The Assessment of Reliability Status of Power System Distribution

M. Odekunle, P.O. Oluseyi, I.D. Adewale, T.O. Akinbulire
Department of Electrical & Electronics Engineering, University of Lagos, Lagos, Nigeria.
Email: dodekunle@unilag.edu.ng, poluseyi@unilag.edu.ng

Abstract
In the era of deregulation of the power sector, it is crucial to devise reliable electricity supply to shield the investment in the industry from negative financial impact on the utility. To ensure that electricity is delivered reliably, then, the substation as a strong nexus for the delivery of electricity must be adequately formidable. In this study, the challenge of poor power delivery is investigated for a typical substation. The Failure Mode and Effect Analysis (FMEA) was adapted for the design of the Risk Priority Number Score software, to reinforce the existing standards mandated for qualitative performance based on IEEE 1366-2000 standard Metrics. The reliability model, herein developed, was tested on the Agbara substation. The system reliability indices were simulated for a period of five (5) years. For further improvement of the network reliability status, the ensuing results inspired the introduction of the Wind Turbine Generators (WTG) which was integrated to the 11kV bus bar. The results obtained from this shows that the reduction in the margin of the energy expected but not supplied (EENS) reduced from 65.316 MW.hr/yr. to 24.555316MWhr/yr in 2018 and from 64.987MWhr/yr to 24.43163MWhr/yr in 2015. Hence, it can be established that the addition of WTG based on the EENS reduction is direct indication of improved reliability of the system which makes the system more reliable.

Keywords: Failure Mode Effect and Analysis (FMEA), Risk Priority Number (RPN), Wind Turbine Generators (WTG).

1.0 INTRODUCTION

The power system reliability is mainly necessary for the safety and security of the network. This is a measure that is heavily utilized for the purpose of placing premium on the network to meet the load requirements. Beyond this, of equal importance is the system's ability to respond to the instantaneous disturbances that arise within the system without resulting in load loss (Jose, 1999) and (Apurba, 2015). For this reason, the assessment of system reliability is paramount and significant in planning and designing of distribution systems. It is often designed to function with regard to least loss of load as well as being cost effective. The planning and maintenance of reliable electrical power systems is essential due to detrimental cost of interruptions and failures that can have grave economic consequences on all stakeholders in the industry; including the utility and its customers. Thus, reliability assessment of the distribution scheme or equipment is crucial to any virile network Lantharthong and Phanthuna (0p and Bertling, Eriksson and Allan (2001).

Over the years, several methods have been developed for decision-making in respect of network reliability assessment. Some of these include: Reliability Cost Maintenance (RCM), Failure mode Evaluation Analysis (FMEA), other classical theories and Bayesian theory. The strategy remains experimental; however, it needs judgment and experience at every point in its execution. The collection of information and decision making may also take a long time, therefore, various numbers of mathematical models to support maintenance planning were suggested Bertling, Eriksson and Allan (2001). In the past, many utilities have been deploying regular or even uninterrupted conditions surveillance and data analysis to replace the manual maintenance routines (Bukhsh, 2013). This has produced commendable reliability of components which gives advanced information on the network conditions for possible early intervention. This has ultimately resulted in healthy network operation as influenced by top-notch maintenance procedure. Thus, reliability assessment is very important in designing and planning of distribution system that operates in an economical manner with little or no interruption of

customer loads Gao, Zhou, Li and Huo (2014). Human development and industrialization imply that in most aspects of life such as health industry, data processing, communications sectors, building, banking and finance as well as homes; reliability and accessibility have become a significant problem. Thus, the system is subject to failure due to automation which then means that more failure that will impact the sustainability of acceptable quality of service provision is experienced. However, the power supply must be kept in operation for effective high return on investments (Balamurugan, 2012).

In systems reliability, there are some factors that provide platform for system interruption. These are natural disasters such as storms, quake, lighting, etc. (Apurba, 2015). In such cases, the Analytical methods are used to evaluate the reliability of the electrical distribution scheme. In addition to this, the thermal overload result in the significantly low voltage collapse; this kind of interruption is often corrected but incipient load rejection (Vishalini *et al.,* 2016). In the same vein, there are various methods of assessing the reliability of power systems. For instance, Monte Carlo simulation was described according to (Apurba, 2015), as the means of evaluating the uncertainty characteristics of the system with connected distributed generators. One drawback of this, is that computer resources restrict the accuracy in the event of the direct current (dc) power flow. The low probability of failures, low voltage and voltage collapse problems cannot be modelled using this method (Vishalini *et al.,* 2016). Other methods have been deployed but they are variously limited in operation due to their respective significant under performance nature.

While investigating the Nigeria's delivery of electricity to customers, there are several multidimensional issues that need immediate intervention for the power industry to break even. Thus, improving the distribution system reliability would address some of these challenges which include intentional planning for future development of distribution networks, reserve connections for back-feeding in the event of fault isolation after disruption, enhanced substations, use of specialized approach in transformer operation to compensate for earth faults or failure and distribution automation that reduces interruption time (Bukhsh, 2013). Thus, in some previous works, the degree of supply reliability is evaluated using the frequency, duration, and extent of electrical supply disturbances. However, it has been shown that when the automatic security device is used, it decreases the detection time, which also implies that the outage time is reduced. This also decreases average correction time (CAIDI), average interruption time (SAIDI), complete network risk and complete energy not provided Maher and Al-Maghalseh (2018).

In other studies, the Failure Mode & Effect Analysis (FMEA) has been deployed for a number of supreme reasons but there are also researches that have discovered that this method needs further improvements. Some of its deficiencies as listed were that it is time-consuming, subjective in analysis and tedious to reproduce its graphs. Despite all these it is still advisable to use the method because FMEA can track products failure modes which can help in predicting future products and design process. Actions are usually carried out to help reduce or eliminate failures in the order of quantitative RPN. As said earlier, many of the reliability assessment proffer outright replacement techniques (Bie, 2011)) while less attention is paid to cheap and less efficient maintenance protocol. Most often than not, set maintenance intervals are used when maintenance strategies are modelled. In direct relationship to the above is the analysis of system reliability as it underpins the distribution network’s power delivery. It is evidently and sufficiently established that this is only done using the HL3 for its development. Hence the theoretical approach to this study is conceptualized on the modeling of the reliability of generation, transmission and distribution networks of an entity. Thus, the fundamental

parameters used to assess the reliability of a distribution scheme can be classified as load point and system reliability indices Lantharthong and Phanthunal (2012) while the basic load point indices are evaluated using the load point failure rate (λ), average annual outage time (r) and average annual unavailability or outage (U), the system reliability index involves interruption indices and energy-oriented indices. Since most energy system interruptions are due to breakdown in power devices in distribution systems, it is crucial for a distribution business to have adequate scheduling instruments to evaluate and enhance its reliability and efficiency. The indices of load point and system reliability are normally determined on an annual basis.

Due to the stochastic nature of power system operation, the indicators for any given year are random values. These are functions of component failure rates, repair times and recovery times within the year. However, a complete representation of these indices involves knowledge of the underlying probability distribution. Putting it on record, it is comparatively simple to calculate the average values as the related analytical methods could be developed for both radial and mesh distribution schemes. As such, an automated FMEA based software algorithm that rely less on human judgement and experience is developed.

2.0 MATERIALS AND METHOD

2.1 Materials

The process of data collection is built on a combination of both quantitative and qualitative approach. The standard quantitative methods are used to analyze variables that relates to the IEEE (1366 – 2000) standard metrics while the qualitative method identified as Failure Mode and Effect Analysis is employed to access and review regulatory performance standards that are currently used in practice. This is aimed at ensuring adequate and reliable system performance in promoting and assessing electricity distribution system reliability performance. The data was collected for a period of five years (2014 - 2018) and all the data used were gotten from Eko Electric Distribution Company (EKEDC). Hence, the Failure Mode and Effect Analysis (FMEA) were used to analyze the potential failure of the distribution system to investigate how it affects the system partially or completely. It then evaluates the severity of the effects of the failure, chances of occurrence and the current controls available to detect or prevent the future failure.

The AGBARA Substation is used as pilot study to evaluate the strength of the EKEDC. The Daily Technical Report/ Log-book Data Outages of the Eko Distribution Network were accessed to generate data on Load Allocation, Number of Feeders in the network, Customers in each network, Number of Failures in a given year, and Average repair time for Failures. This is simulated using the Electrical Transient Analyser Program (ETAP) software (Prem-Prakash, 2014).

2.2 Method

In undertaking the calculations, the applicable steps are as follows:

i. The one-line diagram of the AGBARA distribution network is drawn in ETAP. The one-line diagram is a means of representing power system components with simple electrical power system distribution symbols. It shows the main connections of the components using symbols. It expresses a three-phase system as a single-phase system (Prem-Prakash, 2014).
ii. The average failure rates (λ) and mean time to repair (MTTR) is inputted for the network buses and the distribution cables.

$$\lambda = \frac{frequency\ of\ outages}{number\ of\ hours\ in\ operation} \quad (1)$$

$$\text{MTTR} = \frac{duration\ of\ outages}{number\ or\ frequency\ of\ outages} \quad (2)$$

iii. The reliability analysis was run, and the following indices were generated as output; SAIFI, SAIDI, CAIDI, ASAI, ASUI, EENS and AENS.

The key input variables used for ETAP simulation are: Line diagram of the AGBARA substation, load parameters of the network, number of feeders, number of customers in each feeder, number of failures in a year and average repair time for failures (Prem-Prakash, 2014).

2.2.1 The Risk Priority Number (RPN) Score

In line with the foregoing, the Risk Priority Number (RPN) as a qualitative method developed to evaluate the distribution system reliability was duly implemented. To achieve this, a web-based software solution was designed to calculate the risk priority number (RPN) using the Failure Mode and Effect Analysis (FMEA) based on the core logic modules namely: Measures of failure frequency, Measures of failure severity and Measures of failure detectability. The software features an interface that allows users to input individual variables used in determining the measure of efficiency and reliability.

The software interface was designed primarily using Hyper Text Markup Language (HTML) to provide web page presentation for the deployment of Cascading Style Sheet (CSS) as a web for layout formatting application. The logic used to score the individual variables is embedded within the web application and is written in JavaScript. The results are not stored and no data base was used in the design of this web application. Thus, as depicted in Fig. 1, the RPN web application will allow users to input the variables for determining the measure of efficiency and reliability. It evaluates, analyses all variables upon value submission, consequently calculates a final RPN value and displays the condition of the system.

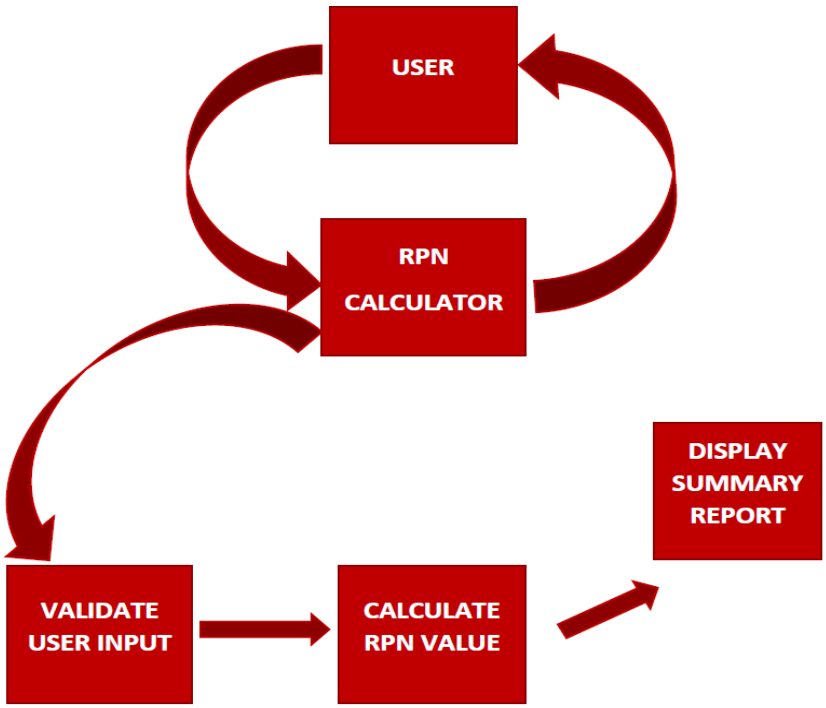


Figure1: A Data flow diagram of the RPN software system

In implementing the RPN web solution, some sample data were used as input variables to generate a test result. Upon running the software, it displayed, at a glance the RPN value as well as the condition status of the system. The Test input used to verify the accuracy of the web

software are: Measures of failure frequency (i.e., failure occurrence), Measures of failure severity (once a fault occurs a lot of consumers will experience black out) and Measures of failure detectability (faults are most times not detected on time).

Often times, measure of failure severity is deployed in judging risk importance, but using it alone is fraught with the tendency for users wanting to inflate the severity score so as to give it urgent attention; as such, this may not really reflect the risk based on the failure but how much someone wants the failure rectified. However, the adoption of the RPN focusses on risk exposure, thus, it allows the algorithm to assess the priority of fault rectification while relating priority with the knowledge of risk from different viewpoints (provider and consumers' viewpoints). In other words, RPN allows for multiple input measures for a robust risk assessment. For better understanding of this ranking process, the Risk Priority Number (RPN) and Criticality analysis could then be evaluated using the following ranking procedure in eqn (3) – eqn (5).

$$\ell = Ъ * ₡ * \Delta \quad (3)$$

$$Ɽ = Ъ * ₡ \quad (4)$$

and then,

$$\ell = Ɽ * \Delta \quad (5)$$

where, ℓ (script small L) represents RPN,
Ъ (Cyrillic capital letter Yat) represents Severity,
Δ (increment del) represents Detectability,
₡ (Cruzeir sign) represents Occurrence and
Ɽ (Latin capital letter R with tail) represents Criticality.

From the above equations, it is clear that the criticality number (Ɽ) is really important for identifying those failure modes that affect or cause unsafe or undesirable conditions whether or not they can be detected beforehand and mitigate them. The Risk Priority Number (RPN) would provide information on which subsystem needs attention or which subsystem presents unacceptable risk level.

2.2.2 Design of Failure Mode and Effect Analysis (FMEA)

In Failure Mode and Effect Analysis, it is essential to determine some parameters that are paramount for generating the status of system reliability. To this end; the four major stages of activities as identified are namely; identification of system, quantifying of risk, evaluation of system high risk status and re-evaluation of risk. Each of these stages is as discussed below.

Stage I: Identifying the System

This stage involves finding out information of the system like, the length of the line, the current demand, the load allocation, consumption and outages. The location and total number of consumers connected to the network is also determined. All the components in the system are identified and their roles or functions are understood. All the possible failure modes are identified and the causes or condition at which these failures occur. The effects of these failures of the system are also to be identified. The methods of detection of these failures are found and prevention of these outages.

Stage II: Quantifying Risk

The network is divided into its individual substations with the following information: potential failure mode of each component, potential effect of the failure and causes or mechanism of the failure. The following are ranked based on the information gotten from above. The occurrence of failure; ranked based on probability of the failure occurring again from 10 (will occur) – 0 (will not occur). The table 1 shows how it is ranked.

Table 1: The Ranking of Failure Occurrence in FMEA Method

Occurrence	Failure Rate	Criteria	Rank
Very High	>1 in 2	Failure is almost inevitable	10
	1 in 3		9
High	1 in 8	Repeated failures	8
	1 in 20		7
Moderate	1 in 80	Occasional failures	6
	1 in 400		5
	1 in 2000		4
Low	1 in 15000	Relatively few failures	3
	1 in 150000		2
Remote	1 in	Failure is unlikely	1

The severity of the effect; is ranked from (10 – 0) based on the effect of the failure on the system, this is shown in Table 2.

Table 2: The Ranking of Severity of the Effects in FMEA Method

Criteria for ranking 'severity'	Effect	Rank
Failure occurs without warning	Deadly	10
Failure occurs with warning	Hazardous	9
System inoperable, with loss of function	Very serious	8
Network operable but with loss of performance	Serious	7
Network operable, but with loss of comfort	Moderate	6
Network operable but with low effect on performance	Low	5
Noticeable effect by most consumers	Very low	4
Noticeable effect by average consumers	Minor	3
Noticeable effect by discriminating consumers	Very minor	2
No effect	None	1

In the detection of the fault; the effective control of power equipment parameters to prevent the occurrence of fault is highly required as shown in Table 3.

Table 3: The Ranking of Detection of Failure in FMEA Method

Chances of detection of failure	Rank
No known controls available	10
Very remote chances of	9
Remote chances of detection	8
Very low chances of detection	7
Low chances of detection	6
Moderate chances of detection	5
Moderately high chances of	4
High chances of detection	3
Very high chances of detection	2
Almost certain of detection	1

Stage III: Correction of High-Risk Causes
In this stage, prioritizing the work to be carried out on the network so as to reduce the failure mode of sub system is carried out. This is made possible through adopting the detailed actions and assigning responsibility to individuals.

Stage IV: Re-Evaluation of Risk
In entrenching this stage; the RPN value is recalculated again; this is done iteratively till a reasonable value of RPN is obtained; which is usually within the range of 100 – 200. Thus, the real-life parameters of network were then subjected to the model herein developed. This implementation selected the AGBARA distribution substation. The system comprised of eleven (11) load buses, one (1) generator bus and three (3) transformers. The one-line diagram of the modelled substation is shown in Fig.2.while the failure rate generation of the original system with and without WTG for the year 2018 are shown in Figures 3 and 4 respectively. So also, Tables 4, 5 and 6 show the ETAP input data, branch input data as well as the branch connection configuration for the calculation.

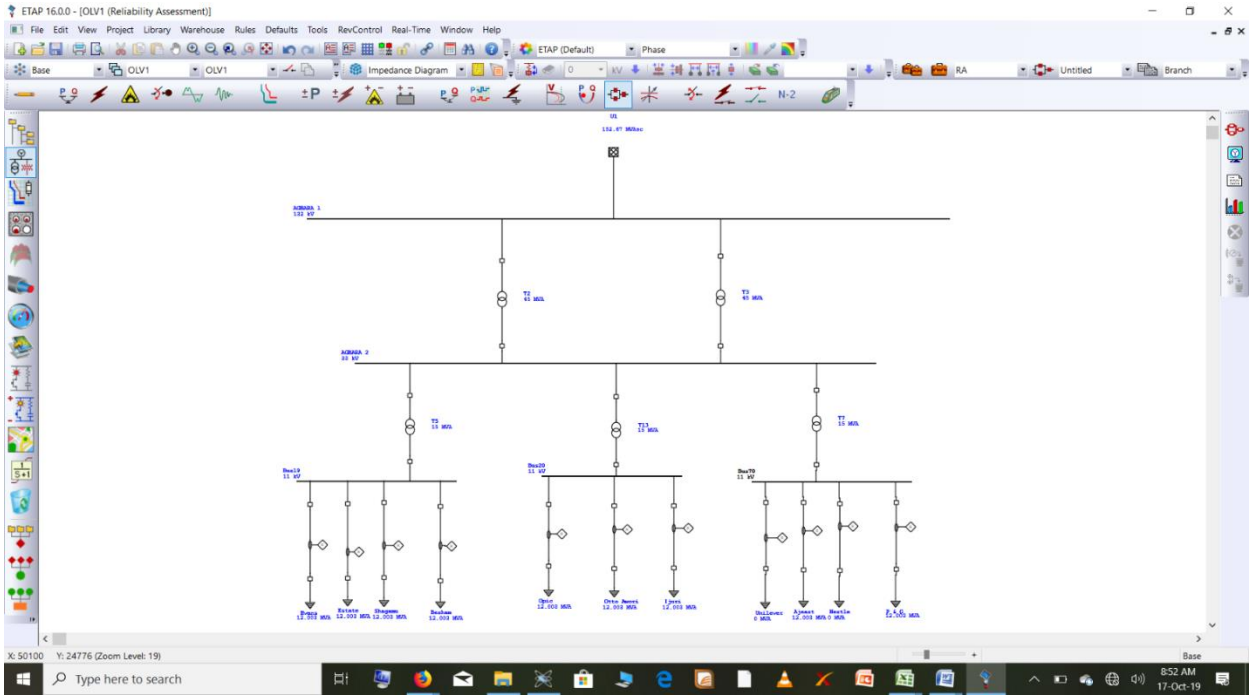


Figure 2: ETAP Model of Agbara Substation

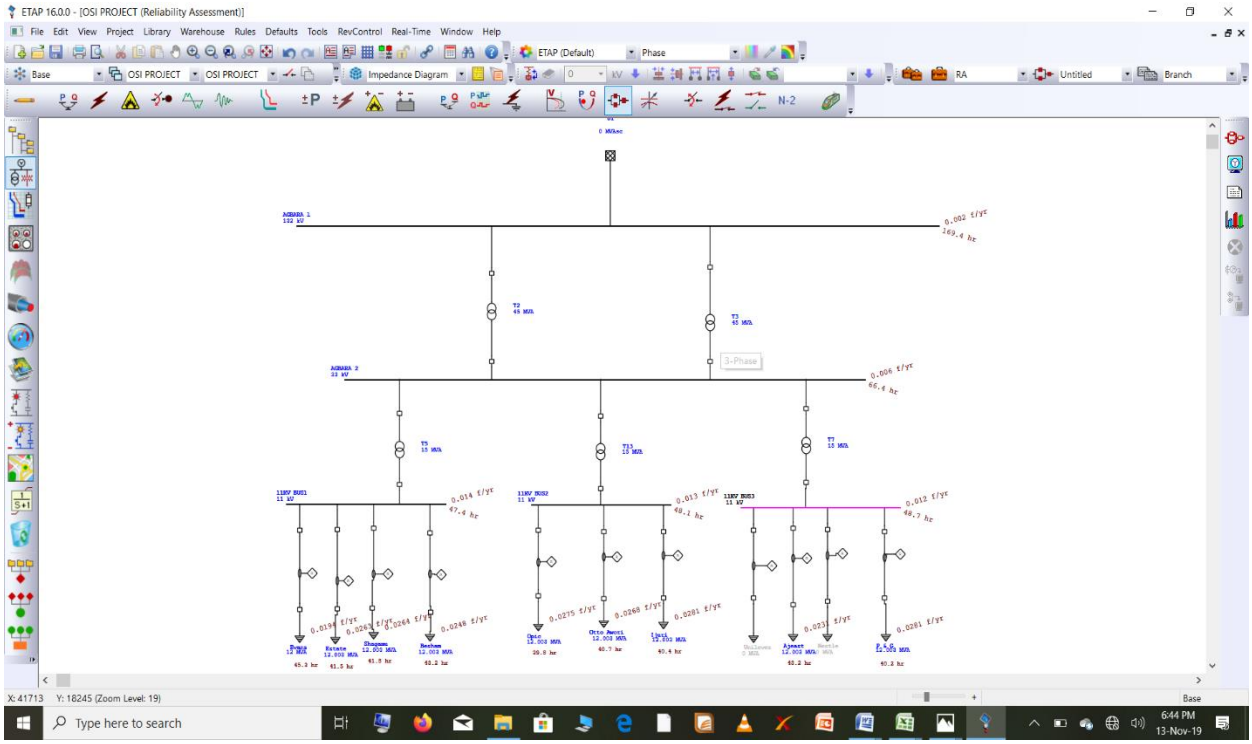


Figure 3: Failure Rates of Original System in 2018

Table 4: Bus Data Input

BUS Identity	kV	λA (f/yr.)	MTTR (hr.)	Switch Time (hr.)	Replacement Available (Yes/No)	Time (hr.)
11kV BUS 1	11.000	0.0020	40.00	1.00	No	10.00
11kV BUS 2	11.000	0.0020	40.00	1.00	No	10.00
11kV BUS 3	11.000	0.0020	40.00	1.00	No	10.00
AGBARA 1	132.000	0.0001	0.50	1.00	No	10.00
AGBARA 2	132.000	0.0010	24.00	2.00	No	10.00

Table 5: Branch Data Input

TRANSFORMER Identity	TYPE	λ_A (f/yr.)	λ_P (f/yr.)	MTTR (hr.)	Switch Time (hr.)	Replacement Available (Yes/No)	Time (hr.)
T2	2W Xformer	0.0050	0.0000	50.00	1.00	No	10.00
T3	2W Xformer	0.0036	0.0000	67.00	67.00	No	39.90
T5	2W Xformer	0.0010	0.0000	3.00	1.00	No	10.00
T7	2W Xformer	0.0010	0.0000	4.00	1.00	No	10.00
T13	2W Xformer	0.0010	0.0000	4.50	1.00	No	10.00

Table 6: Branch Connection

CKT/Branch Identity	TYPE	Connected From Bus	Connected To Bus
T2	2W Xformer	AGBARA 1	AGBARA 2
T3	2W Xformer	AGBARA 1	AGBARA 2
T5	2W Xformer	AGBARA 2	11kV BUS1

The results of the system indices generated using the Original System for 2018 is as shown in Table 7.

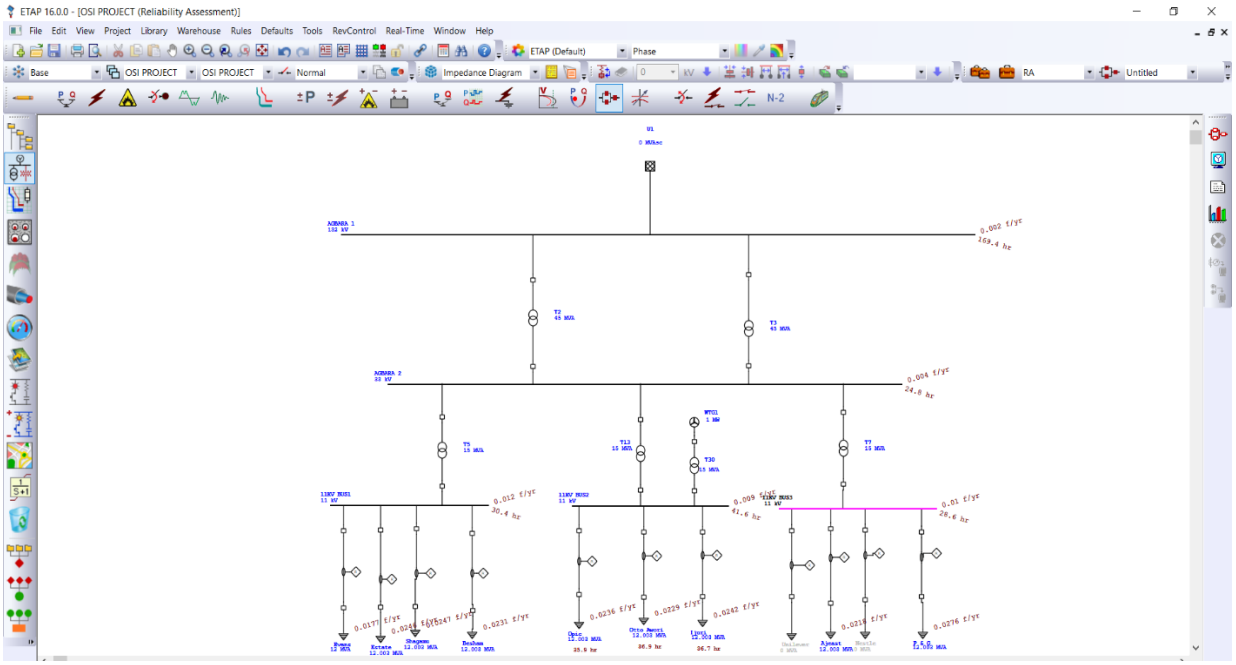


Figure 4: Failure Rates of Original System in 2018 with WTG

3.0 RESULTS AND DISCUSSION

3.1 Results

From the design of RPN scoring process, a number of ranking tables were generated. This is used to develop and evaluate the reliability indices. The occurrence of failure; ranked based on probability of the failure occurring again from 10 (will occur) – 0 (will not occur). The Table 1 above shows how it is ranked. The severity of the effect is as ranked in Table 2. The ranking is from (10 – 0) based on the effect of the failure on the system. So also, in the detection of the fault; the effectiveness of control to prevent the causes of the fault is as shown in the Table 3.
The summary of the Reliability Indices for the period of (2014 - 2018) is as shown in Table 7 while Table 8(a and b) show the comparison of the indices for the years (2015 and 2018) based on Energy Expected but Not Supplied (EENS) for both the Original system and when WTG is added Hall and Bain (2008).

Table 7: Summary of the Reliability Indices of Five Years 2014 - 2018

Year	SAIFI	SAIDI	CAIDI	ASAI	ASUI	EENS	AENS
2014	0.0138	0.6311	47.213	0.9999	0.00007	65.451	7.2562
2015	0.0140	0.6307	46.738	0.9999	0.00007	64.987	7.2207
2016	0.0133	0.6304	46.776	0.9999	0.00007	65.108	7.2334
2017	0.0133	0.6293	47.448	0.9999	0.00007	65.316	7.2573
2018	0.0131	0.6287	47.908	0.9999	0.00007	65.316	7.2573

Table 8a: Agbara Substation Reliability Comparison for the Year 2015

Indices	Original System	System with Wtg Added
SAIFI	0.0140 f/customer year	0.0006753 f/customer year
SAIDI	0.6307 hrs/customer year	0.2380811 hrs/customer year
CAIDI	46.738 hrs/customer interruption	366.157 hrs/customer interruption
ASAI	0.9999 per unit	1.0001 per unit
ASUI	0.00007perunit	0.00002625 per unit
EENS	64.987MWhr/year	24.43163MWhr/year

Table 8b: Agbara Substation Reliability Comparison for the Year 2018

Indices	Original System	System with Wtg Added
SAIFI	0.0131 f/customer year	0.0006657 f/customer year
SAIDI	0.6287 hrs/customer year	0.23732613 hrs/customer year
CAIDI	47.908 hrs/customer interruption	375.32306808hrs/customer interruption
ASAI	0.9999 per unit	1.0001 per unit
ASUI	0.00007perunit	0.00002625 per unit
EENS	65.316MWhr/year	24.555311637MWhr/year

The SAIDI and SAIFI values are much lower with the WTG installed which indicate much better performance. The Expected Energy Not Supplied (EENS) with the Wind Turbine Generator (WTG) installed is much lower than that of the original system, thereby ensuring improved reliability of the system as shown in Table 8.

The Wind Turbine Generator (WTG) is designed to generate an extra 1MW to the system which has a capacity of generating voltages up to 0.69KV. The WTG is then connected to the 11kV feeder with an extra 15MVA, 0.69/11kV transformer added to the modeling to step up the voltage generated by the WTG to 11kV.

3.2 Discussion

The specific findings, discussions and implications of the system indices of AGBARA substation are analyzed using Tables 7 and 8. From the results obtained, it can be observed that no pattern or trend for all the reliability indices during the five-year period while the **EENS** was approximately constant. The system neither improved nor declined (that is a bit stable but not reliable). This implies that proper attention has not been given to improving reliability of the power distribution system in AGBARA substation over the five-year period as shown in Table 7.

Similarly, like the SAIFI, higher values of the SAIDI also indicate poor system performance. The year 2018 records the best performance over the five-year period, in terms of the interruption duration of the system as observed in Table 7 that the customers' satisfaction was very low; this is as a result of the distribution network not able to handle what is being produced due to the state of the power equipment in the country, the types of loads used by the consumers and lack of maintenance of the power equipment.

Likewise, the expected and average energy not supplied varies over the five years in no particular order as shown in Table 7. Meanwhile the National Electric Regulatory Commission (NERC) does not include the IEEE standard metrics as indicators of measures of distribution reliability. From Table 8, the consideration of a hybrid power distribution system shows an improved system

reliability. In addition, amongst other things, the reason for the selection of wind turbine generator over other forms of renewable energy distributed generators is the presence of the vast land available in AGBARA.

The key findings arising from the design of the RPN calculator include the fact that there is no standard software in existence in Nigeria to generate measures of RPN, which helps to determine directly whether the system is reliable or not and can be used by anyone as it is easy to understand and use, once all the required parameters are keyed. Thus, a combination of the findings and results of analysis using ETAP and the RPN, lead to very important conclusions and recommendations as there are numerous adverse consequences of neglecting power system distribution reliability analysis. This can lead to low KV per Capita, low industrial output, creates unemployment, high cost of power and inflation. It also leads to environmental pollution from multiple domestic power generation, loss of revenue and business losses.

4.0 CONCLUSION

The model of reliability assessment has been used to evaluate the existing system reliability. This then leads to the ranking of the risk through the development of a novel technology chart. This has been applied to the distribution substation to test its proficiency. From the available results; the indices show an improved reliability of a distribution network that needs huge investment into the sector by government and private sectors similar to what is happening in transmission and generation sectors. Thus, it is recommended that it is necessary or essential that investment into the distribution network should be further improved for the system reliability to become better than it's currently in existence. Also, the IEEE metrics and RPN Scores forecasts should form part of the benchmarks for evaluating technical proposals in selecting future investors in the Nigeria electricity sector. This should also be used for measuring post investment reliability of electricity supply to customers.

REFERENCES

Apurba, C. Y. (2015). Reliability Assessment of Distribution System at Presence of Distributed Generation, National Institute of Technology, Rourkela, India.

Balamurugan, K. S. (2012). Impact of Distributed generation on Power Distribution System efficiency.

Bertling, L., Eriksson, R. and Allan, R. N. (2001). Relation between preventive maintenance and reliability for a cost-effective distribution system, Paper accepted for presentation at PPT 2001 IEEE Porto power tech. Conference.

Bie, Z. A. (2011). Review on reliability evaluation of new distribution system.

Prem-Prakash, V. A. (2014). Distribution system reliability Analysis using ETAP. International Journal of Advanced Research in Electrical and Electronics Engineering, 24-29

Bukhsh, W. G. (2013). Local solutions of the optimal power flow problem. IEEE Transactions on Power Systems.

Hall, P. J., and Bain, E.J. (2008). Energy storage technologies and electricity generation. Energy policy, 36(12), 4352-4355.

Gao, L., Zhou,Y. , Li, C., Huo, L. (2014). Reliability Assessment of Distribution Systems with Distributed Generators Based on Bayesian Networks, Engineering Review, 34(1), 55-62.

Jose, F. P., (1999). The Value of Reliability in Power Systems, MIT Energy Laboratory.

Lantharthong, T. and Phanthuna, N. (2012). Techniques for Reliability Evaluation in Distribution System Planning, World Academy of Science, Engineering and Technology, 64.

Maher, M. A. and Al-Maghalse, A. (2018). Evaluating the Reliability Worth Indices of Electrical Medium Voltage Network: Case Study, The 8th International Conference on Sustainable Energy

Vishalini, D., Keshavan, B. K., and Raviprakasha, M. S. (2016). A Survey on Methods of Evaluation of Reliability of Distribution Systems with Distributed Generators, International Journal of Engineering Research & Technology, 5(8).