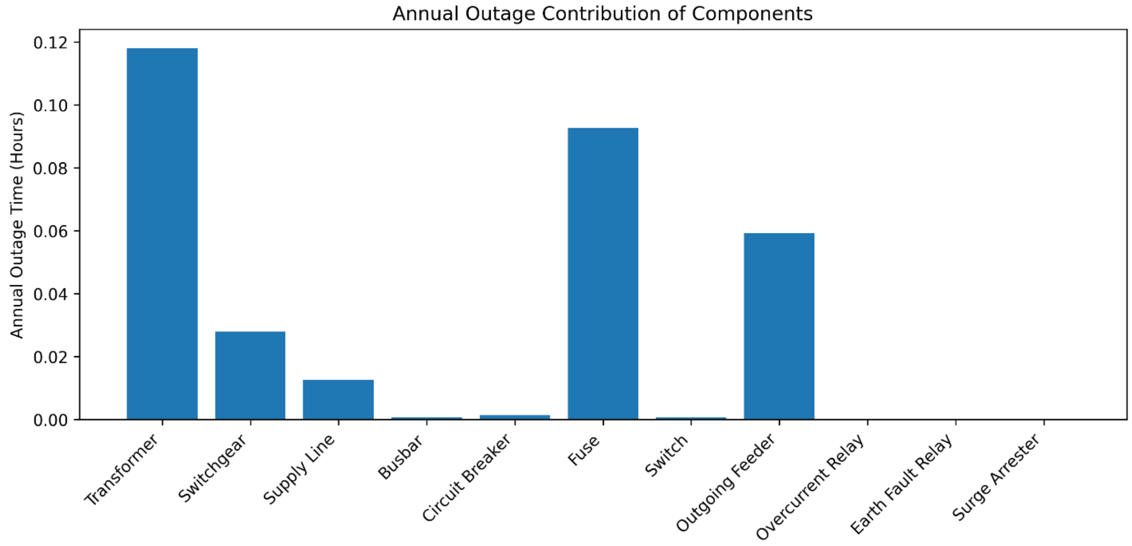

Figure 5 presents the annual outage contribution of each component.
The transformer contributed the highest annual outage time (0.1181 hours/year), making it the most significant contributor to system unavailability.
The fuse (0.0927 hours/year) and outgoing feeder (0.0593 hours/year) followed, showing that these components have substantial effects on service continuity.
Switchgear and supply lines contributed moderate outage durations, while relays, switches, and surge arresters contributed minimal outage time.
The results indicate that maintenance resources should prioritize transformers, fuses, and feeders.

4.6 Asset Criticality Ranking

Figure 6: Asset Criticality Ranking

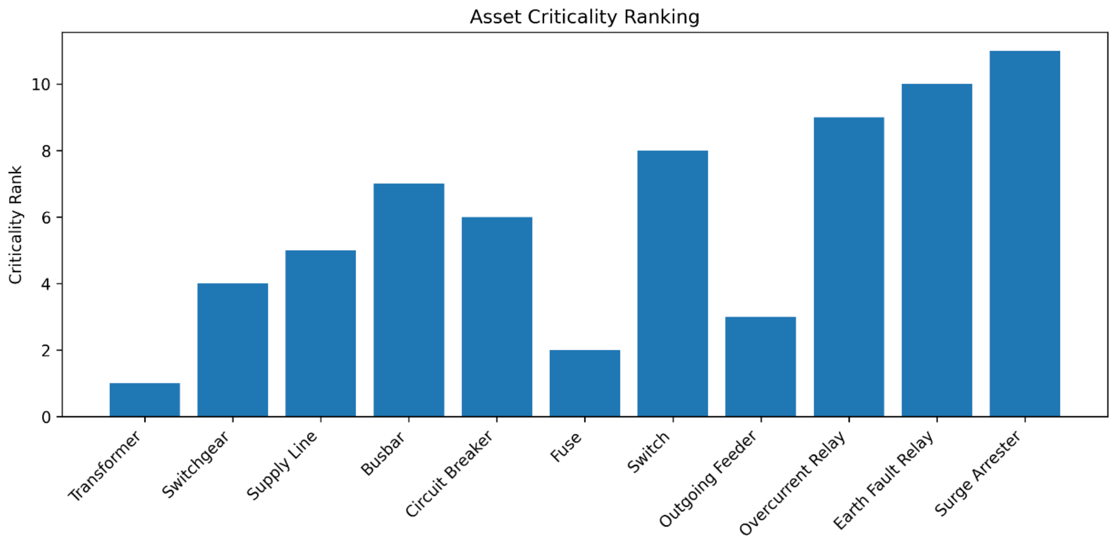

Figure 6 presents the ranking of substation components according to reliability criticality.
The ranking identifies:
Asset criticality assessment was performed by considering component failure frequency, outage duration, availability performance, and overall impact on service continuity.
Based on the reliability analysis, the components were ranked in order of criticality as follows:

Table 7. Reliability analysis of how components were ranked in order of criticality

Rank	Component	Criticality Level
1	Transformer	Very High
2	Fuse	Very High
3	Outgoing Feeder	Very High
4	Switchgear	High
5	Supply Line	High
6	Circuit Breaker	Moderate
7	Busbar	Low
8	Switch	Low
9	Overcurrent Relay	Very Low
10	Earth-Fault Relay	Very Low
11	Surge Arrester	Negligible

The ranking indicates that transformer failures pose the greatest threat to system reliability because of their extensive outage impacts and long repair durations. Fuses and outgoing feeders also demonstrated high criticality due to their significant contributions to outage frequency and service interruptions.
The transformer was ranked as the most critical component because its failures result in long outages and significant customer impact. Fuses and feeders were also classified as critical due to their frequent failures.

4.7 Discussion

The results demonstrate that the reliability performance of the distribution substation is largely influenced by a small number of critical components. Although fuses recorded the highest failure frequency, transformers contributed the greatest outage duration and annual unavailability.
This finding highlights the importance of considering both failure frequency and repair duration when assessing equipment criticality. Components that fail infrequently may still have significant impacts on system reliability if their repair times are extensive.
The prominence of transformer and feeder-related outages suggests the need for enhanced preventive maintenance, load management, and condition monitoring programs. Regular transformer oil analysis, thermographic inspections, and load balancing strategies can help reduce failure occurrence and improve operational reliability.
The high contribution of fuses to outage frequency further indicates the need for improved protection coordination and network reinforcement. Frequent fuse operations may be symptomatic of overload conditions, poor feeder performance, or recurring downstream faults.
Overall, the results confirm that reliability-centered maintenance can significantly improve distribution system performance by directing maintenance resources toward the most critical assets. Prioritizing transformers, outgoing feeders, and protection devices is likely to yield the greatest improvements in reliability, availability, and customer service continuity.
The findings of this study provide valuable information for utility operators seeking to optimize maintenance planning, improve asset management practices, and enhance the reliability of electricity distribution networks.

V. Recommendations

Based on the reliability assessment, availability analysis, and asset criticality evaluation of the distribution substation components, the following recommendations are proposed to improve system reliability, reduce outage occurrences, and enhance maintenance effectiveness within the distribution network.

5.1 Reliability-Centered Maintenance Implementation

The distribution utility should adopt a Reliability-Centered Maintenance (RCM) approach for managing critical substation assets. Maintenance activities should be prioritized according to component criticality rather than relying solely on fixed maintenance schedules or corrective maintenance practices. This strategy will enable maintenance resources to be allocated more efficiently and reduce the likelihood of unexpected equipment failures.

5.2 Enhanced Transformer Maintenance Program

Transformers were identified as the most critical assets due to their high outage contribution and prolonged repair duration. To improve transformer reliability, the following measures are recommended:

1. Regular transformer oil testing and dissolved gas analysis (DGA).
2. Periodic thermographic inspections to identify hot spots.
3. Routine insulation resistance testing.
4. Load balancing among feeders to prevent overloading.
5. Installation of online condition monitoring systems.
6. Provision of standby transformers for emergency replacement.

These measures will reduce transformer failures and minimize outage durations associated with transformer faults.

5.3 Improvement of Feeder Reliability

Outgoing feeders exhibited high failure rates and significant outage contributions. Therefore, feeder maintenance programs should be strengthened through:

1. Regular line patrol and inspection.
2. Vegetation management along feeder routes.
3. Replacement of deteriorated conductors and accessories.
4. Installation of fault indicators for rapid fault location.
5. Deployment of feeder automation and remote monitoring systems.

Improved feeder management will significantly reduce service interruptions and enhance network performance.

5.4 Protection System Optimization

The high failure frequency associated with fuses indicates the need for improved protection coordination and fault management practices. The utility should:

1. Review and update protection coordination settings.
2. Replace aged and deteriorated protective devices.
3. Conduct periodic relay calibration and testing.
4. Introduce modern digital protection systems where necessary.
5. Investigate recurring faults responsible for frequent fuse operations.

These actions will reduce unnecessary outages and improve fault-clearing performance.

5.5 Adoption of Condition-Based Maintenance

Condition-Based Maintenance (CBM) should be integrated into the maintenance strategy to complement routine preventive maintenance. Equipment condition indicators such as temperature, vibration, insulation condition, and oil quality should be monitored continuously to detect potential failures before they occur.

The adoption of CBM will improve equipment availability, reduce maintenance costs, and extend asset life.

5.6 Asset Replacement and Rehabilitation Program

Components exhibiting persistent reliability problems should be prioritized for replacement or rehabilitation. Particular attention should be given to:

1. Aging transformers.
2. Obsolete switchgear.
3. Deteriorated feeder conductors.
4. Frequently operated fuses and switches.

A structured asset replacement program will improve long-term network reliability and reduce maintenance expenditure.

5.7 Deployment of Smart Grid Technologies

The utility should gradually implement smart-grid technologies to improve monitoring, control, and fault management capabilities. Recommended technologies include:

1. Supervisory Control and Data Acquisition (SCADA) systems.
2. Intelligent Electronic Devices (IEDs).
3. Automated feeder switching systems.
4. Remote fault detection systems.
5. Smart sensors for equipment condition monitoring.

These technologies will facilitate rapid fault identification, reduce outage duration, and improve operational efficiency.

5.8 Capacity Building and Personnel Training

Regular training programs should be organized for engineers, technicians, and maintenance personnel on modern reliability assessment techniques, condition monitoring technologies, and reliability-centered maintenance practices.

Improved technical competence will enhance maintenance effectiveness and support sustainable reliability improvements.

5.9 Establishment of a Reliability Monitoring Framework

The utility should establish a dedicated reliability monitoring framework for continuous assessment of component performance. Key reliability indicators such as:

1. Failure rate (λ),
2. Mean Time Between Failures (MTBF),
3. Mean Time To Repair (MTTR),
4. Availability,
5. Unavailability,
6. Annual outage duration,

should be monitored and reviewed periodically to support informed decision-making and continuous improvement.

5.10 Regulatory and Investment Support

Government agencies, regulators, and utility operators should collaborate to provide adequate funding and policy support for infrastructure modernization and maintenance improvement programs. Increased investment in distribution network assets will facilitate equipment upgrades, reduce system failures, and enhance electricity service delivery.

VI. Conclusion

This study presented a comprehensive reliability assessment and asset criticality analysis of major distribution substation components within the Ikorodu Distribution Network. Historical outage and maintenance data were analyzed to evaluate the reliability performance of transformers, switchgear, supply lines, busbars, circuit breakers, fuses, switches, outgoing feeders, protection relays, and surge arresters. Reliability indices including failure rate, Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR), availability, and annual outage contribution were determined and used to assess component performance.

The results revealed significant variations in reliability characteristics among the studied components. Fuses recorded the highest failure rate, indicating frequent operational disturbances and protection-related interruptions within the network. Transformers exhibited the longest repair durations and contributed the highest annual outage time, making them the most significant contributors to system unavailability. Outgoing feeders and switchgear also demonstrated considerable impacts on reliability performance due to their relatively high failure frequencies and outage contributions. In contrast, busbars, protection relays, switches, and surge arresters exhibited comparatively high reliability and availability throughout the study period.

The asset criticality assessment identified transformers, fuses, and outgoing feeders as the most critical components affecting the reliability of the distribution substation. The findings demonstrate that equipment criticality is influenced not only by failure frequency but also by outage duration, maintainability, and overall impact on service continuity. Consequently, maintenance priorities should focus on components whose failures result in the greatest operational and customer service consequences.

The study further demonstrated the importance of Reliability-Centered Maintenance (RCM) as a strategic approach for improving distribution network performance. By integrating reliability analysis with asset criticality ranking, utilities can optimize maintenance planning, allocate resources more effectively, and reduce the occurrence of unexpected equipment failures. The adoption of condition-based maintenance, continuous equipment monitoring, and proactive asset management practices can significantly improve system availability and service reliability.

Overall, the study confirms that reliability assessment and criticality analysis provide valuable tools for enhancing the operational performance of distribution substations. The results offer practical guidance for utility operators, maintenance engineers, and policymakers seeking to improve electricity service delivery and asset management within Nigerian distribution networks. Implementing the recommendations proposed in this study is expected to reduce outage frequency, shorten restoration times, improve equipment availability, and enhance customer satisfaction.

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