Assessment Evaluation of Nigeria's 330kV Electric Power System Reliability Indices for Benchmarking and Operational Improvement Planning

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Abstract. This work determines the reliability indices of the Nigeria 330kV electric power network, which is susceptible to disturbances. Besides, the network configuration is inadequate as it is vulnerable, resulting in transmission line outages. The cardinal object, therefore, is to benchmark the indices against established standards to enable effective operational improvement planning. First, a simulation was conducted using the Electrical Transient Analyzer Program (ETAP) and validated with the Power System Simulator for Engineering (PSS/E) software to assess bus voltages, line flows, and system losses. Subsequently, the ETAP software was applied to determine reliability indices such as the System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), Average Service Availability Index (ASAI), Average Energy Not Supplied (AENS) and Expected Energy Not Supplied (EENS). The simulation results obtained for SAIFI, SAIDI, CAIDI, and ASAI on the test network are 3.2684 f/customer. yr, 9.4140 hours per customer in a year, 2.880 hours per customer interruption, and 0.9989 respectively. Likewise, the AENS with gave a high value of 1360.9340 MWh/customer. yr indicating that on the average, customer is are expected to lose access to 1360.9340 MWh of energy annually. Furthermore, the high value of EENS estimated at 55,798.300 MWh/yr means that the power system is expected to fail to supply 55,798.300 MWh of electricity in one year due to various incidents of failure. These values were compared with the standard IEEE values and were found to be outside the threshold; thus, making it imperative that the indices be utilized to undertake further work that would result in improved and efficient operation of the national grid.

Introduction

As dependence on power continues to rise, the underlying inadequacies of power systems that have made them unreliable should be examined and remedied. The spate of perturbations in the Nigerian power system engenders uncertainties, and risks that manifest in outages and consequential commercial losses, which often result in power failure and operational challenges [1]. In Nigeria, for example, there is no established correlation between the grid available generation and the historical actual demand profile in Nigeria's power system operations. Grid generation is largely non-dispatchable while, on the other hand, demand is, in most cases, non-conforming. When generation is available, demand may (or may not) be adequate; conversely, when there is much load (demand) to be served, available generation may (or may not) be adequate. This incongruous operational trend, attributable to system unreliability, often results in unplanned outages that periodically leave end-users without electricity for long [2-4]. The importance of a reliable power supply cannot be overstated since any interruption to the supply has consequences for its users [5]. Additionally, as the power grid is undergoing several changes due to decarbonization, increased electrification, and penetration of renewable energy, power system planning is becoming even more crucial due to

increased reliability issues. Therefore, these high-risk conditions impact on how the grid is designed and operated to maintain secure and reliable power supply [6].

The reliability of an electric power system is its ability to supply power to users without degradation of the power being delivered [7]. It is one of the yardsticks that can be used to measure the performance of the grid by carrying out a reliability analysis [8]. The reliability analysis uses analytical tools/indices to quantify and monitor the reliability of a system and to track the improvements or failures in the system's reliability [9,10]. To assess the reliability of the system, basic indices based on frequency and duration of interruption and outages are system point indices and customer point indices such as SAIFI, SAIDI, CAIDI, and ASAI [11,12], as well as EENS, and AENS [13]. The analysis of reliability is important to study the impact of equipment and system failure due to several types of faults that may appear in the system. The reliability analysis can suggest the period for planned maintenance of a component in a power system [14].

Literature Review

Several studies have been conducted over the years in relation to reliability evaluation of the power system. The study by [15] gave the outcome of reliability indices obtained through analytical methods. The technique utilized the Monte Carlo method to estimate the performance indices of the reliability of load points and feeders. Key reliability indicators, such as SAIDI and SAIFI, were systematically determined using failure data collected annually from the Transmission Company. The work by [16] calculated the probability based on the solar power generation capacity levels and outage conditions. After that, other indices plus CAIDI, SAIFI, and SAIDI were computed. The results were from the solar photovoltaic (PV) plant tied to the 132kV system in Diyala, Iraq, which was used to find the system's weakest points. A hybrid data-driven strategy in the work by [17] was used to achieve an assessment of grid reliability in the offline training and online evaluation modes. The results showed that the method proposed achieved an online solution of second-level reliability indicators with some level of accuracy. Building on this work, future studies should focus on establishing a more comprehensive reliability evaluation model tailored to the dynamics and complexities of integrated energy networks. Also, the study by [18] introduced a reliability approach that effectively characterized various equipment linked to the grids, accounting for diverse stress and aging factors. The reliability assessment was determined for CAIDI, CAIFI, SAIFI, SAIDI, and ASAI. As a direction for further research, the work can focus on evaluating the reliability of individual components and their cumulative impact on overall power system adequacy, particularly in the context of increasing system complexity and integration.

The review also covers reliability works carried out on the Nigerian power system. The research by [19] presented the modeling and evaluation of the reliability of the Auchi and Government Residential Area (GRA) feeder in a distribution network using SAIDI, SAIFI, and CAIDI. From the analysis, the results show that in 2016 and 2018, the Auchi feeder was more reliable than the GRA feeder based on the SAIDI, SAIFI, and CAIDI, while in 2017, the two feeders had the same index. The Auchi feeder was more reliable than the GRA feeder between 2019 – 2021, as indicated by the SAIDI and SAIFI. The study's findings give vital information to help increase the system's reliability and overall performance of the Auchi network. However, the study can be extended to cover the larger grid system. In a related development [20] carried out a reliability assessment for the Greater Port Harcourt 33kV feeder at Rumuosi Transmission Station feeding Port Harcourt International Airport. The results of the reliability assessment on SAIDI for January - March 2023 were 73.47 hours, 65.71 hours, and 67.59 hours. Similarly, the results of reliability assessment on SAIFI for January - March 2023 were 23.88, 21.24, and 21.94 interruptions per customer respectively while results on CAIDI for January - March 2023 were 3.08hrs, 3.09hrs, and 3.08hrs.

In another study, [21] investigated the assessment of power transformer reliability with an emphasis on the transmission network within the Rivers State of Nigeria. The focus of the study covered electricity consumers, personnel, and business operators using descriptive surveys. The work can be extended to more technical details such as the determination of the reliability indices. Also, the study by [22] evaluated the reliability of power supply within the Igwuruta distribution network in Nigeria. Using data sourced from the injection substation, the frequency and duration of outages were analyzed. The base case simulation revealed that earth faults led to the lowest substation availability (72.8%), followed by over-current faults (83.1%) and planned outages (95.8%). Overall, the substation maintained an average annual availability of approximately 93%. When compared to the IEEE ASAI benchmark of 99.9% for distribution substations, this availability is relatively low. However, the introduction of distributed generation significantly enhanced the reliability indices. In a related development, [23] reviewed the state of the reliability of the power system network in Nigeria and compared it with related works in different climes to determine the current practices. The reviewed work shows that most work on reliability outside Nigeria deals with optimization and enhancement of performance, outage prediction, risk analysis, and size reduction, amongst others. On the other hand, most of the research on reliability in Nigeria covered the determination of how reliable a system can be using the indices which could either be from the customer or load perspective. Therefore, future research should focus on network optimization and the determination of the effect of poor reliability on a given network. The work by [24] studied the outage management and reliability indices of four 11kV feeders for one year. The results were computed for different reliability indices such as SAIFI, SAIDI, ASAI, and others. The results show that more improvement is needed in the distribution network.

Additionally, in studies focused on high-voltage networks, the work by [25] employed the transmission lines contributing to the Energy Not Supplied (ENS) indicator as a quantitative measure to enhance network resilience through targeted transmission line redundancy. The findings demonstrated that incorporating redundancy significantly mitigated the effects of line failures, thereby promoting a more stable and reliable power supply. However, the study did not include other reliability indices for comprehensive benchmarking. Furthermore, [26] investigated the impact of Distributed Generation (DG) on the reliability of the Yola Electricity Distribution Company (YEDC) network. The results indicated notable improvements in reliability metrics with DG integration- SAIDI improved by 69.4%, SAIFI by 40.5%, and CAIDI by 29.7%, while ASAI increased from 0.830924 (without DG) to 0.960587 (with DG). The study suggests that extending this approach to the high-voltage transmission network could yield broader benefits across the entire power grid.

This research determines and evaluates the reliability indices of the 330kV transmission network of Nigeria. The network was modeled using the ETAP and validated with the PSS/E program. The ETAP software was applied to determine the reliability indices of the Nigerian grid study on account of its advanced tools, suited for power system analysis and reliability assessment. The uniqueness of this work may be viewed from the following perspectives.

This study presents the reliability assessment of Nigeria's 330kV transmission network using uniquely sourced operational and outage data from the national grid operator—data not previously utilized in existing literature. Unlike most prior works focused on lower voltage distribution networks (11kV and 33kV), this research developed and calibrated a comprehensive 330kV transmission system model in ETAP and PSS/E to compute key reliability indices (SAIFI, SAIDI, CAIDI, ASAI, AENS, and EENS). The resulting indices were critically evaluated against IEEE benchmark standards, offering a more accurate and system-wide reliability characterization of Nigeria's high-voltage transmission grid.

The remaining sections are organized as follows: Part 2 covers the literature review, while Part 3 provides the reliability indices. Part 4 presents materials and methods, Part 5 dwells on results and discussion, while Part 6 gives the conclusion.

Materials and Methods

Reliability analysis is essential in power system studies, with commonly used indices including: SAIFI, SAIDI, CAIFI, CAIDI, and ASAI amongst others [5, 27-29].

a) SAIFI

SAIFI measures the average number of service interruptions experienced by each customer over a given time period, as expressed in Eq. 1 [7, 27, 30]:

$$SAIFI = \frac{\sum_i \lambda_i N_i}{\sum_i N_i} \tag{1}$$

Where; N_i is the number of users at the load point i and λ_i is the failure rate

b) SAIDI

SAIDI is the average duration of the customer's power outage over a year. The SAIDI is calculated using Eq. 2 [7, 27, 30]:

$$SAIDI = \frac{\sum_i N_i U_i}{\sum_i N_i} \tag{2}$$

Where; U_i represents the average annual power outage time of an outage event i

c) CAIDI

CAIDI is the average duration of power outages per customer over a year, and it is shown in Eq. 3 [7, 27, 30]:

$$CAIDI = \frac{SAIDI}{SAIFI} \tag{3}$$

d) CAIFI

CAIFI is the average number of power outages per customer in a year. It is expressed mathematically as shown in Eq. 4 [7, 27, 30]:

$$CAIFI = \frac{\sum_i \lambda_i N_i}{\sum_{j\epsilon\rho} N_j} \tag{4}$$

Where; ρ is the set of load points where the outage occurred.

e) ASAI

ASAI represents the ratio of the total time a customer receives uninterrupted power supply over a year to the total number of hours in that year, and it is expressed mathematically in Eq. 5 [7, 27, 30]:

$$ASAI = \frac{8760 - SAIDI}{8760} \tag{5}$$

f) EENS

The EENS is defined as the amount of energy the system fails to deliver to consumers over a given period as a result of system contingencies or failures [31]. The EENS is calculated using Eq. 6 [32, 33]:

$$EENS = \sum_{j=1}^{m} \left(P_j * t_j * p_j \right) \tag{6}$$

Where; P_j is the load curtailed in scenario j, t_j is the duration of outages in hours, while p_i is the probability of occurrence of scenario j, while m is the total number of contingencies or failure scenarios.

g) AENS

The AENS index quantifies the average energy not supplied to consumers over a specified time period. It can be calculated using Eq. 7 [32, 33]:

$$\text{AENS} = \frac{\sum_i P_i * t_i}{\sum_i D_i} = \frac{\text{ENS}}{\sum_i D_i} \tag{7}$$

Where; P_i represents the measure of work lost due to outages, while D_i indicates no energy delivery due to interruptions.

h) Reliability Performance Compared to the IEEE 1366 Standard

The reliability indices presented in this section are compiled from the reviewed literature. These findings offer illustrative examples and highlight the varying performance levels of power systems across different regions globally. It is noteworthy that IEEE Standard 1366 offers benchmark values for network reliability indices, as presented in Table 1.

Table 1. Reliability indices of countries compared [34].

S/N	Reliability Indices	SAIDI (hr/year)	SAIFI (interruptions/ yr)	CAIDI (hr)	ASAI (%)
1	IEEE 1366	1.50	1.10	1.36	99.9999
2	India	0.27	0.17	1.62	----
3	Algeria	45.0	1.40	----	----
4	Egypt	1.27	0.09	14.11	----
5	Kenya	11.5	4.5	2.6	----
6	USA	4.08	1.49	2.05	99.91
7	UK	1.50	0.80	1.67	99.96
8	Australia	0.93	0.80	1.16	----

The data obtained from the Transmission Company of Nigeria (TCN) shows that Nigeria's grid network is made up of 330kV and 132kV transmission lines that supply power to the different load centers. The records obtained from TCN indicate that there are 52 numbers of 330/132kV substations, 171 numbers of 132/33kV substations, and over 11,000km of 330kV transmission lines made up of single and double circuits. The indicative data used to determine the reliability indices are computed and presented in Table 2.

Table 2. Outage data from the System Operator.

Date	330kV Lines	Duration (Mins)	Load (MW)
:	:	:	:
:	:	:	:
06/04/2023	Afam/Alaoji 330kV line 1	93	108
31/05/2023	Afam/Alaoji 330kV line 1	70	149
31/05/2023	Afam/Alaoji 330kV line 2	206	145
27/05/2023	Ajah/Alagbon 330kV line	338	51
:	:	:	:
08/06/2023	Ugwuaji/Makurdi 330kV line 2	331.0	407
10/06/2023	Ugwuaji/Makurdi 330kV line 2	6.0	306
24/06/2023	Ugwuaji/Makurdi 330kV line 2	15.0	119
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The data used are for a period of about twelve months in the year 2023. It covers the 330kV lines affected; duration of outage; load loss during the outage, and the customers affected. From the data collected, the number of failures (594) and the time period considered, the failure rate as shown in Eq. 8 was computed thus:

$$\text{Failure Rate } (\lambda) = \frac{\text{Number of Failures}}{\text{Time Period (hours)}} \tag{8}$$

Therefore, the computed failure rate of 0.0678 was obtained for the period covered by the data provided by the grid operator.

i)   Modelling and Simulation of the 330kV Network

The power flow simulation determined the bus voltage magnitude, branch loading, and losses. The peak model of 5003MW achieved by the grid in May 2024 (daily broadcast report from the Transmission Company of Nigeria) was used as the base case generation. The ETAP and PSS/E software were used to model the grid using the parameters in Table 3.

Table 3. Parameter for the power flow.

S/N	Parameter	Value
1	Generation	5003.1 MW
2	Load	4959.5 MW
3	Losses	43.8MW

The single line diagram showing the 330kV network of Nigeria is shown in Fig. 1.

Fig. 1. 330kV network of Nigeria.

j) Procedure for Reliability Analysis

After obtaining a converged power flow solution for Nigeria's 330kV network, reliability indices were determined based on the following procedure. The flow chart for realizing the reliability indices of the 330kV network of Nigeria based on the ETAP program is shown in Fig. 2.
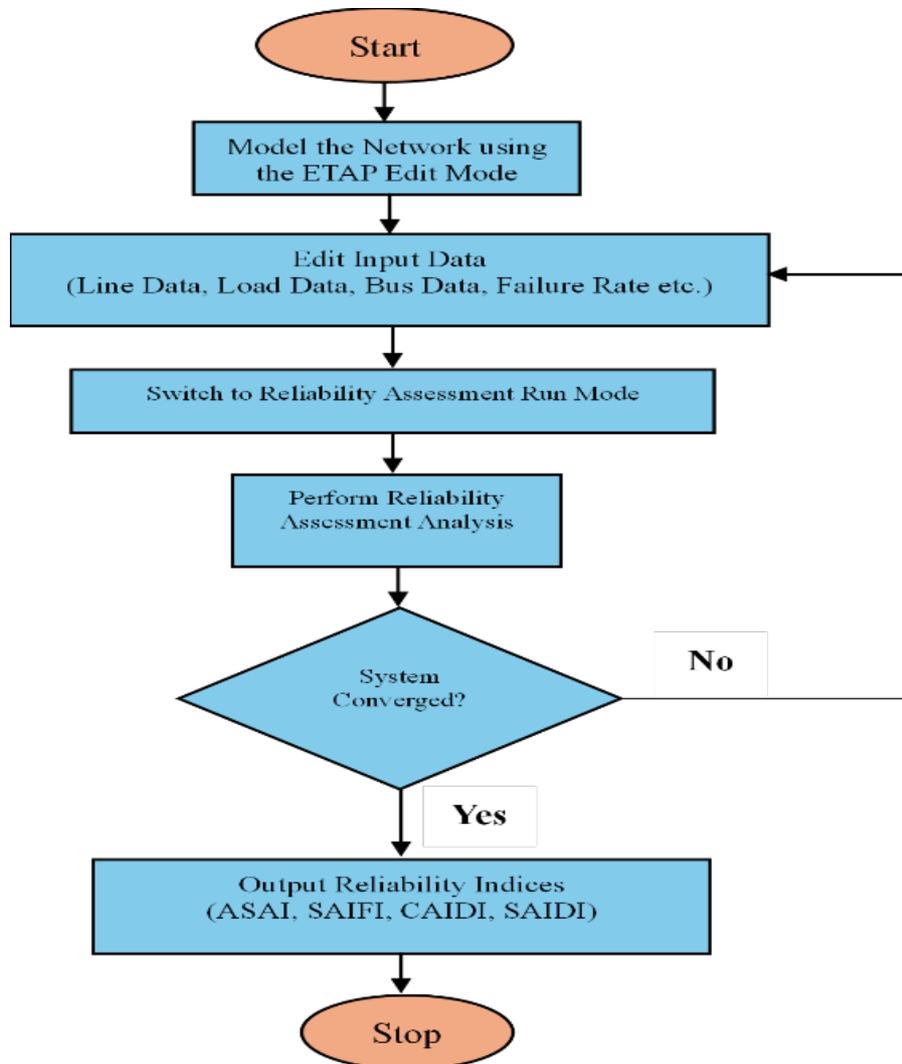

Fig. 2. Flow Chart for the ETAP-based reliabilty assessment.

Results and Discussions

a) Steady-state Power Flow Results

The ETAP and PSS/E programs were used to obtain a converged power flow. The results of the steady-state simulation in ETAP are presented in the single-line diagram shown in Fig. 3.
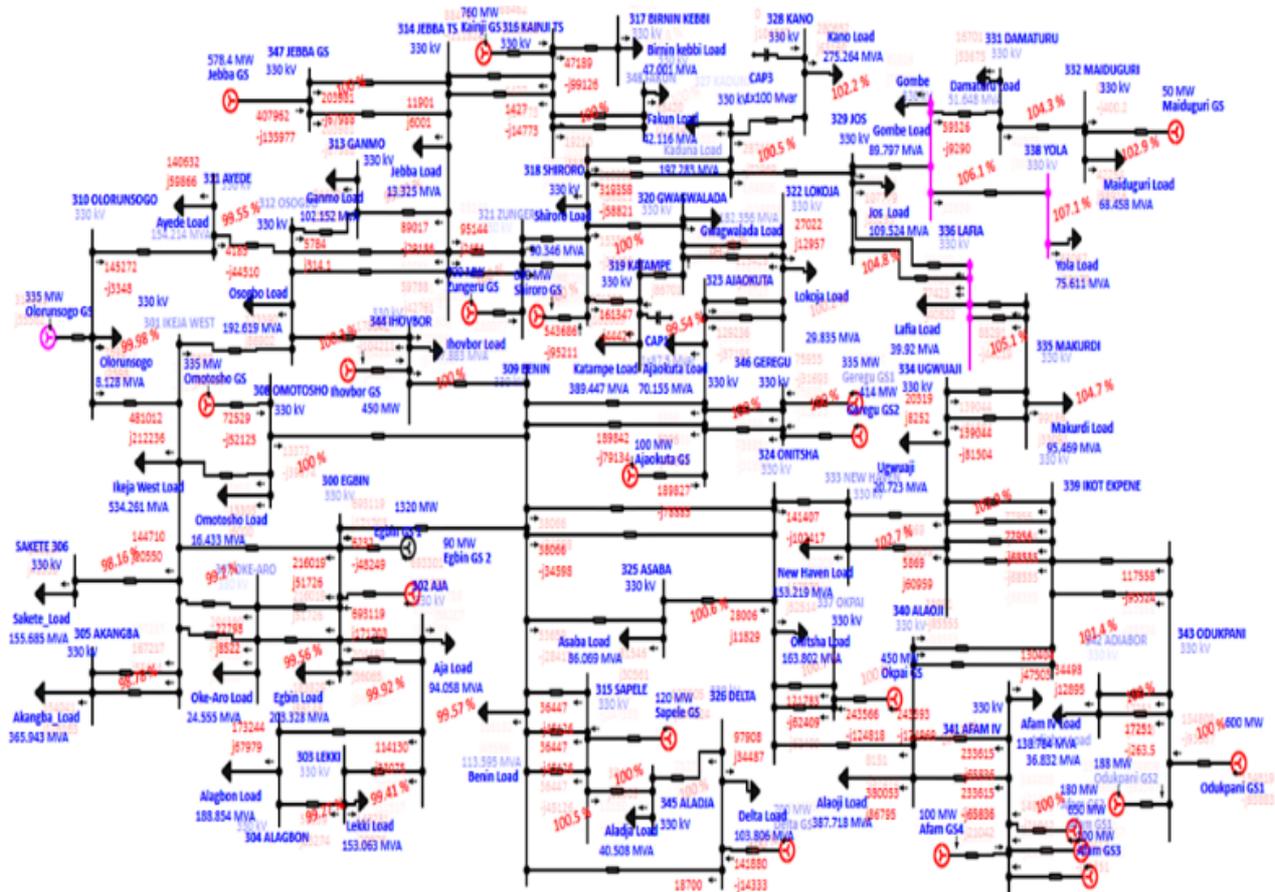
Fig. 3. The single-line power flow diagram in ETAP.

The power flow parameters for the 330kV network of Nigeria were modeled using the ETAP program as shown in Table 4.

Table 4. Power flow results in ETAP.

S/N	Parameter	Value
1	Generation	5003.285 MW
2	Load Demand	4959.478MW
3	Power Losses	43.807MW

Fig. 4 shows the total generation and load parameters that were used to model the network in the PSS/E program. The PSS/E program was used to validate and model the power flow parameters in Table 3.

Fig. 4.

Power flow results in PSS/E

Following the power flow simulation, the result of the voltage profile was computed for the ETAP and PSS/E program in Fig. 4. The power flow results indicate a total grid generation of 5,003.3 MW, serving a system load of 4,959.5 MW.
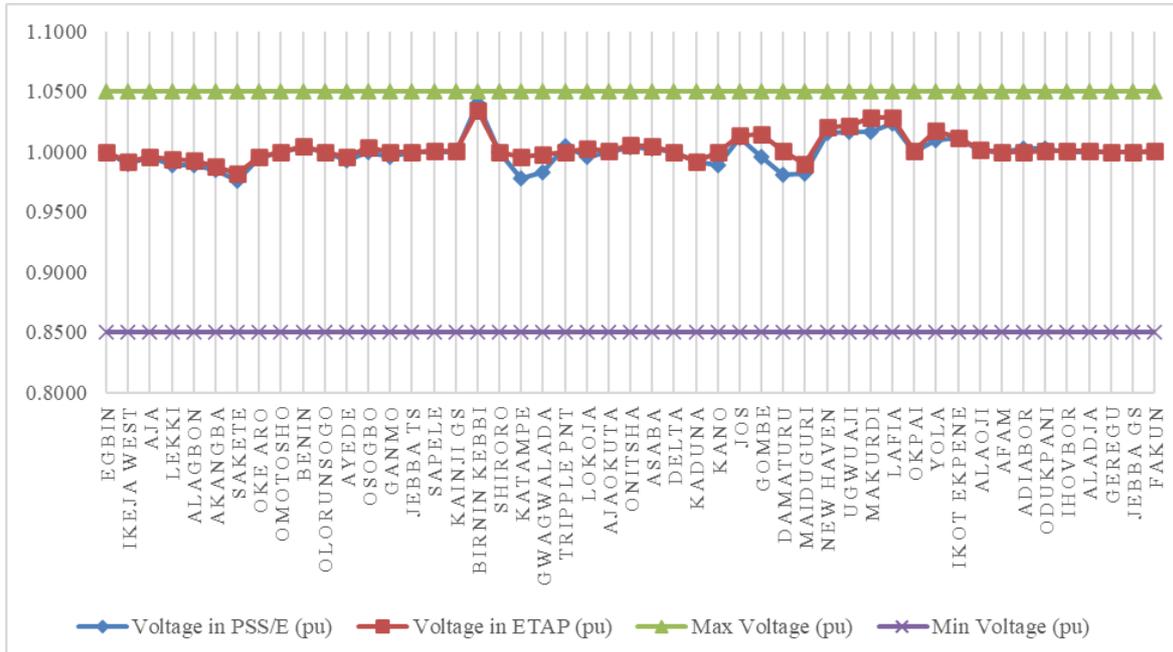

Fig. 5. Voltage profile of the 330kV buses.

Fig. 5 shows the bus voltage magnitudes for the 330kV network of the Nigerian grid in both ETAP and PSS/E programs. The 330kV voltages are within the acceptable limits of 0.85pu - 1.05pu as specified in the Grid Code. With the successful calculation of the power flow parameters, the reliability analysis was determined in the second stage.

b) Results of the Reliability Evaluation

The reliability indices of the network correspond to the results of the work by [35]. Based on the data provided by the System Operator in Table II, the failure rate was determined and used to calculate the SAIFI, SAIDI, CAIDI, ASAI, AENS, and EENS using the ETAP program. The results of the reliability assessment as determined from the ETAP program are shown in Table 5.

Table 5. Reliability results for the 330kV Network.

S/N	Reliability Indices	Value
1	ASAI	0.9989
2	SAIDI (hr/customer.yr)	9.4140
3	SAIFI (f/customer.yr)	3.2684
4	CAIDI (hr/customer interruption)	2.880
5	EENS (MW hr/yr)	55,798.300
6	AENS (MW hr/customer.yr)	1360.934

Table 5 shows the summarized results of reliability indices for the 330kV Nigeria transmission network. From the results, SAIFI has a value of 3.2684 f/customer. yr, which indicates the average frequency of interruptions during the year. The SAIDI is equal to 9.4140 hr/customer. yr - depicting the average duration of power outages per year. CAIDI is the ratio of SAIDI to SAIFI, with a value of 2.880 hr/customer interruption. This implies it takes 2.880 hours to restore power whenever an interruption or a major failure occurs in the system. Likewise, the AENS which gave a high value of 1360.9340 MWh/customer. yr indicating poor reliability. This high AENS value indicates that on the average, customer is are expected to lose access to 1360.9340 MWh of energy annually. Furthermore,

the high value of EENS was estimated at 55,798.300 MWh/yr. This means the power system is expected to fail to supply 55,798.300 MWh of electricity in one year due to various failures. Given the results, the SAIFI, SAIDI, CAIDI, AENS, and EENS are outside the acceptable operational range.

One contributing factor to this discrepancy is the short-circuit (fault) levels across the critical nodes in the network, which are largely unknown. As such, accurate determination of circuit breaker types and their rupturing capacities is impaired. This often results in prolonged outage duration of system equipment when they fail catastrophically. Furthermore, the maintenance practice in place is still the primitive form; equipment is left to fail before repairs are undertaken. The reliability-centered maintenance technique, which identifies and resolves incipient faults on equipment before they deteriorate into full-blown faults, has not been adopted. Also, transmission line trace clearing is not mechanized across the expanse of difficult terrains. These factors, amongst others, contribute to the deviations of the base case values from the IEEE standard reliability values.

These reliability indices were compared to the reliability indices based on IEEE 1366 and other countries' indices given in Fig. 6.
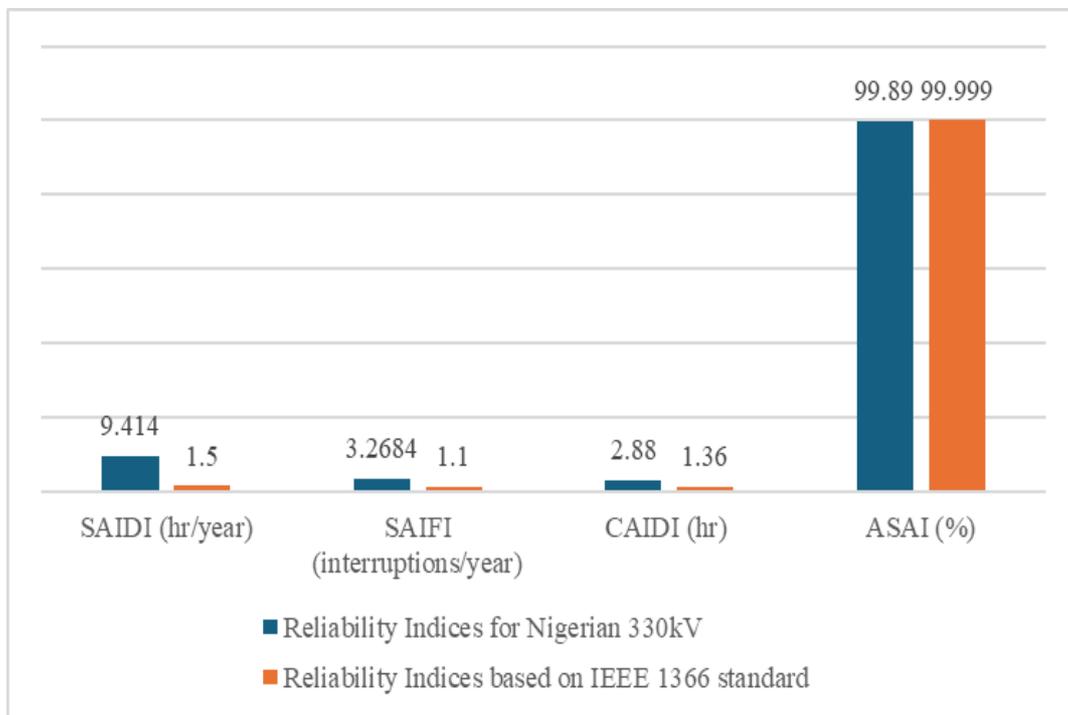

Fig. 6. Reliability indices compared to the IEEE standard.

The results of the reliability indices obtained for the 330kV Nigerian network were compared with the IEEE 1366 standard shown in Fig 6. It was observed that the base case reliability values for SAIDI, SAIFI, and CAIDI were higher than those of the IEEE 1366 standard while the ASAI for the base case was lower than that of the IEEE. This implies that the indices over the period of 2023 were all below the standard IEEE threshold - signifying the imperative for improvement. In the case of the AENS and EENS, it varies across several utilities around the world. Typically, the value of AENS obtained is extremely high suggesting poor reliability, while the value of the EENS depends on how large the network is. It is important to reduce these values to be able to compare with common values from utilities.

When reliability indices are established and benchmarked against standards, such as the IEEE standard, the acceptable performance thresholds are set; as such, deviations are easily computed periodically from the grid operations database. The system operator is then able to hold the transmission service provider accountable for infractions - with consequential penalty imposed for sub-optimal performance. This would drive compliance and culminate in improved performance.

Conclusion

This study undertook a comprehensive reliability assessment of the Nigerian 330kV transmission network using grid and outage data from the year 2023. The network was modeled using ETAP and PSS/E software platforms, and key indices were evaluated to benchmark system performance against IEEE 1366 standards. The analysis yielded values of 3.2684 f/customer.yr for SAIFI, 9.4140 hr/customer.yr for SAIDI, 2.880 hr/customer interruption for CAIDI, and 0.9989 for ASAI. Additionally, the assessment produced values of 1360.9340 MWh/customer.yr for AENS and 55,798.300 MWh/yr for EENS, both of which indicate suboptimal system reliability.

The findings underscore the need for targeted reliability improvement measures. These include adopting reliability-centered maintenance (RCM) practices, optimizing network configurations such as busbar arrangements, implementing correctly set and coordinated protection schemes, and deploying auto-reclosers to address transient faults, which account for line interruptions. These measures, when guided by simulation-based studies, can significantly enhance grid stability and service availability.

Future work will focus on the application of advanced optimization techniques to determine optimal intervention strategies for minimizing outage impacts and improving reliability indices across the network. The ongoing research by the authors aims to develop a decision-support framework that integrates reliability modeling with automated optimization algorithms for enhanced operational planning.

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