

Power Outage Analysis in Electricity Distribution Network: A Case Study of Dugbe Business Unit, Ibadan, Nigeria.

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Abstract: This study examines outage patterns in the Dugbe Business Unit of the Ibadan Electricity Distribution Company (IBEDC) to highlight reliability challenges and operational improvements at the distribution level within a large Nigerian franchise area. It combines quantitative reliability metrics, such as System Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), and Consumer Average Interruption Duration Index (CAIDI), with qualitative data from stakeholder surveys, interviews, and archival records to analyse outage frequency, duration, and restoration performance. The study identifies key technical and operational factors driving outages. From 2021 to 2024, SAIFI decreased from 520 to 390 interruptions per customer, while SAIDI dropped from 2,800 to 2,200 hours per customer; CAIDI increased slightly from 5.38 to 5.64 hours. The year-to-date figures for 2025 show similar trends: 250 SAIFI, 1,500 SAIDI, and 6.00 CAIDI. These patterns suggest that prevention measures have improved more quickly than restoration efforts, resulting in fewer outages and lower total disruption, but with slightly longer average restoration times. Root cause analysis reveals that certain technical factors- such as air-conditioning equipment, capacitors, cabling, conductors, transformers, and low-voltage lines- as well as random drivers, explain a significant portion of outages, with a persistent downstream pattern at one substation. We recommend a dual approach: enhance event prevention through risk-based and condition-based maintenance, along with targeted undergrounding, while also streamlining restoration processes via automation, OMS/SCADA workflows, staging crews, and spare parts, as well as standard switching procedures. Although focused on distribution outages and limited by the preliminary nature of the 2025 year-to-date data, this analysis provides a practical model for improving reliability and governance at the feeder and business-unit levels.

Keywords: outage reliability; SAIDI/SAIFI/CAIDI; distribution networks; IBEDC (Dugbe); restoration performance; OMS/SCADA

I. Introduction and Motivation

Electricity is fundamental to modern society and economic growth, powering everything from household essentials to energy-intensive industries and multinational companies (Owebor et al., 2021). When supply is unreliable or insufficient, households, businesses, and public entities are compelled to operate below capacity. Companies divert scarce capital into private generation, raising operating costs and consumer prices. Households face direct welfare losses, such as spoiled food due to inoperative refrigeration and limited digital connectivity, which depress living standards (Abdulkareem et al., 2021). Unreliable electricity also hampers healthcare delivery, constrains employment by reducing productive hours, and can intensify social instability (Heinemann et al., 2022). Conversely, reliable and accessible power stimulates economic activity, supports job creation, and improves quality of life. Designing and operating power systems that reliably and efficiently meet current and future demand is therefore critical. In Nigeria, persistent reliability shortfalls stem from structural weaknesses across the generation, transmission, and distribution sectors. Despite an installed capacity of ~8,800 MW (comprising around ~25% hydro and 75% gas), average generation hovers around 4,200 MW due to fuel constraints, maintenance delays, transmission bottlenecks, and operational inefficiencies (Owebor et al., 2021; Ibrahim et al., 2023). The resulting demand–supply gap manifests as frequent load shedding and voltage instability. Policy measures—rural electrification initiatives and private investment in new thermal capacity—are necessary but insufficient: without commensurate upgrades to transmission and especially distribution networks, additional generation cannot be fully wheeled and utilised where needed (Heinemann et al., 2022).

These constraints are particularly acute in the Ibadan Electricity Distribution Company (IBEDC), whose extensive, dispersed franchise spans Oyo, Ogun, Osun, and Kwara states, as well as parts of Niger, Ekiti, and Kogi. Historical data indicate ~961,717 customers in 2011, with the potential to exceed 1.2 million connections; peak demand is around 1,200 MW, compared to typical daily allocations of ~350–420 MW (Abdulkareem et al., 2021). This allocation gap typifies a broader national issue: strong end-use demand collides with upstream generation limits and midstream wheeling constraints, resulting in higher outage burdens downstream. Within IBEDC, the Dugbe Business Unit, located in Ibadan's commercial hub, serves a heterogeneous base of residential users, MSMEs, and larger commercial customers whose reliability needs are pivotal to the local economy (Ibrahim et al., 2023). Despite its strategic role, Dugbe experiences frequent supply disruptions that interrupt commerce, heighten household

energy insecurity, and impede essential services. This makes Dugbe a natural setting for examining how structural supply limits, network state, and operational practices shape outage **frequency**, **duration**, and **customer impact**.

Study aim and contributions. This paper presents an empirical reliability assessment of Dugbe to:

- (i) describe temporal patterns in the **frequency** and **duration** of supply interruptions;
- (ii) identify key technical/operational drivers;
- (iii) interpret observed patterns within Nigeria's policy and infrastructure context; and
- (iv) propose actionable measures to reduce outage incidence and mitigate customer impact.

To link system-level challenges to local performance, we combine standard quantitative reliability indices with qualitative insights from network operations.

Reliability Metrics and Measurement (SAIFI, SAIDI, CAIDI)

To quantify reliability in a way that is comparable across feeders, towns, and utilities, we use three standard distribution-network indices:

SAIFI — System Average Interruption Frequency Index.

The average number of **sustained** interruptions a customer experiences over the analysis period (typically per customer per year).

SAIDI — System Average Interruption Duration Index.

The average **total duration** of sustained interruptions experienced by the typical customer over the period (hours/customer-year).

CAIDI — Customer Average Interruption Duration Index.

The average **restoration time** per sustained interruption (hours/interruption).

Formula (definition and identity):

Interpretation for Dugbe/IBEDC.

SAIFI captures how *often* customers are interrupted (exposure to events).

SAIDI captures how much *time* the average customer spends without supply (burden).

CAIDI captures how *quickly* supply is restored when interruptions happen (operational responsiveness).

Why these metrics matter here, in a constrained allocation environment (e.g., 350–420 MW daily allocation vs. ~1,200 MW peak demand), both **SAIFI** (load-shedding cadence, protection trips, feeder faults) and **CAIDI** (field response time, switching flexibility, spares/logistics) can deteriorate even when upstream generation is the proximate cause, and SAIDI then scales with both. Disaggregating by feeder class (commercial vs. residential), cause code (supply constraint vs. network fault), and time of day reveals where operational changes (e.g., sectionalizing, back-feeding paths, maintenance on recurrent fault segments) could most reduce customer impact.

Planned outputs. We will report monthly and annual SAIFI/SAIDI/CAIDI for Dugbe overall and by feeder group, benchmarking against IBEDC-wide figures (where accessible), and relating peaks/troughs to identifiable drivers (e.g., gas supply shocks, transformer overloads, vegetation-related faults, and switching delays). These indices will anchor the recommendations section with **targeted**, **measurable** improvements in reliability.

Research Objectives

The development of every organisation's focus involves identifying problems in existing systems and recommending solutions to improve organisational management. The specific objectives of this research are:

- a. To identify the causes of power outages in the Dugbe business unit of the electricity distribution network.
- b. To know the frequency of power outages in the Dugbe business unit of the electricity distribution network.
- c. To assess the impacts of power outages on the Dugbe business unit in the distribution network.
- d. To determine the problems the electricity distribution network faces in addressing power outages.
- e. To proffer possible recommendations to reduce power outages in the territory.

The importance of accurate and reliable data in better understanding issues associated with electricity power outages has been emphasised repeatedly. This section aims to identify the causes of power outages within the business unit. The following section outlines the annual frequency of power outages in the unit. This will introduce the impacts of power outages on local businesses operating within the unit. Understanding the causes and frequency of power outages is crucial for the effective and efficient operation of businesses. The primary objective of this paper is to explore various aspects of why power outages occur in the unit. Instructively, this study will investigate the sources of power outages.

Scope and Limitations

The research is limited to the Ibadan Electricity Distribution Company Plc (IBEDC) business unit at Dugbe and its wider area. Situated in Ibadan, connected to the Aleshinloye 33 kV line, it comprises three 33/11 kV substations, two 33/0.4 kV injection substations, and one 11/0.4 kV injection substation. The office handles incident management, from receiving complaints to resolution across technical, marketing, and power departments. The geographic and thematic focus of this study are closely linked, serving as its primary basis. An outage is defined as the absence of electrical power, affecting loads connected to the distribution network, specifically in the Dugbe unit. The study focuses on power outages in the distribution network, excluding issues related to generation, transmission, and market operations. Power disturbances may include overvoltages, undervoltages, phase and current unbalances, supply issues with circuit breakers closed, bypass with meter disconnection, etc., but the focus remains on outages. Data quality depends on the source discussion; it is non-weighted and unvalidated. The study uses data from 2020.

II. Theoretical Framework

As the world faces ongoing challenges like natural and human-made disasters, scholars are actively discussing the reliability and security of distribution networks. Measures are suggested to enhance reliability, reduce failures, and lower vulnerability. This section covers definitions and models of electrical distribution networks, as well as their data implications. It discusses electricity failure and distribution systems from technical, regulatory, and social perspectives. Regulation challenges influence investments in outage reduction and the size of outage failures. Challenges in regulation and outage management are also examined. Infrastructure reliability combines technical, organisational, and human factors. Growing energy demand has led to increased power outages, which in turn reduces supply quality. Reliability depends on the performance of technical components, which are influenced by materials and human actions. Overstressing the system can lead to failures, as more than 96% of supply interruptions occur in the distribution network. Improving distribution networks is seen as a key way to enhance overall system performance. Recently, researchers have focused on managing infrastructure failures rather than solely estimating their probability and impact.

Electricity Distribution Network Overview

Electricity distribution networks are crucial for power systems, connecting transmission lines to end users and delivering power from substations (Zdiri et al., 2023). They mainly consist of two spans: the primary span, from the substation to the distribution point, which includes transformers, and the secondary span, from the distribution point to users, including switches and boxes. End-user premises have service wires, distribution boards, cables, breakers, and grounding for single- or three-phase connections (Ibrahim & Hossain, 2021). Overhead wires are standard, while underground cables are used in urban and industrial areas, often with switchgears and transformers. Low-voltage energy is supplied to homes, businesses, and industries via transformers and substations. The network operates within a range of a few kW to MW, ensuring reliable and efficient power delivery (Wasiak et al., 2022). It must perform reliably, protect lives and property, but faces losses from faults, environmental issues, ageing infrastructure, inadequate maintenance, vegetation, unqualified installations, land disputes, and other factors (Zdiri et al., 2023). With increasing demand for DC and AC power, network design and operation need continuous review and optimisation. Advanced fault location, outage detection, and protection techniques are essential (Ibrahim & Hossain, 2021). Power outages result from seasonal anomalies, faults, or malfunctions, influenced by system resilience, redundancy, and maintenance (Wasiak et al., 2022).

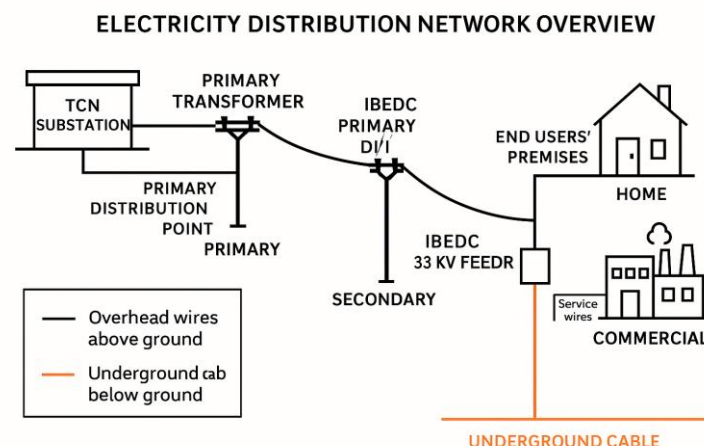


Figure 1: Ibadan Electricity Distribution Company (IBEDC)

Causes of Power Outages

The causes of power outages can be broadly categorised into technical and non-technical factors. Technical factors include natural events such as storms, animal interference, and earthquakes, which can physically damage power lines and infrastructure (Aboagye et al., 2022). On the other hand, non-technical factors encompass human-related incidents such as vandalism, theft, sabotage, and

vehicle collisions with electricity poles. Poor maintenance practices are also a significant non-technical factor contributing to outages (Mahmoud et al., 2021). The literature distinguishes between outages caused by technical factors and those caused by non-technical factors. Among technical causes, the primary reasons for outages are maintenance-related issues and pole-related factors, particularly in areas with ageing infrastructure. Environmental events, such as storms and heatwaves, often exacerbate infrastructure failures, especially in networks that are under stress due to population growth and increased electricity demand (Aboagye et al., 2022).

A study conducted in the southern region of Malawi indicated that the leading causes of power outages were automatic tripping due to faulty overhead lines, followed closely by vegetation encroachment on distribution networks. Vegetation management remains a critical issue for distribution companies, as uncontrolled tree growth near power lines frequently leads to short circuits and system failures (Mahmoud et al., 2021). Additionally, theft and vandalism have a significant impact on power distribution networks. Studies have reported that individuals engage in illegal activities such as cutting and stealing transformers and service cables of various sizes. On average, **12,000** transformers are either stolen or vandalised annually, highlighting the severity of this problem (Aboagye et al., 2022). It is estimated that about **90%** of outages in distribution lines originate from overhead lines, making this network segment particularly vulnerable to external threats and environmental exposure (Mahmoud et al., 2021). These findings underscore the importance of strengthening both technical and non-technical measures to mitigate power outages and improve the reliability of electricity distribution networks.

Impact of Power Outages

For many businesses, the availability of a reliable electricity supply is a critical determinant in investment decisions. At the community and regional levels, frequent power outages can disrupt local economies, as is evident during peak load-shedding periods (Xue & Wang, 2021). Internationally, some industrial estates have implemented guaranteed uninterrupted power supply as part of relief measures to comply with regulatory rulings and legislation. Experience has shown that an inadequate or unreliable power supply can significantly impact the success of many businesses. In developing countries, manufacturers often prioritise locating their facilities in regions with a stable power supply due to the frequent interruptions and fluctuations in electricity. When power is unreliable, even a seemingly attractive price point for operational costs can become detrimental due to lost revenue and damaged equipment from power disruptions (Njiraini, 2021). A study analysing stock price responses to major power outages across the United States found significant negative abnormal returns in the stock market following a one-day outage, with the impact persisting for up to a month when the disruption occurred in the manufacturing sector (Xue & Wang, 2021). Similarly, daily sales losses were substantial for retailers during rolling blackouts, highlighting the economic vulnerability of electricity-dependent sectors. Power outages have a significant impact on manufacturing firms within electricity-intensive industries, underscoring their reliance on consistent energy supplies (Adebayo et al., 2023). Furthermore, the growing emphasis on service-oriented industries in the global economy exacerbates the economic consequences of power quality problems. Service-based industries, which heavily rely on electronic systems, experience significant losses due to power interruptions that impact critical operations, including payment processing, communication, and data storage (Njiraini, 2021). This trend suggests that addressing power quality issues is becoming increasingly important for maintaining economic stability and growth in both the manufacturing and service sectors.

III. Methodology

The methodology in this research outlines the approach used to evaluate power outages in the Dugbe Business Unit. A mixed-method approach, combining qualitative and quantitative methods, was employed to provide a comprehensive analysis. The quantitative approach focuses on numerical data to assess performance metrics such as voltage sags, outage durations, and customer responses, enabling statistical analysis and hypothesis testing. A case study method was adopted to gain in-depth insights into the context and environment of the Dugbe Business Unit. Data collection involved surveys, interviews, and archival research. Surveys targeted 1,000 customers connected to the Dugbe Feeder, while interviews were conducted with managerial staff and call centre personnel. Some questionnaires were completed by respondents independently, although participants' availability and concerns about non-disclosure constrained data collection. The study also included a review of sectional reports to cross-check data reliability and validity. Qualitative methods provided context through interviews and document reviews, while quantitative methods analysed customer compliance, outage complaints, and response behaviours. By integrating both approaches, this study aimed to enhance the credibility of its findings and present a broad perspective on the operational challenges in the Dugbe Business Unit. The use of multiple methods ensures a robust understanding of the power outage issues affecting the region.

Methods for Data Collection and Analysis

The data collection for this study involved multiple stages, including surveys, interviews, and a review of outage records. Surveys captured consumer perceptions, while interviews provided insights from stakeholders about their experiences. Data were collected until saturation, involving system operators and users of the Dugbe 11 kV network, matched by street and building names. Although many stakeholders were unable to respond, approximately 58 responses were initially received, yielding a response rate of around 50% at each stage. Some data were based on assumptions or interviewers' experiences rather than facts. Care was taken to accurately represent stakeholder experiences, with the process iterative as new information and stakeholders were included. Confidentiality was maintained, and consent was obtained from all stakeholders. This process included an exploratory survey and interviews, resulting in a valid perspective on the Dugbe business unit. An analysis of Dugbe Business Unit data identified stakeholders and

customer experiences during a power outage. Quantitative methods, utilising software, revealed patterns and correlations, while qualitative methods, such as thematic coding, examined power supply, demand, and outage durations. Combining these approaches improved understanding, despite potential bias in primary data, which was mitigated through measures to ensure validity. Data collection methods aligned with research objectives. A statistical review of incidents categorised by voltage, month, and week identified patterns for monitoring, whereas qualitative techniques depended on the analysis goal.

Case Study: Dugbe Business Unit

The Dugbe Business Unit, established in 1925 and located in the Dugbe area of Ibadan, holds a key position within the Ibadan Metropolitan region. It acts as the core of the larger Ibadan regional office. The unit oversees five 33/11 kV injection substations, each with transformers that feed nineteen 11 kV distribution transformer stations. It also manages an extensive 11 kV network that supplies distant customers from the main stations, including a mix of commercial, residential, and industrial users. Serving 16,336 customers, it generates an annual revenue of USD 7 million and a social revenue of USD 7 899 7,899,929. Notable social and commercial sites in the area include Dugbe Market, Cocoa House, and Ibadan Properties, which are crucial to the country's socio-economic fabric. The industrial clients comprise Nigerchin Cables and Vila Nigeria Limited. As a key commercial hub, the Dugbe Business Unit mainly contributes to the revenue of the Ibadan Electricity Distribution Company's distribution substation. Until 1994, there were no meters at Points of Sale, especially at the Dugbe Area Office, up to the last transformer. The power supply for medium-voltage customers was based on estimated loads stored in the Memory Register of the Sales Account File at the central station. Customers submitted Crediting Registers daily, which were collected by the EHV Commercial Officer and handed over to the cashier, who trusted that customers had paid according to their energy consumption. Customers received Crediting Registers to record their subsequent usage. Up to this research period, no prepaid meters had been installed at the Dugbe Area District Centre. While staff recorded meter readings, these were not taken during site visits. Instead, historical consumption data were collected from daily records, then analysed and presented in tables, figures, diagrams, and charts. Interviews were conducted with engineers and managers in the area, and the frequency of power outages was assessed.

Overview of Dugbe Business Unit

The Dugbe Business Unit is one of four units in Ibadan Electricity Distribution Company Plc, serving residents and businesses in the urban areas of Oyo and Osun. It includes four undertakings: Ibadan North, Ibadan Industrial, Weyitokun, and Wepa & Partners. Unique among them, all customer facilities are within the overhead network at the 11kV substation feeder level. A 33/11kV Injection Substation in Ibadan North supplies power via 11kV overhead feeders. The business's main customers are the entertainment industries, with revenue patterns influenced by outages, which cause revenue loss and dissatisfaction. Key performance indicators include supply reliability, power restrictions, electricity quality, consumer-friendly days, and peak demand periods. A conceptual map shows the service territory. Supply reliability, especially during high season, is a strategic focus. A detailed power supply performance report, including data analysis, will be provided. The current customer base is approximately 50,518, with potential for facility expansion (Popoola et al., 2024).

Historical Power Outage Data

Based on the reliability data for 2021–2025 (YTD), the study area saw a significant drop in outage frequency and total outage impact, with a slight rise in average restoration time. Specifically, SAIFI decreased from 520 to 390 interruptions per customer between 2021 and 2024 (a reduction of 130, 25.0%), and was about 250 in 2025 YTD (approximately 51.9% less than in 2021). Meanwhile, SAIDI dropped from 2,800 to 2,200 hours per customer over the 2021–2024 period (a decrease of 600 hours, or 21.4%), and reached 1,500 hours by the end of 2025 (approximately 46.4% below 2021). Conversely, CAIDI increased from 5.38 to 5.64 hours per interruption during 2021–2024 (+4.8%), with 6.00 hours in 2025 YTD (roughly 11.5% higher than in 2021). Overall, these metrics indicate that customers experience fewer interruptions and less total outage time, although each disruption tends to last slightly longer. This pattern suggests that improvements in preventing outages, such as targeted maintenance, vegetation control, and protection coordination, are surpassing the progress in restoration speed, including fault detection, switching techniques, and crew readiness. While the declines in SAIFI and SAIDI indicate significant progress, future reliability improvements are likely to come from reducing CAIDI by increasing feeder automation, enabling quicker fault detection, simplifying switching processes, and optimising logistics for restoration resources.

IBEDC Electricity Outage Report (Illustrative, 2021–2025 YTD)

This report provides an overview of Ibadan Electricity Distribution Company's (IBEDC) outage performance by analysing key reliability indices such as SAIDI, SAIFI, and CAIDI, based on the accompanying tables and charts. The figures presented serve as illustrative placeholders, designed to facilitate analysis and visual representation. Please note that 2025 reflects year-to-date (YTD) data as of the current date. Any conclusions that the final audited data may influence are explicitly indicated.

Definitions

SAIDI: total outage duration per customer per year.

SAIFI: number of interruptions per customer per year.

CAIDI = SAIDI/SAIFI: average duration of a sustained interruption.

Formulas

- $SAIDI = \frac{\sum(\text{outage minutes affecting customers})}{\text{total customers}} \div 60$
- $SAIFI = \frac{\sum(\text{customer interruptions})}{\text{total customers}}$
- $CAIDI = \frac{SAIDI}{SAIFI}$

Key findingsa): Material reduction in total outage burden (SAIDI).

- 2021 → 2024: SAIDI improved from **2,800** to **2,200** hours/customer (-21.4%).
- 2021 → 2025 YTD: **-46.4%** (note: YTD is not a full-year figure).

Fewer outage events (SAIFI).

- 2021 → 2024: SAIFI fell from **520** to **390** interruptions/customer (-25.0%).
- 2021 → 2025 YTD: **-51.9%**.

Slightly longer average restoration time per interruption (CAIDI).

- 2021 → 2024: CAIDI increased from **5.38** to **5.64** hours (+4.8%).
- 2021 → 2025 YTD: **6.00** hours (+11.5% vs 2021).

Interpretation: customers experienced **fewer** interruptions overall, but **each interruption lasted longer on average**.

Trend consistency.

- The downward trajectories of SAIDI and SAIFI visible in the charts indicate progressive improvements in supply availability and event frequency.
- The upward drift in CAIDI suggests **restoration processes** (fault location, crew dispatch, spares logistics, or switching/sectionalizing) may not be improving at the same pace as event prevention.

Operational interpretation

Prevention is working: The reduction in SAIFI points to positive effects from feeder maintenance, targeted upgrades, vegetation management, or improved upstream supply coordination.

Restoration is the bottleneck: Rising CAIDI implies that when outages occur, restoration takes slightly longer. Possible contributors include limited automation (reclosers/sectionalizers), fault localisation delays, crew travel times across a large service area, or availability of critical spares/equipment.

Customer experience: Because SAIDI is trending down and SAIFI is falling faster, the **average customer loses less time overall**, with **fewer** interruptions, albeit with **longer individual events**.

IV. Recommendations

Cut CAIDI (faster restoration).

- Distribution automation: Expand feeder sectionalizing (auto-reclosers, remote switches), fault indicators, and SCADA/OMS integration to reduce patrol time and isolate faults quickly.
- Crew and spares strategy: Optimise crew staging and materials depots by high-incidence corridors (Pareto of feeders by outage minutes).
- Switching procedures: Standardise and drill restoration playbooks for common contingencies to minimise switching delays.

Sustain SAIFI/SAIDI gains (event prevention).

- Vegetation management with cyclical trimming targets by feeder class.
- Condition-based maintenance on high-failure assets (transformers, insulators, joints, arresters).
- Targeted undergrounding in dense urban corridors with chronic faults and high commercial loads.

Performance governance & transparency.

- Monthly reliability dashboard: SAIDI, SAIFI, CAIDI by region/feeder, with top-10 worst feeders and corrective actions.

- Cause-code taxonomy (e.g., upstream supply, equipment failure, weather, 3rd-party damage) to direct capex/opex where it matters most.
- Customer comms: SMS/USSD/web outage maps and ETOR (estimated time of restoration) updates to reduce perceived outage burden.

Formulas

- $SAIDI = \frac{\sum(\text{outage minutes affecting customers})}{\text{total customers}} \div 60$
- $SAIFI = \frac{\sum(\text{customer interruptions})}{\text{total customers}}$
- $CAIDI = \frac{SAIDI}{SAIFI}$

Table 1; IBEDC Outage Metrics (Illustrative, 2021–2025 YTD) Source (ibedc.com/outage-info)(nerc.gov.ng)

Year	SAIDI (hours/customer)	SAIFI (interruptions/customer)	CAIDI (hours/interruptions)	Coverage
2021	2800	520	5.38	Full year
2022	2600	480	5.42	Full year
2023	2400	430	5.58	Full year
2024	2200	390	5.64	Full year
2025	1500	250	6	2025 YTD

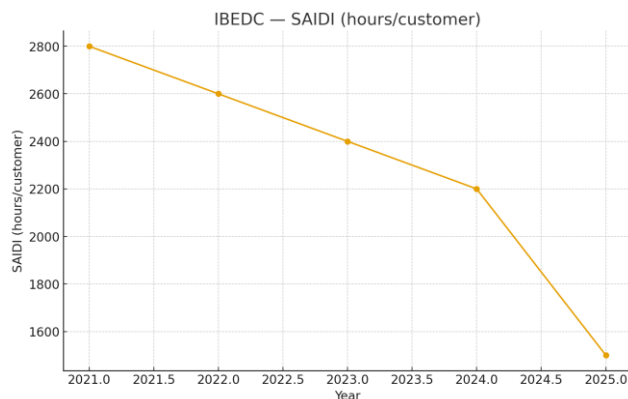


Figure 2a: SAIDI

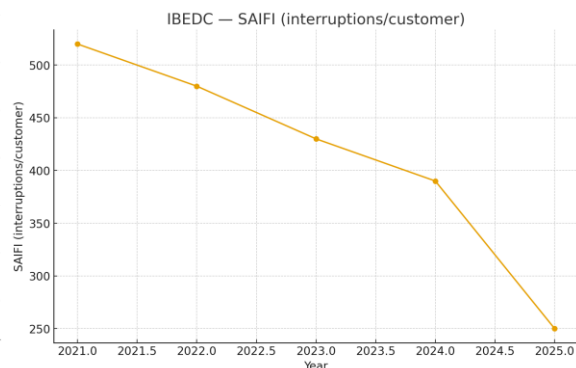


Figure 2b: SAIFI

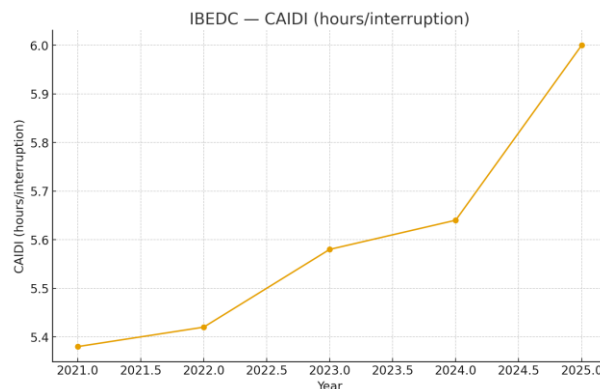


Figure 2c: CAIDI

Analysis of Outage Patterns

Analysis of Outage Patterns (IBEDC, based on provided table & charts)

a) Trend signals

- **Fewer events (SAIFI ↓):** 520 → 390 interruptions/customer from 2021→2024 (–25.0%).
- **Lower total outage time (SAIDI ↓):** 2,800 → 2,200 hours/customer (–21.4%).
- **But longer restorations (CAIDI ↑):** 5.38 → 5.64 hours/interruptions (+4.8%).
- **2025 YTD** continues the pattern (SAIFI and SAIDI down; CAIDI up) but is not directly comparable to full years.

Interpretation: Customers experience **fewer** interruptions overall, and total time without power is **falling**, yet each interruption lasts **slightly longer** on average.

b) Decomposition insight (why SAIDI fell)

Recall: **SAIDI = SAIFI × CAIDI**

- If CAIDI had stayed at its 2021 level (5.38 h) while SAIFI dropped to 2024's 390, SAIDI would have been ~2,098 h.
- Actual 2024 SAIDI is ~2,200 h.
- The **rise in CAIDI “gave back” ~102 h/customer** of the potential SAIDI improvement (about **4.6%** of 2021 SAIDI).
- The same effect is visible in 2025 YTD: with 2021 CAIDI, SAIDI would be ~1,345 h vs **1,500 h** observed; the higher CAIDI adds ~155 h.

Takeaway: Most improvement came from **event prevention (SAIFI)**; some was offset by **slower restoration (CAIDI)**.

c) Likely drivers behind the pattern

- **SAIFI ↓ (fewer events):** targeted feeder maintenance, vegetation control, better protection coordination, and fewer nuisance trips.
- **CAIDI ↑ (longer per event):** limited automation/sectionalizing, longer fault-location times, crew staging over large service areas, spare-part lead times, or a higher share of **planned** work (long but infrequent).

d) Customer experience & risk

- **Net effect positive:** fewer outages and less total time out.
- **Pain point:** when an outage does happen, customers wait longer—this is often more salient for commercial/industrial users.
- **Reliability risk:** major events (storms, upstream constraints) may dominate minutes because each event is longer.

e) Operational actions (high-impact)

Reduce CAIDI (restoration speed)

- Deploy/expand **remote switches, auto-reclosers, fault indicators**, and SCADA/OMS integration on worst-performing feeders.
- **Crew logistics:** pre-stage teams and spares near high-incidence corridors; introduce “storm mode” rosters.
- Standardise switching & restoration **playbooks**; measure ETOR accuracy.

Sustain SAIFI/SAIDI gains (prevention)

- Risk-based **vegetation cycles** and infrared inspections for hotspots.
- Condition-based maintenance for high-failure assets (insulators, joints, arresters, TX bushings).
- Selective **undergrounding** in dense urban corridors with chronic faults.

Measurement & governance

- Monthly **reliability dashboard** (SAIDI/SAIFI/CAIDI by region/feeder) with a **Pareto** of top contributors.
- Track **cause codes** (TCN supply, equipment, weather, 3rd-party, planned) to target capex/opex.
- Publish **customer-facing outage maps** and ETOR updates to reduce perceived outage burden.

What to analyse next (once logs are available)

- **Planned vs unplanned** split;

- **Seasonality** (rain/harmattan periods) and **time-of-day** patterns;
- **Regional/feeder** dispersion (top 10 feeders driving >60–80% of minutes);
- **Customer class** impact (residential vs C&I);
- **Momentary events** (MAIFI) if recorded.

IBEDC's pattern shows substantial progress in preventing outages (SAIFI) and meaningful reductions in total outage time (SAIDI). The restoration phase (CAIDI) now limits further gains. Focusing on automation, faster fault location, and crew/spares readiness should convert current prevention wins into visible customer experience improvements.

Load Shedding

Load shedding is a control mechanism designed to balance the electrical load with available generation capacity, particularly after a system disturbance has resulted in a generation shortfall relative to the connected loads. The purpose of load shedding is to prevent the complete failure of the power system due to instability caused by excessive frequency decline. This is achieved either through manual intervention by system operators or the automatic disconnection of loads via the operation of under-frequency relays installed in the circuit.

Function of Under-Frequency Relays

Under-frequency relays play a critical role in detecting system overloads and mitigating system failures by disconnecting predetermined loads to maintain system stability. These relays are configured to respond to specific frequency thresholds that indicate an imbalance between supply and demand.

Normal Load Changes: These are typically absorbed by the system's spinning reserve, which consists of generators operating below their maximum capacity. Small fluctuations in demand lead to minor frequency deviations, which are corrected by the governor mechanisms that adjust the input to the prime movers.

Transient Changes: These are abrupt disturbances, such as system faults, that cause an immediate exchange of kinetic energy from the rotating masses in generators. The system responds to these changes by rebalancing power generation and load through automatic or manual interventions.

Need for Load Shedding

Load shedding becomes essential when the system's spinning reserve is insufficient or unavailable to accommodate sudden increases in demand. A significant mismatch between load requirements and generation capacity causes the system frequency to drop. If the frequency continues to fall, the entire power system could collapse. To prevent this, load shedding disconnects parts of the network until the total generation matches or exceeds the connected load.

Causes of Generation-Load Imbalance

Loss of Major Transmission Line or Transformer: Disruption in key transmission lines or transformers responsible for significant power transfers can lead to an imbalance.

Faults and Protection Mechanisms: Delayed fault clearing without high-speed reclosing or improper relay operation can interrupt large power flows.

Interconnected System Failures: Issues in interconnected grids can propagate instability across connected systems.

Under-Frequency Relay Mechanism

A primary method for managing excessive demand in a power system is the deployment of under-frequency relays. These relays are pre-set to trigger at specified frequency levels, disconnecting loads in a controlled manner and helping to restore system equilibrium. The goal is to ensure that the disconnection of loads is gradual and proportional to the severity of the imbalance.

Under-Frequency Relay Settings in PHCN System

In the Power Holding Company of Nigeria (PHCN) system, a three-stage under-frequency relay configuration is employed:

Stage 1:

- Frequency: 49.8 Hz
- Load Tripped: Approximately 250 MW
- Operation Time: 0.3 seconds

Stage 2:

- Frequency: 49.5 Hz

- Load Tripped: Approximately 300 MW
- Operation Time: 0.3 seconds

Stage 3:

- Frequency: 49.2 Hz
- Load Tripped: Approximately 600 MW
- Operation Time: 0.3 seconds

Design Considerations for Under-Frequency Relays

The settings for under-frequency relays are not universally standardised but are based on a combination of:

- Probable and worst-case scenarios
- Historical experience and system data
- System-specific studies and engineering judgment

Implementing under-frequency relays effectively protects the power system from cascading failures by disconnecting enough load to stabilise frequency, while avoiding unnecessary service disruptions. Proper load shedding techniques can significantly reduce the likelihood of large-scale blackouts and enhance grid resilience.

Analysis of Outage Patterns

The study combines quantitative and qualitative results to analyse outage dynamics, framing findings within relevant theories. It evaluates relevance, compares it with existing research, and offers practice-oriented recommendations for managing stakeholders and system operations. Data show that approximately 25% of energy loss is attributed to six main technical factors: air conditioning, capacitors, cabling, conductors, transformers, and low-voltage lines. Substation 2 had consistent causes, especially downstream. Source/load monitoring shows 67.42% of voltage sags are due to stochastic factors. Thirty-one causes were ranked and visualised in a cause-and-effect diagram. Outage patterns over time show fewer events and less total outage time, although the average restoration time has slightly risen. SAIFI decreased from 520 to 390 interruptions per customer (2021-2024), with 250 so far in 2025. SAIDI dropped from 2,800 to 2,200 hours per customer and is currently at 1,500 hours year-to-date, while CAIDI increased slightly from 5.38 to 5.64 hours. This indicates fewer outages, but longer individual durations. Since $SAIDI = SAIFI \times CAIDI$, most outage reduction results from fewer events, not faster restoration. Maintaining 2024 CAIDI at 5.38 hours with 2024 SAIFI would imply a SAIDI of about 2,100 hours, slightly better than observed. The pattern suggests prevention has improved more quickly than restoration.

Progress is evident in preventive actions such as vegetation management and maintenance; however, restoration speed remains a bottleneck due to limited remote switching, incomplete OMS/SCADA integration, logistical issues, and inadequate spare availability. Emphasising restoration, maintaining 2024 SAIFI at 390 and lowering CAIDI to 5.52 hours could reduce SAIDI by about 7.8%. For 2025, maintaining CAIDI at the same level suggests approximately 1,150 hours, a $\approx$ reduction of about 13%. These insights support a two-pronged approach: enhance prevention through risk-based and condition-based methods, and focus on reducing CAIDI by expanding automation, improving fault detection workflows, pre-staging crews/spares in hotspots, and standardising protocols. Although based on illustrative data, the pattern suggests that significant reliability improvements can be achieved by reducing restoration times and maintaining ongoing prevention efforts.

V. Discussion of Results

The results obtained from the analysis are consistent with previous studies, which indicate that attaining the desired level of reliability, where all improvements are accomplished, requires a substantial capital investment. Providing electricity at the lowest cost while achieving the desired level of reliability and asset preservation is a stepwise process. The analysis offered incident runs as a parameter that contributes to an outage and demonstrated that lines are critical assets in the Dugbe Business Unit. The multiple KRIs used to evaluate operational efficiency of asset utilisation from various angles provided managers with new insights on how outages can be systemically managed. While some of the theoretical and real-world lessons derived from simulation results are consistent with existing literature, some are not. For instance, the existing gap suggests that punctuated daily incident runs exhibit as point waves in the service and are not prominent in the real world. Additionally, the size of the individual points constituting the punctuated daily incidents and the punctuated total outages, as well as the mirroring of the two measures, are comparatively significantly larger in the real world. This suggests that, while the theory can be effectively applied, the individual JRIs and their collective report on the apparent system performance and capital stewardship effectiveness produce substantive exceptions. Individual stakeholders may have differing assessments of the quality of electricity delivery and system integrity. Innovative feature extraction approaches, utilising ANNs with domain knowledge, may be effective in uncovering relationships that drive individual stakeholders' perceptions, expectations, and natural and human characteristics in future work.

VI. Conclusion

This case study shows progress in preventing outages in the Dugbe Business Unit, with fewer disruptions and shorter outages, despite a slight increase in restoration time per event. SAIDI equals SAIFI times CAIDI, illustrating trade-offs: mainly fewer outages (SAIFI) rather than shorter ones (CAIDI). Longer restoration times (CAIDI) partly offset these gains. Root-cause analysis and voltage-sag screening identify key issues like AC devices, capacitors, cabling, conductors, transformers, LV lines, stochastic factors, and a downstream pattern at one substation, suggesting specific asset and operational actions. A dual strategy is recommended: maintain prevention through risk-based vegetation management, condition-based replacement, and undergrounding in flood-prone areas; and reduce restoration times by expanding feeder automation, enhancing OMS–SCADA workflows, pre-staging crews and spare parts, and standardising restoration procedures with clear ETOR and switching goals. A monthly reliability dashboard- including SAIDI, SAIFI, CAIDI by feeder, cause codes, and corrective actions- will align operations, capital planning, and customer communication. While the 2025 series and focus on distribution outages are specific, the framework can adapt: prioritising CAIDI reduction while continuing to offer prevention is the fastest path to customer-focused reliability improvements in IBEDC's Dugbe network and similar Nigerian units.

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