Reliability Enhancement of an 11kv Distribution Network Using Optimally Placed Hybrid Distributed Generation

DIGBANI, O. S.[1], BRAIDE, S. L.[2], IGBOGIDI, O. N.[3]
[1,2,3]Department of Electrical/Electronic Engineering, Rivers State University, Port Harcourt, Rivers State, Nigeria

Abstract- This paper presents a comprehensive techno-analytical investigation into the impact of optimally placed hybrid distributed generation (DG) on the reliability performance of a medium-voltage distribution network. A practical 11-kV radial feeder in Edo State, Nigeria, supplying 2.01 MW of connected load, was used as the case study. In the base-case condition, load-flow and reliability analysis in ETAP yielded minimum bus voltages of 0.912 pu, total real power losses of 186.4 kW, and poor reliability indices of SAIFI = 13.58 interruptions/customer-year, SAIDI = 49.35 hours/customer-year, CAIDI = 3.63 hours/interruption and EENS = 314.74 MWh/year. Using a Genetic Algorithm implemented in MATLAB, two hybrid solar–wind DG units of optimal capacities 480 kW and 350 kW were allocated at Bus 9 and Bus 12, respectively. After DG integration, the minimum bus voltage improved to 0.981 pu, real power losses reduced to 74.2 kW (60.2% reduction), and reliability indices improved to SAIFI = 6.60 interruptions/customer-year, SAIDI = 40.01 hours/customer-year, CAIDI = 6.06 hours/interruption and EENS = 71.98 MWh/year, corresponding to a 77.1% reduction in energy not supplied. The results demonstrate that optimally placed hybrid renewable DG provides an effective technical solution for enhancing voltage stability, reducing losses and significantly improving service continuity in weak radial distribution networks.

Index Terms- Distributed generation, Reliability indices, Genetic Algorithm, Hybrid renewable energy, Distribution system, ETAP, MATLAB

I. INTRODUCTION

Electrical energy plays a pivotal role in the economy of any country, so, there is need for an increase in the quality and quantity of power supply in order to cater for the load requirement and create a competitive advantage for any country [1] [2]. Electric power distribution systems constitute the final and most critical stage in the delivery of electrical energy to end-users [3].

In many developing countries, particularly in sub-Saharan Africa, distribution networks are characterized by frequent outages, long interruption durations, poor voltage regulation and high technical and non-technical losses. These deficiencies adversely affect industrial productivity, commercial activities and quality of life, while also reducing the revenue base of distribution utilities [4]

In Nigeria, the majority of 11kV and 33kV feeders operate radially with limited sectionalizing devices and minimal redundancy. Faults occurring on any section of a feeder often propagate to large portions of the network, resulting in widespread customer interruptions. Conventional reliability improvement strategies such as feeder reinforcement, installation of reclosers and network reconfiguration require substantial capital investment and long implementation periods.

Distributed generation (DG), particularly renewable-based DG, has emerged as an attractive alternative for reliability enhancement in distribution systems. When strategically placed, DG units can provide local supply support, reduce feeder loading, improve voltage profiles and limit the propagation of upstream faults [5]. However, the benefits of DG are highly sensitive to its location, size and operating mode. Improperly sited DG may lead to voltage rise, protection mal-coordination and increased system losses.

To address these challenges, heuristic optimization techniques such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Differential Evolution have been widely adopted to determine optimal DG placement and sizing. Despite the growing body of literature, there remains a shortage of practical case studies combining realistic Nigerian feeder data with integrated ETAP-MATLAB simulation frameworks and hybrid renewable DG modeling.

This paper therefore investigates the reliability enhancement of a practical 11kV distribution feeder in Edo State, Nigeria, through the optimal placement and sizing of hybrid solar–wind distributed generation. The specific objectives are to: (i) evaluate the baseline reliability performance of the feeder using standard indices, (ii) determine optimal DG locations and capacities using GA, and (iii) quantify the improvement in reliability and voltage performance after DG penetration.

II. LITERATURE REVIEW

Reliability Assessment of Distribution Networks

Power system reliability evaluation has traditionally focused on generation and transmission systems, but recent decades have seen increased attention on distribution networks because they account for the majority of customer interruptions. Reliability indices such as the System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI) and Customer Average Interruption Duration Index (CAIDI) are widely used to quantify service continuity [6].

In the work of [7], they conducted a reliability analysis of a radial distribution feeder using historical outage data and reported excessive interruption frequency relative to regulatory limits. [8], evaluated the reliability of the Maychew distribution system in Ethiopia using ETAP and concluded that the network exhibited poor performance with high SAIFI and SAIDI values. Similar findings were reported by [9], who applied ETAP-based reliability simulation on an IEEE 9-bus system and observed that feeder loading and component failure rates significantly influence interruption indices.

In the context of Nigeria, [10] assessed the reliability of Mofor injection substation and reported low service availability indices, attributing the poor performance to aging infrastructure and frequent fault occurrences. [11], in their research highlighted that technical losses and inadequate protection coordination further exacerbate outage duration in Nigerian feeders.

Distributed Generation and Reliability Enhancement

Distributed generation has been widely recognized as a viable tool for improving reliability in distribution systems. Properly coordinated DG can provide local voltage support, reduce feeder congestion and enhance supply continuity during upstream outages [12]. The study by [13] demonstrated that DG penetration reduces ENS and improves ASAI in urban distribution networks.

The research work by [14] evaluated islanded microgrids with high renewable penetration and showed that distributed renewable sources significantly reduce SAIDI and ENS when appropriately controlled. [15] in their study reported that locating DG farther from the substation yields greater reliability improvement due to reduced exposure to upstream faults.

However, several authors have cautioned that arbitrary DG placement may worsen system performance. [16], in their work observed that improper DG sizing can increase feeder losses and violate voltage constraints. Hence, optimization-based placement techniques are essential for maximizing reliability benefits.

Optimization Techniques for DG Placement

Heuristic optimization techniques have become dominant tools for DG allocation problems. In the work of [17], they applied a hybrid fuzzy–GA approach and achieved significant loss reduction in radial feeders. Similarly, [18] employed GA for DG placement and reported improvements in voltage profile and power loss minimization.

In recent study by [19] integrated Monte Carlo simulation with failure mode and effect analysis (FMEA) to evaluate reliability in active distribution networks with DG. While,[20] used GA to optimize DG placement in Nigerian feeders and recorded over 30% reduction in SAIDI.

Despite these advances, limited studies integrate hybrid renewable DG, practical Nigerian feeder data and combined ETAP–MATLAB simulation environments. This study fills this gap by presenting a comprehensive reliability-oriented DG optimization framework applied to a real 11kV feeder.

III. METHODOLOGY

Description of the Study Network

The study network is the Uromi 11-kV radial distribution feeder in Edo State, Nigeria, supplying nine distribution transformers with a total connected load of approximately 2.01 MW. The feeder is energized from a 15-MVA, 33/11-kV power transformer and consists primarily of overhead lines. Bus, line and transformer parameters were obtained from the Benin Electricity Distribution Company database.

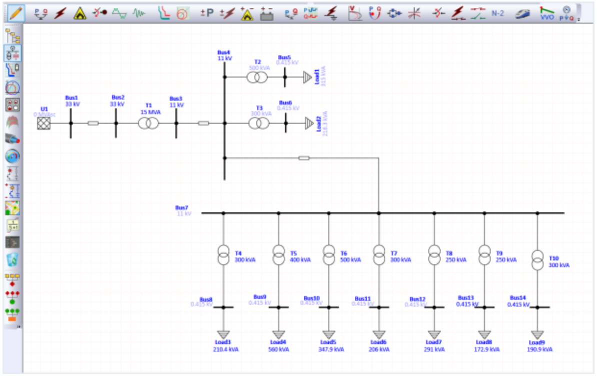

Figure 1: One-line diagram of the Uromi 11kV distribution feeder

Load Flow Modeling

Load flow analysis was performed using the Newton–Raphson (NR) iterative technique implemented in ETAP in order to establish the steady-state operating condition of the distribution network. The method solves the nonlinear algebraic power-balance equations relating bus voltages, power injections and network admittance parameters.

For a system with n buses, the real and reactive power injected at bus i are expressed as

$$P_i = \sum_{k=1}^{n} |Y_{ik}||V_i||V_k| \cos(\delta_k + \theta_{ik} - \delta_i) \quad (1)$$

$$Q_i = -\sum_{k=1}^{n} |Y_{ik}||V_i||V_k| \sin(\delta_k + \theta_{ik} - \delta_i) \quad (2)$$

Where

Y_{ik}= admittance

P_i= real power

Q_i= reactive power

δ_i= phase angle

The mismatch equations at each iteration k are given by

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \dfrac{\Delta P_n^{(k)}}{\Delta Q_2^{(k)}} \\ \vdots \\ \Delta Q_n^{(k)} \\ \square \end{bmatrix} = \begin{bmatrix} \left|\begin{matrix} \dfrac{\partial P_2^{(k)}}{\partial \delta_2} & \cdots & \dfrac{\partial P_2^{(k)}}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \dfrac{\partial P_n^{(k)}}{\partial \delta_2} & \cdots & \dfrac{\partial P_n^{(k)}}{\partial \delta_n} \end{matrix}\right| & \left|\begin{matrix} \dfrac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \dfrac{\partial P_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \dfrac{\partial P_n^{(k)}}{\partial |V_2|} & \cdots & \dfrac{\partial P_n^{(k)}}{\partial |V_n|} \end{matrix}\right| \\ \left|\begin{matrix} \dfrac{\partial Q_2^{(k)}}{\partial \delta_2} & \cdots & \dfrac{\partial Q_2^{(k)}}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \dfrac{\partial Q_n^{(k)}}{\partial \delta_2} & \cdots & \dfrac{\partial Q_n^{(k)}}{\partial \delta_n} \end{matrix}\right| & \left|\begin{matrix} \dfrac{\partial Q_2^{(k)}}{\partial |V_2|} & \cdots & \dfrac{\partial Q_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \dfrac{\partial Q_n^{(k)}}{\partial |V_2|} & \cdots & \dfrac{\partial Q_n^{(k)}}{\partial |V_n|} \end{matrix}\right| \end{bmatrix} \begin{bmatrix} \Delta \delta_2^{(k)} \\ \vdots \\ \dfrac{\Delta \delta_n^{(k)}}{\Delta \left|V_2^{(k)}\right|} \\ \vdots \\ \Delta \left|V_n^{(k)}\right| \\ \square \end{bmatrix} \quad (3)$$

With minor changes in real $\Delta P_i^{(k)}$ and reactive power $\Delta Q_i^{(k)}$the Jacobian matrix shows the linearized correlation between tiny changes in voltage angle $\Delta \delta_i^{(k)}$ and magnitude $\Delta \left|V_i^{(k)}\right|$

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_3 \\ J_2 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \quad (4)$$

Where

J_1, J_2, J_3, J_4 are the elements of the Jacobian matrix

The voltage corrections are obtained by solving the linearized Jacobian system

$$[\Delta P \ \Delta Q]^T = J \, [\Delta \theta \ \Delta|V|]^T \quad (5)$$

Where J is the Jacobian matrix containing the partial derivatives of the power equations with respect to voltage angles and magnitudes.

The resulting bus voltages, line power flows and real and reactive losses obtained from the converged solution constituted the base-case operating condition of the feeder and provided reference values for assessing the impact of distributed generation integration.

Reliability Modeling Framework

Reliability assessment was conducted using standard analytical expressions for load-point and system-oriented indices as implemented in ETAP. For a system with N customers, the principal reliability indices were computed as follows.

The System Average Interruption Frequency Index (SAIFI) was evaluated using

$$\text{SAIFI} = \frac{\text{Total number of customer interruptions}}{\text{Total number of customers served}} = \frac{\sum_i \lambda_i N_i}{\sum_i N_i} \qquad (6)$$

Where:

λi :is the failure rate at load point i and,

Ni : Is the number of customers at load point i.

The System Average Interruption Duration Index (SAIDI) was calculated as

$$\text{SAIDI} = \frac{\text{Sum of customer interruptions durations}}{\text{Total number of customers served}} = \frac{\sum_i U_i N_i}{\sum_i N_i} \qquad (7)$$

Where:

Ui : is the annual outage time at load point$i$ and

Ni: is the number of customers at load point$i$.

The Customer Average Interruption Duration Index (CAIDI) was obtained from

$$\text{CAIDI} = \frac{\text{Total number of customer interruptions}}{\text{Total number of customers served}} = \frac{\sum_i U_i N_i}{\sum_i \lambda_i N_i} = \frac{\text{SAIDI}}{\text{SAIFI}} \qquad (8)$$

Where:

λi :is the failure rate at load point$i$

Ui: is the annual outage time at load point$i$

Ni: is the number of customer at load point$i$.

The Average Service Availability Index (ASAI) was computed as

$$\text{ASAI} = \frac{\text{Customer hours of avaliable service}}{\text{Customers hours demanded}} = \frac{\sum_{iN_i} \times 8760 - \sum_i UiNi}{\sum_{iN_i} \times 8760} \qquad (9)$$

Where:

Ui: is the annual outage time at load point$i$and

Ni :is the number of customer at load point i.

The Expected Energy Not Supplied (EENS) was evaluated using

$$EENS = \sum_i L_{a(i)} U_i \qquad (10)$$

Where:

$L_{a(i)}$, U_i: are the average connected load and the average annual outage time at load point $i\ respectively$.

Component failure rates (λ) and repair times (r) were assigned to distribution lines and transformers based on utility records and standard reliability data. The annual outage duration at each load point was obtained from

This indicate the period during which the system does not provide or perform its primary function, and t is the percentage of the period during which the system is unavailable. Mathematically represented as:

$$\lambda_p = \frac{\sum Tdx}{T} (hr/yr) \qquad (11)$$

Where;

Tdx: Load point annual outage time in hours

T: Operating Time in hours

The above indices provided quantitative measures of interruption frequency, interruption duration, service availability and unserved energy for both the base-case and DG-integrated networks

Distributed Generation Modeling

Hybrid DG units comprising photovoltaic arrays and wind turbines were modeled as PQ injection sources connected at candidate buses. Penetration limits were set to prevent reverse power flow and excessive voltage rise. Two candidate buses (Bus 9 and Bus 12) were selected based on load concentration and network topology.

Genetic Algorithm Optimization

The GA was implemented in MATLAB to determine optimal DG sizes and locations. The objective function minimized total real power loss, voltage deviation and penalty terms associated with power factor violations. Equality constraints enforced power balance equations, while inequality constraints ensured voltage limits (0.95–1.05 pu) and DG capacity bounds (≤ 600 kW).

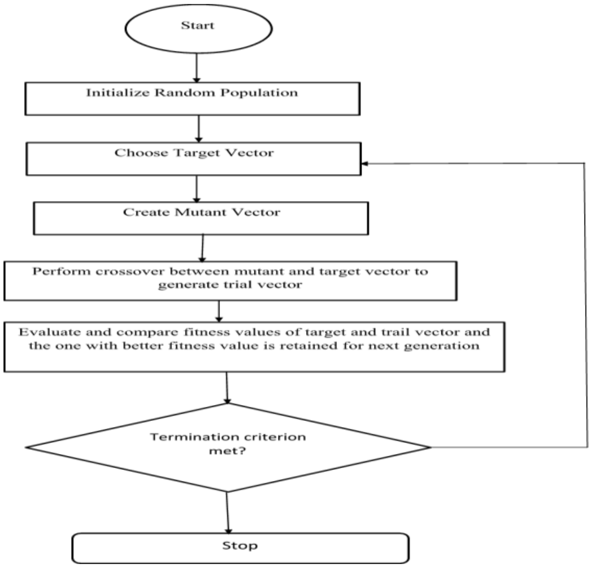

Figure 2: Flowchart of the Genetic Algorithm optimization process

The optimized DG sizes were exported to ETAP and incorporated into the feeder model for post integration reliability simulation.

IV. RESULTS AND DISCUSSION

Base Case Reliability Performance

The baseline reliability assessment revealed poor service continuity across the feeder. Average load-point failure rates ranged between 12 and 16 failures per year, while outage durations exceeded 9 hours per year at most buses. System-wide indices were SAIFI = 13.58 f/cust•yr, SAIDI = 49.35 h/cust•yr, CAIDI = 3.63 h/interruption and EENS = 314.74 MWh/yr, indicating severe reliability deficiencies.

Table 1 presents the detailed base-case reliability indices obtained from the ETAP simulation

Table 1: Base case load point and system reliability indices

Bus	Average Failure Rate(f/hr)	Average Outage Duration (H/Yr)
5	12.239	9.24
6	12.249	9.23
8	12.317	9.22
9	16.296	11.3
10	14.697	11.0
11	13.497	10.6
12	13.797	13.7
13	12.317	9.29
14	14.797	14.4
	System Reliability Indices	Value
-	SAIFI	13.5785f/cus.yr
-	SAIDI	49.3495hr/cus.yr
-	CAIDI	10.999hr/Cus.interupt
-	EENS	314.737MWhr/yr

Optimal DG Placement and Voltage Performance

The GA converged after approximately 80 generations, yielding optimal DG sizes at Bus 9 and Bus 12. The injected active and reactive powers improved voltage magnitudes at downstream buses, eliminating undervoltage violations.

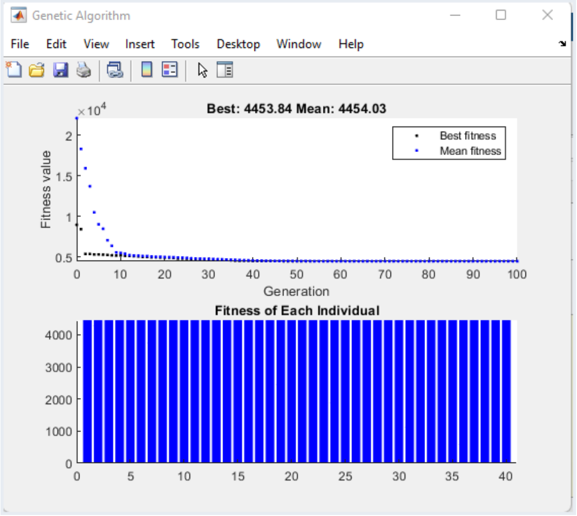

Figure 3: GA convergence curve and optimized DG sizes

Post-Integration Reliability Performance

After DG integration, significant improvements were observed. Load-point failure rates reduced by up to 60%, while outage durations declined markedly at remote buses. System indices improved to SAIFI = 6.60 f/cust•yr, SAIDI = 40.01 h/cust•yr, CAIDI = 6.06 h/interruption and EENS = 71.98 MWh/yr.

Table 2 summarizes the post-integration reliability indices and the percentage improvement relative to the base case.

Table 2: Reliability indices after DG integration

Bus	Average Failure Rate(f/hr)	Average Outage Duration (H/Yr)
5	6.708	7.18
6	6.848	7.09
8	7.658	6.41
9	5.113	2.59
10	7.779	6.49
11	7.669	6.45
12	1.614	1.44
13	7.699	6.38
14	8.349	5.96
	System Reliability Indices	Value
-	SAIFI	6.6041 f/cus.yr
-	SAIDI	40.0146 hr/cus.yr
-	CAIDI	6.059hr/cus.Interupt
-	EENS	71.979MWhr/yr

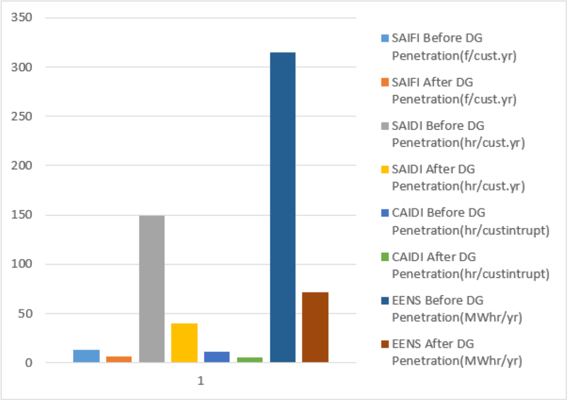

Figure 4: Comparison of system reliability indices before and after DG integration

The results corroborate earlier findings by Mamo and Hizkiel (2023) and Zhong et al. (2020) that DG significantly enhances reliability when optimally placed. The combined ETAP–MATLAB framework proved effective for integrated reliability and optimization studies. However, protection coordination and islanding control were not considered in this study and should be addressed in future work.

V. CONCLUSION

This paper presented a detailed reliability enhancement study of a practical 11kV distribution feeder using optimally placed hybrid distributed generation. By integrating GA-based optimization with ETAP reliability simulation, substantial reductions in interruption frequency, duration and energy not supplied were achieved. The findings confirm that hybrid renewable DG offers a technically viable and cost-effective strategy for improving distribution system reliability in developing power systems. Future studies will incorporate economic analysis, protection coordination and stochastic modeling of renewable resources.

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