IJAAR PUBLISHING®

Engineering Research Journal | ISSN: 2782-8212
Vol. 5, Issue 4 (2025) | www.ijaar.org/erj

RELIABILITY EVALUATION OF 11KV DISTRIBUTION SYSTEM IN THE PRESENCE OF DISTRIBUTED GENERATION

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ABSTRACT

This paper evaluates the reliability of a typical 11kV distribution system in Nigeria using one year outage frequency and duration data gotten from the utility company. The reliability performance of the system was assessed by determining key reliability indices, and proposes inclusion of distributed generation (DG) to enhance the indices, since the set standard was not met. Electrical Transient Analyzer Program (ETAP) software was used for the simulation. This was done by carrying out reliability study of the existing 11kV distribution network using embedded analytical equations in ETAP; reliability indices were determined, and improved upon by the penetration of PSO optimized distributed generation (1.63MVA) in bus 9 and reliability study was performed with DG deployment. The results obtained show that at the instant of DG injection into the system, average failure rate and average outage duration at load point 6, reduces by 34.2% and 23.8% respectively, then, it continues so up to load point 14. Similarly, at the penetration of DG, there were significant improvement in the customer's oriented reliability indices; SAIFI, 0.4747 to 0.2535f/yr, SAIDI, 13.56 to 8.2585hr/yr, CAIDI, 32.577 to 28.581hr.intr and EENS, 56.216 to 43.376MWhr/yr. The availability index ASAI improved from 86.8 % to 99.85% which is close to the 99.9989% IEEE benchmark.

Keywords: PSO, Electrical Transient Analyzer Program, Distributed Generation, SAIFI, IEEE, ASAI

Okogbule, U. S., & Ekeriance, D. E. (2025). Reliability Evaluation Of 11kv Distribution System In The Presence Of Distributed Generation. *Engineering Research Journal. 5*(4), 1-11. DOI: https://doi.org/10.5281/zenodo.15792822

INTRODUCTION

In this modern age, electricity is an essential requirement for all areas of human endeavor, it has almost now been accepted as a basic human need and it has been asserted that the socio-economic growth and technological development of any nation depends on it [1][2]. The main objective of establishing a power system is to supply all customers with electrical energy as economically as possible with an acceptable degree of reliability and quality [3].In electrical power system, all the generated electricity is consumed by the end users through the distribution system, and it is responsible to feed the electricity demand of all the consumers [4]. Since, distribution system is the connecting bridge between the transmission system and the electricity consumers, evaluating its reliability and devising an improvement strategy is paramount for efficient operation of the power system. System reliability can be defined as the availability or continuity of quality power supply for the consumer service entrance. Distribution system reliability has to be done on the basis of both interruption frequency as well as duration, since the system could be seen as reliable based on frequency of interruption, while not reliable in terms of duration of interruption [5].

Unreliability issues in a distribution network can be as a result of outages, interruptions or failure, and unavailability, which are closely associated with switchgear/protection and control. A distribution system is said to be reliable, if its required function within a specified time period is met. Although, absolute (100%) reliability of distribution systems cannot be guaranteed. However, a very high level (about 99.9%) is aimed at and is being achieved in developed countries [6]. In economy emerging countries, such as, Nigeria, there is mismatch between generated power by available power stations and power demanded by consumers [7]. Due to this, the Utility companies, practices load shedding as a way out to ensure that the available power from each of the distribution feeder from a network get to its respective consumers at any giving time they choose for the customers which is inimical to socio-economic growth and industrialization a the nation [8].

Distribution system account for about 90% of all customer unreliability issues, therefore, improving distribution reliability is to improve customer reliability and satisfaction [9]. This is the motive for this study, to evaluate the reliability of a typical distribution system by determining the key reliability indicators and propose an appropriate improvement strategy, which is penetration of Distributed Generation (DG) in the system, if the results fall outside the acceptable statutory limit, with the intention reducing associated system losses and improving the overall reliability of the network.

Statement of the Problem

The study case distribution network area has been experiencing unreliable power supply coupled with low voltage profile and huge power losses. The utility company supplying power to the area only provides an average of six hours of electricity daily if there is supply, which is inadequate, it can even get worse by not providing electricity to the area for months due to unreliable state of the 11kV distribution system. Due to this inadequate and unreliable power supply, the utility company has yielded to the practice of load shedding, which has in turn led to partial shutdown of businesses in the area that require reliable power supply from grid,: lack of portable water, poor access to functional health care services, lack of quality education and loss of revenue by the utility company. This study seeks to assess the reliability of the study case distribution system by determining key indices and propose the deployment of Distributed generation (DG) into the network to enhance the system reliability and efficiency. Therefore, focuses on assessing the performance and dependability of medium-voltage (11kV) power distribution networks when integrated with distributed generation

(DG) sources, such as solar PV, wind turbines, or small-scale generators. The study examines how DG impacts key reliability indices—including SAIDI (System Average Interruption Duration Index), SAIFI (System Average Interruption Frequency Index), and ENS (Energy Not Supplied), by potentially reducing outage durations, improving fault recovery, and enhancing supply continuity. Challenges such as bidirectional power flow, protection coordination, and islanding operation are also analyzed to determine their effects on system stability. The evaluation helps utilities and planners optimize DG integration while maintaining or improving grid reliability, ensuring efficient and resilient power delivery in modern distribution systems.

LITERATURE REVIEW

In the paper presented by [10], reliability evaluation and improvement of 11kV Karberey-Ramety Feeder II electric power distribution network was carried out. Reliability indices of the network of the network was computed using Failure Mode and Effect Analysis Technique, while a step by step economic analysis was used to determine optimum number and location of automatic switch fulfilling reliability and economic constraints. The results obtained show a significant reduction in customer's interruption cost.

In the research paper presented by [11], reliability optimization of a non-linear transmission network was performed using Genetic Algorithm (GA) based optimization approach. The approach was tested on 33kV transmission feeders within Benin metropolis. The results obtained indicate an appreciable reduction in downtime, increment in MTBF, as well as improvement in reliability and availability of the network.

According to [12], a paper was presented on the assessment of reliability of Cotobie distribution station in Ethiopia, with mitigation strategy using reclosers and disconnectors to minimize urgent and pressing power interruption. The results of the existing network frequency of interruption per year and average interruption duration violates the set reliability indices set by Ethiopian Electric Authority (EEA). When smart recloser and disconnector design model was implemented, the reliability of the network improved significantly.

In the paper presented by [13], reliability assessment of IEEE-RBTS BUS 6 distribution network was carried out. A standardized model of reliability system evaluation was constructed using Failure Mode and Effect Analysis (FMEA) table and the reliability is solved by combining Monte Carlo analysis method. The result obtained show that the method is effective and feasible to quantify the effect of distributed power supply on the reliability.

According to [14], a study on the reliability assessment and enhancement of Dangila distribution system was done with distribution generation being placed at different distance from the supply point. The data from Dangila substation from 2020 to 2021 was used for the assessment. The results obtained by the authors show that as distributed generation was placed further from the supply point, the reliability of the power system improves more significantly.

METHODOLOGY

Reliability studies of the study case network was performed using analytical equations embedded in Electrical Transient Analyzer Program (ETAP) software to determine load and customer's based reliability indices. In order to minimize unavailability and enhance reliability in the network, Particle Swarm Optimization (PSO) technique, implemented in Matrix Laboratory (MATLAB) was used to determine the optimal size and location to place the Distributed Generation (DG) on the network. Then, reliability studies was done again in

ETAP with optimized DG placement on the network. Tables 1, 2 and 3 show load data, average load outage data and line impedance of the distribution system.

Table 1: Load Data at 80% P.F

Bus ID	Transformer (MVA)	Input/Output (KV)	Unit	Load (MVA)
2 – 3	15	33/11	1	2.6
5 – 6	1	11/0.415	1	0.325
7 – 8	0.75	11/0.415	1	0.325
9 – 10	0.5	11/0.415	1	0.325
9 – 11	0.5	11/0.415	1	0.325
9 – 12	0.5	11/0.415	1	0.325
9 – 13	0.5	11/0.415	1	0.325
9 – 14	0.5	11/0.415	1	0.325
9 – 15	0.5	11/0.415	1	0.325

Source: First Independent Power Limited

Table 2: Average Load Outage Data (January – December, 2023)

Substations Identification	Load (MVA)	Rated Voltage ratio	Outage Duration (Hrs)	Number of Interruption Customers	Total Number of Customers
T_2	0.325	11/0415KV	183.6	186	522
T_3	0.325	11/0415KV	205.16	124	731
T_4	0.325	11/0415KV	188.205	177	669
T_5	0.325	11/0415KV	312.53	199	751
T_6	0.325	11/0415KV	366.11	202	973
T_7	0.325	11/0415KV	268.33	179	833
T_8	0.325	11/0415KV	105.32	139	791
T_9	0.325	11/0415KV	361.74	147	942

Source: First Independent Power Limited

Table 3: Line Impedance

LINES ID	R(Ω)	X(Ω)
2 – 3	0.0558	0.04770
5 – 6	0.0495	0.05250
7 – 8	0.0660	0.07000
9 – 10	0.0082	0.0075
9 – 11	0.0825	0.08750
9 – 12	0.0330	0.03500
9 – 13	0.0247	0.02625
9 – 14	0.0165	0.01750
9 – 15	0.0330	0.03500

Source: First Independent Power Limited

Reliability Analytical Equations Embedded in ETAP

The basic equations for calculating the reliability indices at each load point, P are as shown:
Average Failure Rate at load point, P,

$$\lambda p = \frac{\Sigma f}{T}\left(f/_{yr}\right) \quad (1.1)$$

Where:
λp: Average failure rate at load point.
F: Load point failure (Frequency)
T: Operating time in hours
Annual Outage Duration at Load point, P,

$$\mu p = \frac{\sum Tdx}{T}(hr/yr) \quad (1.2)$$

Where;
μp: Annual outage duration at load point, P.
Tdx: Load point annual down time in hours
T: Operating time in hours
Average outage duration at load point, P,

$$rp = \frac{\mu p}{\lambda p}(hrs) \quad (1.3)$$

Where:
rp : Average outage duration at load point, P.
μp : Annual outage duration at load point, P.
λp: Average failure rate at load point, P.

Customer's based reliability indices are calculated using the basic load point indices like average failure rate, (λ), the average duration, (r) and the annual outage duration, (μ).
System Average Interruption Frequency Index,

$$SAIFI = \frac{\sum \lambda}{\sum N_T}\left(f/_{cust-yr}\right) \quad (1.4)$$

Where:
$\sum N_T$: Number of customers connected to the load point, P.
System Average Interruption Duration Index

$$SAIDI = \frac{\sum_T^{\mu} N_T}{\sum N_T}\left(hr/_{cust-yr}\right) \quad (1.5)$$

Where:
μT: Annual outage duration at load point, P

$$CAIDI = \frac{\sum_T^{\mu}.N_T}{\sum \lambda T.N_T}\left(hr./_{cust-yr}\right) \quad (1.6)$$

Average Service Availability Index,

$$ASAI = \frac{\sum N_T.0760 - \sum_T^{\mu}.N_T}{\sum N_T\,.\,8760}(\%) \quad (1.7)$$

Average Service Unavailable Index,

$$ASUI = \frac{\sum_T^{\mu}.N_T}{\sum N_T\,.\,8760}\left(hr./_{cust-yr}\right) \quad (1.8)$$

Expected Energy Not Supplied at Load Point, P.

$$EENs = \sum P_T\,.\,\mu_T\left(Mwhr/_{yr}\right) \quad (1.9)$$

Where:
P_T: Average load of load point, P.
μ_T: Annual outage duration at load Point, P.

Equations 1.1 to equation 1.9 are the basic analytical method equations embedded in ETAP that are used to calculate the reliability indices considered in this study

Optimal Placement of DG Using Particle Swarm Optimization

The major aim is to reduce of losses and maintaining a voltage profile of the distribution system, this was done by penetrating PSO optimized DG of optimal rating at appropriate location. The control variables are generators bus voltages and distributed generation source. The equality constraints are real power/reactive power equalities, the inequality constraints include bus voltage constraints, generator reactive power constraints, and real or reactive power capacity constraints etc. The equality constraints can be automatically satisfied by load flow calculation, while the lower/upper limit of control variables corresponds to the coding on the Particle Swarm Optimization (PSO) Algorithm, so the inequality constraints of the control variables are satisfied.

$$F = \min P_{loss} \tag{2.0}$$

$$P_{loss} = \sum_{k=1}^{ntl} G_k \left(V_i^2 + V_j^2 - 2 V_i V_j \cos(\delta_i - \delta_i)\right) \tag{2.1}$$

$$P_{loss} = \sum_{k=1}^{ntl} G_k \left(V_i^2 + V_j^2 - 2 V_i V_j \cos(\delta_i - \delta_i)\right) \tag{2.2}$$

Real power control variables:

i. Distributed Generation
ii. PV Bus

Constraints:

$$\begin{bmatrix} \Delta P_i \\ \Delta P_i \end{bmatrix} = \begin{bmatrix} P_i(V,\theta) - (P_{gi} - P_{di}) \\ Q_i(V,\theta) - (P_{gi} - P_{di}) \end{bmatrix} = 0 \tag{2.3}$$

Real Power Constraints:

$i \ \varepsilon \ n,$

where set of numbers of buses except the swing bus

2. Reactive Power Constraints:

$$Q_i(V,\theta) = \sum_{j=1}^{nbus} V_i V_j \left(G_{ij} \sin\theta_{ij} + B_{ij} \cos\theta_{ij}\right) \tag{2.4}$$

$i \ \varepsilon \ n,$

where set of numbers of buses except the swing bus

Bus Voltage magnitude constraints:

$$V_{i-min} \leq V_i \leq V_{i-max} \tag{2.5}$$

$i \ \varepsilon \ N$: $Set\ of\ total\ buses$

Generator bus reactive power constraint.

$$Q_{Gi-min} \leq Q_{Gi} \leq Q_{Gi-max} \tag{2.6}$$

$i \ \varepsilon \ \{N_{pv}, N_o\} n,$

Transfer Tap position constraints:

$$T_{i-min} \leq T_i \leq T_{i-max} \tag{2.7}$$

$i\varepsilon \ NT$

Where:

P_{loss}: System loss
N_b : Set of numbers of total buses
N_t: Set of numbers of tap-setting transformer branches
N_c: Set of numbers of possible reactive power source installation buses
N_{pv}: Set of numbers of PV buses

N_o: the swing bus
P_{Gi}: bus i real power supply
Q_{Gi}: bus i reactive power supply
P_{Di}: bus i real power load
Q_{Di}: bus i reactive power load
V_i: bus i voltage magnitude
θ_i: bus i voltage phase angle
θ_{ij}: Phase angle difference between bus i and j
G_{ij}: mutual conductance between bus i and j
B_{ij}: mutual susceptance between bus i and j
G_{ii}: self-conductance of bus i
B_{ii}: self susceptance of bus i
qci: reactive power source i installation
TK: transformer k tap
$V_{i\ min}$,$V_{I\ max}$: bus I voltage limit
$Q_{Gi\ min}$,$Q_{Gi\ max}$: reactive source i reactive power limit
$T_{K\ min}$, $T_{K\ max}$: transformer k tap position limit
$QC_{\ min}$, QC_{max}: reactive power source installation capacity limit

RESULTS AND DISCUSSIONS

Basic Reliability Indices With and Without DG Penetration

Figure 1 and Figure 2 depict one line simulation diagrams of the study case network without and with Distributed Generation penetration respectively. Also, Figure 3 and Figure 4 show a comparative composite bar chart demonstrating the results of basic reliability indices (Average failure rate and average outage duration) with and without deployment of distributed generation in the network.

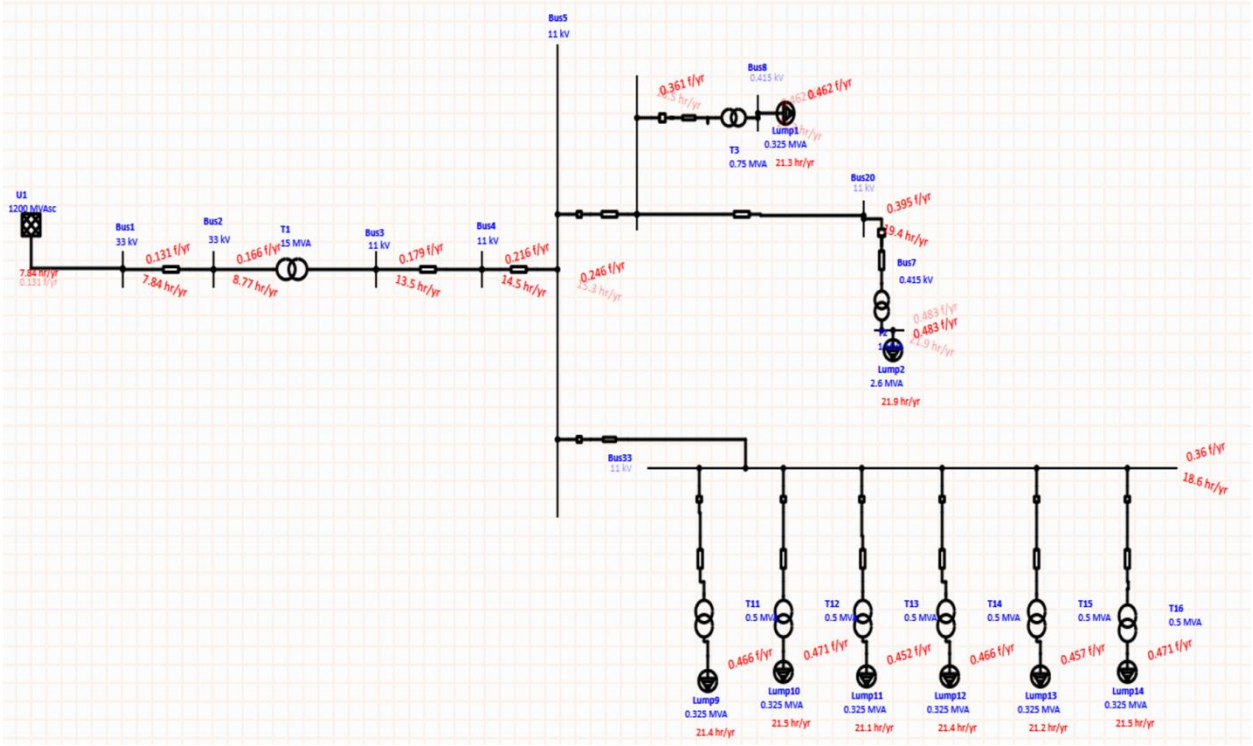


Figure 4.1: One Line Diagram without DG

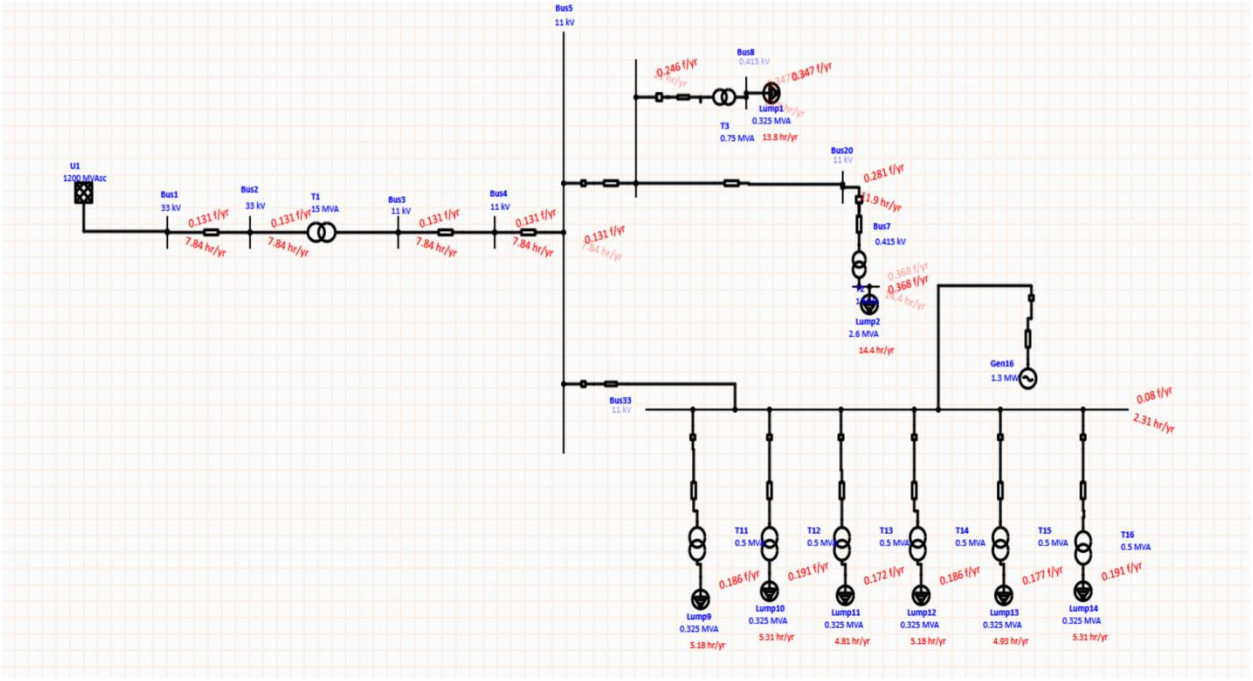


Figure 4.2: One Line Diagram with DG.

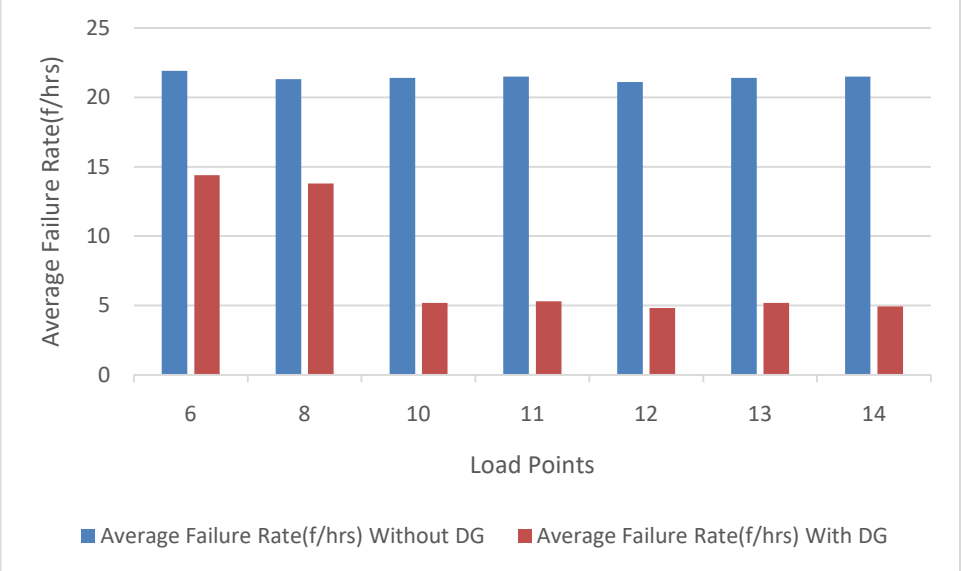


Figure 3: Composite Bar Chart of Average Failure Rate at Load Points

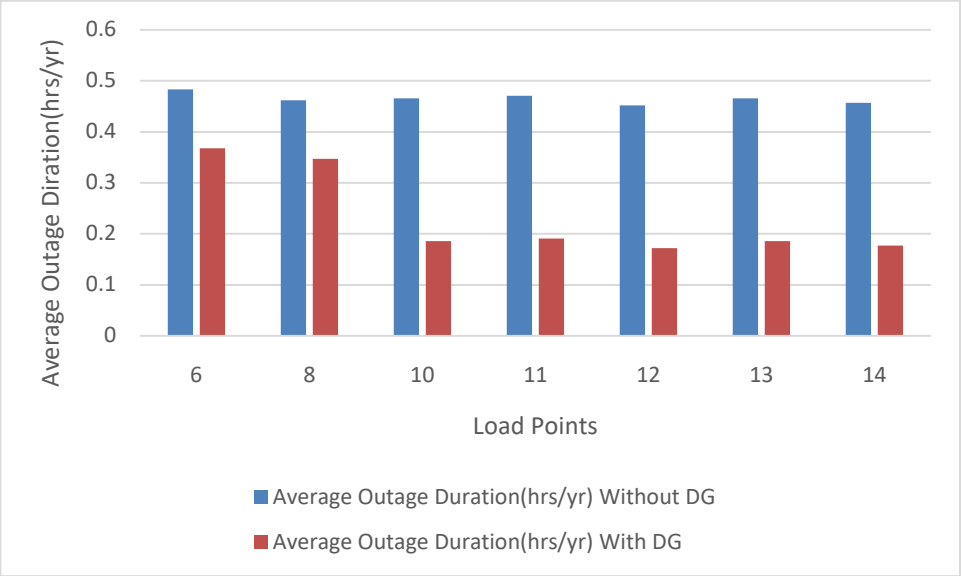


Figure 4: Composite Bar Chart of Average Outage Duration at Load Points

By the integration of PSO optimized DG (1.63MVA) at bus 9, both the average failure rate and average outage duration reduced significantly. For load point 6, average failure rate decreased by 34.2 %, while the average outage duration decreased by 23.8 %. For load point 8, the average failure rate reduced by 35.2 %, while the average outage duration reduced by 24.99 % and continuing reducing up to load point 14.

Customer's Oriented Reliability Indices with and without DG Penetration.
Table 4 show the presentation of customer's based reliability indices results with and without penetration of DG**.**

Table 4: Customer's Oriented Reliability Indices

Without DG		**With DG**	
Index	Value	Index	Value
SAIFI	0.4747f/cu.yr	SAIFI	0.2535f/cu.yr
SAIDI	13.56hr/cu.yr	SAIDI	8.2585hr/cu.yr
CAIDI	32.577hr/cu.intr	CAIDI	28.581hr/cu.intr
EENS	56.216MWhr/yr	EENS	43.376MWhr/yr
ASAI	0,868Pu	ASAI	0.9985Pu
ASUI	0.132Pu	ASUI	0.0015Pu

The base case system has a SAIFI value has 0. 4747f/cu.yr which means that the system has 0.4747 frequency of interruptions over the year, but when a DG of 1.63MVA is penetrated at bus 9, the SAIFI is decreased to 0.2535f/cu.yr. This means that the system now has lower frequency of interruptions within a period of one year investigation. The base case system has

a SAIDI value of 13.56hrs for each customer served for the one year under review. This is more than nine times the IEEE standard 1366-2003 which gives a value of 1.5 hrs for North America Utility. But when DG is penetrated, the SAIDI decreased to 8.2585hrs for each customer connected to the network for one year under investigation, which show that there is an improvement. The base case system has a CAIDI value of 32.577hrs for customer interruption in a year, when DG is penetrated, the CAIDI reduced to 28.581hrs per customer interruptions. The base case system has EENS of 56.216MWhr/yr which mean that 56.216MWh of energy is not supplied by the system under the one year investigation. But when DG is included in the network, the EENS reduced to 43.376 MWhr / yr which mean that 43.376 MWh of energy is not supplied by the system under the one year review.Availability system reliability index, ASAI of the existing network was 86.8%, but when DG was connected, ASAI value improves to 99.85% which is close a value of 99.9989% that has been recorded as standard benchmark.

CONCLUSION

The general reliability of power system is adjudged based on the number of interruptions that occur and the duration the system performs its function. Because of the role of distribution system, it is significant to pay attention to the issue of distribution system reliability and devising approach(s) to improve it. This research evaluates the reliability of a typical 11kV distribution network in Nigeria, with the aim of proposing its improvement through penetration of Distributed Generation (DG). Electrical Transient Analyzer Program (ETAP) software was used as the simulation tool. With the employed of PSO algorithm implemented in MATLAB, the optimal size and location was determined for the proposed DG incorporation. When the PSO optimize DG was penetrated into the network, the system basic and customer's oriented reliability indices such as: SAIFI, SAIDI, CAIDI and EENS were all improved upon significantly. System availability index, ASAI also improves from 86.8% to 99.85%.It is concluded that deployment of DG has proved to be an effective strategy for improving reliability in distribution network.

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