An analytical technique for failure analysis and reliability assessment of grid daily outage performance in distributed power system

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ABSTRACT

This paper modeled and analyzed the reliability performance of the 132/33 kV substation in Abuja, Nigeria through the historical data collected from the APO substation using MATLAB 2021b. The probability distribution model was applied to determine the daily feeder's outage using Reliability, availability, mean time to repair (MTR), Failure rate, distribution indices, and mean time between failures (MTBF). Due to the application of smart energy meters, the use of prepaid energy meters has helped to regulate energy demand, reduce network overloading especially during peak hours, and minimize the cost of energy consumed. There are more forced failures in the distribution system due to the switchgear and Transformer failures. There are more forced failures in the distribution system since 2013, which caused a reduction in the number of interruptions even with an increase in several customers linked to the transmission network. The result shows that the system was most available in the year 2015 with an average service availability index (ASAI) value of 98.9971%. The system was least available in year 2011 with an ASAI value of 98.6558%. The paper recommended that there should be interconnections between different feeders through proper configuration of switches or reclosers, to reduce failure occurrence in the network.

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1. INTRODUCTION

The power system network is vulnerable to random faults caused by component failure, transmission problems, and weather conditions. As a result, the critical task of a power network is to supply energy to customers in a cost-effective and reliable approach, even when exposed to random faults. The analysis of power system reliability usually considers several functional zones, including the Transmission network, generation network, distribution network, interconnected system, industrial systems, protection systems, and commercial systems [1]. Thus, system reliability can be expressed as the probability of a component executing a given task satisfactorily in the designated operational circumstances over time [2]. One of the methods for ensuring that a distribution network can consistently provide uninterrupted power for consumers is reliability evaluation. This is especially necessary because the power system is complicated and made up of many parts of machinery and equipment that are prone to malfunction while being used in the system, resulting in significant financial losses for the nation [3], [4]. About 80% of power outage failures, according to experts, are caused by the equipment and components of the distribution system [5], [6]. The two major techniques used in reliability distribution network analysis are Analytical methods and simulation (Monte Carlo) methods. The analytical method deals with statistical distributions of failure rate and time required to restore it to normal service conditions. The Monte Carlo method usually requires much time due to the large inference number needed to converge to precise outcomes. The analytical method applied failure modes assessment, parallel, and series networks methods for the reliability indices evaluation [6].

Franklin and Gabriel [7] assessed the dependability of Nigeria's power distribution system by conducting a monthly evaluation of the Ekpoma Network feeders in Edo State from January to December 2012, using feeder load data acquired from the power holding company of Nigeria (PHCN). Their studies indicated that daily feeder failures were caused by intermittent electrical problems in the distribution system. Uhunmwangho and Eseosa [8] applied the NEPLAN software to forecast the Port Harcourt distribution systems reliability through the data collected from the PHCN for the Choba distribution network and discovered that the use of NEPLAN revealed much about the network's performance and made predicting easierfor the potential outages in the system. The study also found it difficult to get critical data for network research and advised that the Utility guarantee complete recording of all data (operational and maintenance) to improve research in the Port Harcourt power distribution network. Adefarati *et al.* [9] examined the various subsystem components of the Ayede 330/132 KV injection substation, which supply the Jericho, Ijebu ode, Ibadan North, Sagamu, Ayede, and Iseyin substations, and discovered that the substation's reliability can be increased by lowering the component failure rate and improving the mean time between failures (MTBF). Ogheneovo [10] compared the reliability of the Onitsha distribution network between 2009 and 2011 before and after the installation of some photovoltaic (PV) systems at the injection substations using ETAP software. Researcher found that the PV system's inclusion significantly improved the substation's performance and the utility's revenue.

Gazijahani and Salehi [11] developed dynamic reconfiguration and incentive-based demand response to determine the cost-reliability using the exchange market algorithm (EMA). Ghiasi *et al.* [12] focused on the management risk of metro structures for economic assessment and risk evaluation in transmission network problem expansion using the probability technique. Hu *et al.* [13] classified outage time load points from 4 types to 7 types and identified different types of corresponding reliability parameters. Rocha *et al.* [14] analyzed reliability for the distribution networks that involved islanding dynamics using Non-sequential Carlo Monte models and stability transient simulation with a complete synchronous machine model which includes a voltage regulator and speed. Šnipas *et al.* [15] applied a stochastic automatic network to evaluate the reliability and failure rate of power system substations. The [16], [17] applied novel prediction models that focus on hybrid engine forecasts for energy cost and energy not used. Gazijahani and Salehi [18] developed an integrated technique that depends on time rate smart demand response operation and distributed heterogeneous energy sources for multi-microgrids-oriented reliability planning.

Teera-achariyakul and Rerkpreedapong [19] proposed a technique to determine the failure rate time variation of each feeder's future interruptions using customer interruption time, interruption energy rates, and total service areas KVA. The game theory method is applied to balance preventive maintenance costs and the importance of reliability enhancement. Mirhosseini *et al.* [20] developed an analytical novel method for the distribution network through the development of a new reliability-weighted cumulative diagnostic factor. Abbasghorbani *et al.* [21] developed reliability-centered maintenance for power system networks through the preventive maintenance mechanism. The application of the proposed technique was validated in the Khorasan substation transmission network of Iran. Mahdavi *et al.* [22] determined the importance of maintenance in the expansion of the generation-transmission network considering the generation and transmission reliability. The research focuses on generation and transmission expansion, reliability availability, and failure rate with network maintenance. The optimal value of a cooling tower's functional availability in a steam turbine generator was predicted by Kumar *et al*. [23] using metaheuristic algorithms. In order to estimate the availability of the hydroelectric generator, Maan *et al.* [24] used an adaptive neural fuzzy inference system. The configuration is made of four elements which comprise hydropower systems: turbine, turbine governor, generator converter, and generator. The system's availability is also affected by human error and the lack of water, which are connected in series. Kumar *et al.* [25] developed an effective stochastic model for generators through the principles of cold reserve reliability, geometrically dispersed failure, and maintenance guidelines.

In automatic distribution grids with potential customer outage cost estimation in the presence of DG units, the authors of the paper [26] presented a reliability optimization method. Gazijahani and Salehi [27] presented a reliability survey for electrical energy systems. An evolution economic algorithm (EMA) was employed to solve the suggested cost-reliability-based framework in Ghiasi *et al.* [28], which proposes a unified incentive-based demand-management (DR) and adaptive reconfiguration approach. Jayappa *et al.* [29] address risk management in metropolitan structures, which offered a probabilistic method of evaluating risks and assessing the economics of transmission network development planning issues.

Whenever a fault occurs in a distribution line, it is important to act quickly, isolate the fault part, allow the operation of non-fault parts, and minimize the area of the power outage. The combination of recloser and switch devices may successfully isolate more than 95% of the fault area, improving not only the social and economic but also the dependability of the power supply and establishing the groundwork for distribution automation.

This research paper applied the analytical model method in the assessment of the reliability of the APO 132/33 KV power substation in Abuja, Nigeria through the historical data collected from the APO substation from 2009 to 2018. To increase the value of system average interruption duration index (SAIDI), system average interruption frequency index (SAIFI), customer average interruption duration (CAIDI), and average service availability index (ASAI) of the substation, there is a need to apply interconnections between different feeders through proper configuration of switches or reclosers, to reduce failure occurrence in the network which other researcher in literature did not considered. Also, the paper recommends a proper control mechanism to monitor the state of MTBF and downtime for reliability and availability improvement in the network. Artificial intelligence is also recommended to ascertain the effectiveness of the network.

2. METHOD

The study analyzed the reliability of the APO 132/33 KV substation in the Abuja electricity distribution network between January 2009 to December 2018 using the probability distribution models. The substation has two incoming lines that link to the National grid at the 330/132 KV Katampe and Kukwaba (Gwagwalada) stations with a capacity of 250 MVA. The 132/33 kV Apo Substation is a feeder station that is part of the Federal Capital Territory (FCT) in Abuja, Nigeria. The substation has 10 by 33kV and 1 spare outgoing feeder line, which is as follows: H37, H35, H33, H31, H3, H7, H11, H13, H15, H21, & H23. The study carries out the models on MATLAB software for fast real-time performance operations. The collected data failure comprises downtime and outages of each feeder. After that, the probability approach was applied to determine the daily outage feeder's reliability using reliability, availability, mean time to repair (MTTR), Failure rate, Distribution indices, and MTBF.

2.1. Probability distribution models

Probability Distribution Models are used in reliability analysis to model the likelihood of failure or performance degradation in system components over time. These models are essential for calculating reliability indices and understanding the behavior of components under uncertain conditions. The methodology begins with selecting an appropriate probability distribution to model the failure behavior of each component. Common distributions used in reliability analysis include:

- Exponential distribution: Often used to model the time between failures of systems with a constant failure rate, such as electrical components that degrade randomly over time.
- Weibull distribution: A versatile distribution used to model various failure rates, suitable for both early-life failures and wear-out failures. It can model increasing, constant, or decreasing failure rates.
- Normal distribution: Applied when the component failures are related to variations around a mean value, typically in cases of wear and tear.
- Log-normal distribution: Useful when the failure times are influenced by multiplicative random variables, like environmental stress factors.

After choosing the appropriate distribution, failure data (e.g., time-to-failure or failure rates) is gathered from system performance history or component testing. The parameters of the chosen distribution (e.g., scale, shape) are estimated, often using methods like maximum likelihood estimation (MLE). With the distribution model in place, reliability indices such as the MTBF or availability can be calculated, helping to predict system performance and guide maintenance decisions

2.2. Availability

Availability is the probability that the system will be in a functional state within the specific period of operation. It is usually expressed as the ratio of the expected value of operational time to the sum of the expected values of operational time and downtime. Availability (A) is given in (1) to (6) [26].

$$A = \frac{X[Operationaltime]}{X[Operationaltime] + X[downtime]} \tag{1}$$

Given a state function of the system Y(t), it can thus be expressed as (2).

$$Y(t) = \begin{cases} 1, system\ function\ at\ time\ t = 0 \\ 0,\ otherwise \end{cases} \quad (2)$$

Availability A(t) at any time t > 0 is given by (3).

$$A(t) = \Pr[Y(t) = 1] = X[Y(t)] \quad (3)$$

Define the average availability based on real line intervals with an assumption of an arbitrary constant c > 0, then, average availability is given by (4).

$$A_c = \frac{1}{c}\int_0^c A(t)dt \quad (4)$$

The availability in a steady state condition of the system is given in (5).

$$A = \lim_{c\to\infty} A_c \quad (5)$$

Substituting (4) into (5):

$$A = \lim_{c\to\infty} \frac{1}{c}\int_0^c A(t)dt \quad (6)$$

2.3. Mean time between failure (MTBF)

Mean time between failure (MTBF) is the arithmetic mean value of the reliability function R(t), which can be expressed as the probability value of the density function f(t) of time between failure, which can be expressed in (7) [27].

$$F(t) = \lambda e^{-\lambda t} \quad (7)$$

Where λ is the failure rate
MTBF is the solution of the definite integral of R(t), which is given in (8) to (11):

$$\text{MTBF} = \int_0^\infty R(t)dt \quad (8)$$

$$\text{MTBF} = \int_t^\infty tf(t)dt \quad (9)$$

where:
$f(t)$ is the failure density function and t is the time until failure;
The discrete failure rate can be determined by substituting (7) with (9); and
Thus, MTBF is given by (10).

$$\text{MTBF} = \int_t^\infty t\lambda e^{-\lambda t}dt \quad (10)$$

Solving the definite integral using integration by parts

$$\text{MTBF} = \frac{1}{\lambda} \quad (11)$$

2.4. Distribution indices

The most common distribution indices include the SAIDI, CAIDI, SAIFI, momentary average interruption frequency index (MAIFI), customer average interruption frequency index (CAIFI), customers interrupted per interruption index (CIII), average service unavailability index (ASUI), and the ASAI.

2.4.1. Interruption duration index (SAIDI)

SAIDI is a measure of the total interruption duration for a customer average over a given period. It is often calculated monthly or annually. For a given total number of customers NT supplied by a distribution system, in case of interruption, I, there are several customers not affected for a duration of interruption d. The total customer duration of interruption CDI for any given interruption is given in (12) to (13) [28]:

$$\mathrm{CDI} = \mathrm{d} * \mathrm{N} \tag{12}$$

So, for a total number of faults for n = 1, 2, 3, …, n, the CDI is given by:
CDI = $d_1N_1 + d_2N_2 + d_3N_3 + \ldots + d_nN_n$
Therefore CDI = $\sum_{i=1}^{n} d_i N_i$
Thus, SAIDI is given by:

$$\mathrm{SAIDI} = \frac{\sum_{i=1}^{n} d_i N_i}{N_T} \tag{13}$$

where,
d_i = the duration of the interruption
N_i = the number of customers interrupted
N_T = the total number of customers

2.4.2. Customer average interruption duration (CAIDI)

This is the average time to restore interrupted customers for a given period. This index allows the measurement of the average outage duration for customers. The formula to calculate CAIDI is given in (14) [27]:

$$\mathrm{CAIDI} = \frac{\sum_{i=1}^{n} d_i N_i}{N_i} \tag{14}$$

where,
d_i = the duration of the interruption
N_i = the number of customers interrupted

2.4.3. SAIFI

This is the average number of times a customer is affected by a power outage during the year (or period). The SAIFI is the ratio of the total number of customers interrupted to the total number of customers served. The formula to calculate SAIFI is given in (15), (16) [28]. It provides the fraction of the time customers are without electricity throughout the predefined interval of time. It is expressed as:

$$\mathrm{SAIFI} = \frac{\sum_{i=1}^{n} N_i}{N_T} \tag{15}$$

N_i = Total number of customers interrupted.
N_T = Total number of customers served.
SAIFI may also be given in (16) as:

$$\mathrm{SAIFI} = \mathrm{SAIDI} / \mathrm{CAIDI} \tag{16}$$

2.4.4. Customer average interruption frequency index (CAIFI)

CAIFI is the measure of the average number of customers interrupted per year. It is simply the number of interruptions that occurred divided by the number of customers affected. For any interruption, several customers are affected. If Σ(No) is the number of interruptions that occurred in a year, then the number of customers affected that year is given by Σ(Ni). Hence**,** CAIFI is given in (17) as [28]:

$$\mathrm{CAIFI} = \frac{\sum_{i=1}^{n} N_0}{\sum_{i=1}^{n} N_i} \tag{17}$$

where the customer average interruption frequency index.
No = Number of interruptions.
N_i= the Total number of customers interrupted.

2.4.5. Customers interrupted per interruption index (CIII)

The CIII is defined as the average number of customers interrupted during an outage. It is an inverse of the CAIFI and can be calculated in (18) as [29]:

$$\text{CIII} = \frac{\sum_{i=1}^{n} N_i}{\sum_{i=1}^{n} N_0} \quad (18)$$

where the customer average interruption frequency index.
No = Number of interruptions.
N_i= the Total number of customers interrupted.

2.4.6. Average service unavailability index (ASUI)

It provides a fraction of the time customers are without electricity throughout the predefined interval of time. It is expressed in (19) as [28]:

$$\text{ASUI} = \frac{\sum r_i N_i}{N_T.T} \quad (19)$$

where,
d_i = the duration of the interruption
N_i = the number of customers interrupted
N_T = the total number of customers.

2.4.7. Average service availability index (ASAI)

This is a measure of the average availability of the distribution system that serves customers. It is usually represented in percentages. It is expressed in (20) as [28]:

$$\text{ASAI} = 1 - \frac{\sum r_i N_i}{N_T.T} \quad (20)$$

Where,
d_i = the duration of the interruption
N_i = the number of customers interrupted
N_T = the total number of customers
T = Time period under study

3. RESULTS AND DISCUSSION

Feeders 2, 3, 4, 6, and 10 also recorded a relatively high number of failures. The distribution system encountered a total of 3818 failures over the ten years of study. When the ASAI is low, it indicates that the network is frequently unavailable, meaning customers experience a higher number or longer durations of power outages. A low ASAI signifies poor service reliability and is often the result of several factors. One common cause of a low ASAI is poor infrastructure maintenance. If the equipment, such as transformers, circuit breakers, and power lines, is aging or inadequately maintained, it may fail more often, leading to increased outages. Weather-related issues can also contribute, such as storms, hurricanes, or flooding, which damage critical infrastructure. Areas prone to natural disasters may experience a more significant drop in ASAI during such events. Additionally, a lack of investment in system upgrades or insufficient capacity to handle peak demand can strain the network. When demand exceeds supply or the network's ability to distribute power effectively, service interruptions become more frequent. In some cases, human errors or inadequate staff training can lead to poor maintenance responses or delays in addressing faults. A low ASAI ultimately results in higher customer dissatisfaction, as prolonged or frequent outages disrupt daily life, businesses, and critical services. Utilities must address these issues by upgrading infrastructure, improving maintenance schedules, and enhancing grid resilience to raise the ASAI and restore service reliability. Table 1 shows the system reliability indices from 2009 to 2018.

The mean time of operation of each feeder between the occurrences of consecutive failures is measured by this index. From Table 1, feeders 9 and 11 show the longest MTBF, having an average of 561.8462 hours of operation before the occurrence of any forced failure. Feeder 1 has the least MTBF, with just 142.9821 hours of operation before an occurrence of a failure. Hence, feeder 1 appears to be the least stable in the distribution network. Feeders 2, 3, 4, 6, and 11, with MTBF of 153.4991 hours, 184.9114 hours, 203.3514 hours, 215.3514 hours, and 228.846 hours, respectively, also appear to be less reliable than the other feeders.

Table 1 shows the MTTR of each feeder in the distribution network. Feeder 11 has the highest MTTR with a value of 8.9551 hours, while feeder 3 has the least MTTR with 6.1477 hours. In other words, feeder 3 is the fastest to be fixed in any case of fault occurrence in the distribution system. This may be due to factors that include the distance of the feeder from the substation, the time to fault discovery, the nature of the fault, and logistical issues. Feeder 9 is the most available, having an availability value of 0.9878 for the 10-year duration of the distribution system. Feeder 1 has the least availability of 0.9552. Other feeders with relatively low availability are feeders 2, 3, 4, and 6, each with 0.9592, 0.9678, 0.9688, and 0.9683, respectively.

The average time of operation between two consecutive failures is recorded to be highest in feeders 9 and 10, while feeder 1 shows the least mean duration of operation between failures. Feeders 5, 7, and 8 also show a considerable duration of operation before a failure occurs. It can be deduced that the feeders with relatively high MTBF are fairly stable in operation, that is, they have a reduced frequency of failure compared to the feeders with low MTBF. The result shows that the MTTR of feeder 3 is relatively quickly restored compared to the other feeders. Feeder 11 has the highest MTTR value, which makes it the slowest to be restored to operation mode after the occurrence of a failure.

Table 1. System reliability indices from 2009 to 2018

Feeder	Total number of failures	Total duration of outage (hr)	Total expected duration of operation (hr)	MTBF	MTTR	Availability
Feeder 1	613	4110	87648	142.9821	6.7047	0.9552
Feeder 2	571	3731	87648	153.4991	6.5342	0.9592
Feeder 3	474	2914	87648	184.9114	6.1477	0.9678
Feeder 4	431	2826	87648	203.3596	6.5568	0.9688
Feeder 5	212	1558	87648	413.434	7.3491	0.9825
Feeder 6	407	2874	87648	215.3514	7.0614	0.9683
Feeder 7	202	1574	87648	433.901	7.7921	0.9824
Feeder 8	213	1688	87648	411.493	7.9249	0.9811
Feeder 9	156	1085	87648	561.8462	6.9551	0.9878
Feeder 10	383	2680	87648	228.846	6.9974	0.9703
Feeder 11	156	1397	87648	561.8462	8.9551	0.9843

3.1. System average interruption duration index (SAIDI)

In Table 2, the system average interruption duration index of the whole distribution network is presented for each year for the ten-year duration of the study. The system recorded the highest value of average interruption in the year 2011 with a SAIDI value of 117.752 hours while the least was recorded in the year 2015 with an average of 87.8544 hours of system interruption. This implies that interruptions are quickly discovered and the system was restored in 2015 compared to the other years. The system has the highest average interruption duration in the year 2011 and the lowest average interruption duration in the year 2015.

3.2. System average interruption frequency index (SAIFI)

The system had the highest average interruption frequency index in the year 2014, with a SAIFI value of 0.4241 interruptions per customer, while the lowest SAIFI value was recorded in the year 2017 with 0.3547 interruptions per customer. This implies that in the entire period, a customer experiences less than one interruption each year in the APO 132 kV/33 kV distribution system. The SAIFI value of this distribution system is observed to be low compared with the IEEE 1366 1998 Standard for North American Utilities, which has a median value of 1.1 interruptions per customer. The system recorded the highest value of SAIFI in the year 2014 and the lowest value in the year 2017. The highest value is observed to be below 0.5 interruptions per customer, which makes it assumable that the system is fairly stable.

It is evident that the average duration of interruption experienced by customers connected to the APO 132 kV/33 kV distribution system was extremely high in the year 2009, with a CAIDI value of 296.2305 hours, followed by the year 2011, which had a CAIDI value of 290.5187 hours. The lowest CAIDI value was recorded in the year 2015 with a CAIDI value of 234.312 hours. This insinuates that electric power was quickly restored to the customers in the year 2015 compared to the other years. Nonetheless, a low value of CAIDI depicts the high reliability of a power system. Comparing the lowest CAIDI value of the APO 132 kV/33 kV distribution system with the IEEE standard value, it can be deduced that this distribution system takes longer hours than the stipulated benchmark to restore power to the customers, hence making the distribution system less reliable.

3.3. Customer average interruption duration index (CAIFI)

The customer average interruption duration index presented in Table 2 shows that the most frequent interruptions experienced by customers connected to the 132 kV/33 kV distribution station were recorded in the year 2017, with an average of 0.0183 interruptions per customer, followed by the year 2019, with an average CAIFI value of 0.0176 interruptions per customer. The lowest value of CAIFI was recorded in the year 2016 with 0.0153 interruptions per customer. Again, considering the CAIFI of this system, one might erroneously assume it is reliable when considering its very low values of frequency of interruptions per customer. Other years with relatively high CAIFI values are 2009 and 2013. Years with low values of recorded CAIFI are 2014 and 2016. The highest CAIFI value in the table is less than 0.02, which could have suggested the system to be fairly reliable, but the results of other more defining indices do not support the assumption.

3.4. Customers interrupted per interruption index (CIII)

The average number of customers that experienced an interruption at a single time is presented in the CIII column in Table 2. From Table 2, it is shown that more customers experienced interruptions at a single time in the year 2016 than in any other year. The result shows that 65.3774 (approximately 65) customers experienced interruptions together at any single occurrence of interruption in that year. The year 2017 recorded the lowest number of customers experiencing interruptions per interruption, with an average of 54.709 (approximately 55) customers per interruption. Using this index to appraise the reliability of this distribution system, the system may be considered unreliable as several customers are interrupted. It can be observed from the graph that the highest number of customers interrupted per interruption was recorded in the year 2016, followed by 2014. The lowest number of customers interrupted per interruption was recorded in the year 2017.

Table 2. Customer reliability indices

Year	Number of failures	Duration of outage (hr)	Expected duration of operation (hr)	Total number of customers served	Total number of customers interrupted	SAIDI (hr)	SAIFI (int./cust.)	CAIDI (hr)	CAIFI (int./cust.)	CIII (cust./int.)	ASAI (%)	ASUI (%)
2009	398	3112	8760	57239	22592	116.921	0.3947	296.2305	0.0176	56.7638	98.6653	1.3347
2010	363	2839	8760	57539	21486	106.0568	0.3734	284.0175	0.0169	59.1901	98.7893	1.2107
2011	400	2912	8760	57898	23467	117.752	0.4053	290.5187	0.017	58.6675	98.6558	1.3442
2012	404	2785	8784	58013	23544	110.6688	0.4058	272.6906	0.0172	58.2772	98.7401	1.2599
2013	392	2686	8760	58181	22597	105.8591	0.3884	272.5577	0.0173	57.6454	98.7916	1.2084
2014	384	2563	8760	58228	24694	113.9334	0.4241	268.6528	0.0156	64.3073	98.6994	1.3006
2015	352	2319	8760	58275	21850	87.8544	0.3749	234.312	0.0161	62.0739	98.9971	1.0029
2016	363	2339	8784	58290	23732	103.2281	0.4071	253.5464	0.0153	65.3774	98.8248	1.1752
2017	378	2508	8760	58306	20680	94.2196	0.3547	265.6465	0.0183	54.709	98.9244	1.0756
2018	341	2374	8760	58372	21018	90.306	0.3601	250.8013	0.0162	61.6364	98.9691	1.0309

3.5. Average service availability index (ASAI)

The result of the average availability index of the APO 132 kV/33 kV distribution system is presented in the ASAI column of Table 2. The system was most available in the year 2015 with an ASAI value of 98.9971%. The system was least available in the year 2011 with an ASAI value of 98.6558%. This shows that there are more forced failures in the distribution system, which is due to the switchgear and Transformer failures. The system recorded the highest availability index in the year 2015. Other years with relatively high availability indexes are 2017 and 2018, while the least availability was recorded in the year 2011.

3.6. Average service unavailability index (ASUI)

The ASUI column of Table 2 presents the result of the unavailability index of the APO 132 kV/33 kV distribution system. The year 2011 had the highest value of ASUI, with a value of 1.3442% while the lowest value of ASUI was obtained in the year 2015, with a value of 1.0029%. Because ASUI is the opposite measure of ASAI, it can be concluded that the system was most unavailable in 2011 and most available in the year 2015. The highest mark of unavailability was recorded in the year 2011, while the lowest mark was recorded in the year 2015.

4. INFERENCE

The practical implications of a high MTBF of an electric feeder are:

- Increased Reliability: The probability of the feeder failing is extremely low, which reduces the frequency of outages and disruptions.
- High MTBF leads to lower cost of maintenance of the grid and vice versa.

- Increased uptime: the feeder remains operational for longer periods, ensuring a consistent power supply to connected loads.
- Improved grid stability: the failure rate reduction contributes to a more reliable and stable power grid.
- Increased customer satisfaction: fewer outages and disruptions result in higher customer satisfaction.

Therefore, feeders 9 and 11 performed better than the other feeders. Also, the practical implications of MTTR are discussed below:

- Longer duration of outages: when a failure occurs, it takes longer to repair, leading to extended downtime.
- Increased downtime costs: the longer the repair time, the more the quantity of undelivered energy and hence, lost productivity, replacement power costs, and revenue loss.
- Reduced grid resilience: A high MTTR means the feeder remains forced out of service for an extended period, potentially triggering cascading failures or straining the grid.
- Decreased customer satisfaction: Longer outages lead to frustrated customers, which could damage the reputation of utilities and strain the relationship between the stakeholders.
- Reduced overall efficiency: High MTTR can indicate inefficiencies in the repair process, either through the use of a quality workforce, potentially impacting the overall performance of the grid.

Therefore, feeder 3 performed better than the other feeders.

5. CONCLUSION

This paper analyzed the reliability performance of the 132/33 KV Transmission substation in Abuja, Nigeria, through the historical data collected from the APO substation from 2009 to 2018. The probability approach was applied to determine the daily outage feeder's reliability using Reliability, availability, MTTR, Failure rate, Distribution indices, and MTBF. There were more forced failures in the distribution system from the year 2013, which caused a reduction in the number of interruptions with the increased number of customers connected to the distribution network. Due to the application of smart energy meters, the use of prepaid energy meters has helped to regulate energy demand, reduce network overloading, especially during peak hours, and minimize the cost of energy consumed. The system interruption duration is extremely high, which causes feeder 1 to have the highest failure rate of the APO 132 kV/33 KV distribution network. There are more forced failures in the distribution system due to switchgear and transformer failures. The result shows that the system was most available in the year 2015 with an ASAI value of 98.9971%. The system was least available in the year 2011 with an ASAI value of 98.6558%. However, the system has the highest duration of outage in the year 2009 with 3112 hours of aggregated outage and 3988 interruptions while the year 2015 has the lowest duration of an outage with 2319 hours but recorded 352 interruptions. The substation should use a proper control mechanism to monitor the state of MTBF and downtime for reliability and availability improvement in the network. Artificial intelligence is also recommended to ascertain the effectiveness of the network. Furthermore, the application of technological advancements such as IoE, IoT, and service robots will reduce outage time and maximization of component revenue. There should be considerations on methods to make the substation network smarter by data integration and collection through autonomous robotics, IoT, analytical big data systems, cognitive systems, artificial intelligence (AI), virtual reality, and augmented. Finally, smart grid should be encouraged in remote and rural areas to reduce the strain on the national grid, automation of the entire network to facilitate the resolution of faults and around substation feeders, and the implementation of the study's findings is anticipated to help electricity experts enhance the design, planning, and operation of distribution substations.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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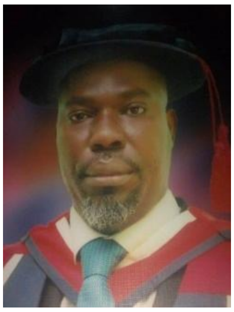

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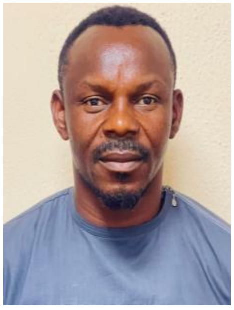

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