Engineering and Technology Journal e-ISSN: 2456-3358
Volume 11 Issue 03 March-2026, Page No.-9268-9277
DOI: 10.47191/etj/v11i03.21, I.F. – 8.595

Performance Analysis of Solar PV-Based Renewable Power Distributed Generation in the Sapele Distribution Network

Omughele Rueben A.[1], Ubeku Emmanuel U[2]
[1,2]Department of Electrical/Electronic Engineering, Delta State University, P.M.B. 1, Abraka, Oleh Campus, Delta State, Nigeria

ABSTRACT: High technical losses, poor voltage regulation, and overloaded transformers remain major challenges in many Nigerian distribution networks, including the Sapele 11 kV feeder. This study evaluated the integration of solar photovoltaic (PV)-based distributed generation (DG) as a technical solution for improving network performance. A simulation-based approach was adopted using ETAP for load-flow analysis and the Newton–Raphson method for steady-state evaluation, while the Bat Algorithm was applied to determine the optimal location and size of DG units. The assessment focused on voltage profile, active power loss, reactive power loss, and transformer loading before and after DG integration. The results showed that DG integration significantly improved network operation. The minimum bus voltage increased from 87.82% to above 97%, total active power loss dropped from 1013.84 kW to 93.11 kW, and reactive power loss was also markedly reduced. In addition, heavily overloaded transformers were relieved, with critical units reduced to acceptable loading levels. These findings indicate that optimally allocated solar PV-based DG can strengthen distribution network performance, improve service reliability, and provide a practical support option for weak radial feeders in Nigeria.

KEYWORDS: distributed generation, solar photovoltaic, distribution network, power loss reduction, voltage profile, Bat Algorithm

1. INTRODUCTION

Renewable distributed generation, particularly solar photovoltaic (PV) generation, is increasingly regarded not only as a clean-energy option but also as a technical intervention for improving weak distribution networks. The argument in the literature is no longer simply that DG adds energy to the grid, but that, when properly planned, it can reduce feeder current, improve voltage magnitude at weak buses, lower technical losses, and relieve stress on overloaded equipment. [1] were among the early studies to frame renewable distributed generation as a network-support resource rather than only a decentralized generation source. That position has since been reinforced by broader reviews, including Ehsan and [2], who showed that the technical value of DG depends strongly on coordinated planning, especially with respect to siting, sizing, and network constraints. In the Nigerian context, the argument becomes even more compelling because solar energy is both geographically abundant and operationally attractive for embedded generation, yet its practical value depends on whether it can solve real feeder-level problems rather than remain only a policy aspiration. [3] argued that solar energy remains one of Nigeria's most viable renewable options because of the country's resource endowment, but they also noted that affordability, policy weakness, and implementation barriers continue to slow adoption. [4] similarly showed that renewable-energy deployment in developing settings is often constrained by a combination of technical, economic, and governance barriers, which means that practical distribution-level studies are still needed to show where renewable integration produces measurable system benefits.

That broader background leads directly to the problem addressed in this study. In many Nigerian networks, the main difficulty is not only inadequate generation at the national level, but also weak power delivery at the feeder level, reflected in undervoltage conditions, high technical losses, overloaded transformers, and poor service quality. [5] showed, in a related Delta State distribution setting, that feeder and substation inefficiencies continue to undermine supply reliability and operational performance. The implication is that the distribution network itself remains a major bottleneck, and this makes DG planning a technical necessity rather than a purely environmental preference. However, much of the existing DG literature still relies on standard IEEE test systems, generic radial feeders, or algorithm-comparison studies that do not fully reflect the operating realities of Nigerian utility networks. This creates a practical gap: utilities need evidence not merely that DG can work in theory, but that optimally placed solar PV can improve a real feeder under actual network conditions. The present study addresses that gap by focusing on the Sapele 11 kV distribution network and examining whether solar PV-based DG can be used to reduce power loss, improve bus voltages, and relieve equipment loading in a real distribution environment.

The related literature strongly supports the idea that DG improves radial distribution performance only when it is optimally allocated, not when it is indiscriminately connected. [6] showed that DG size and location are decisive in achieving loss minimization in primary distribution networks, while [7] further demonstrated that the analytical treatment of DG type, power factor, and allocation can significantly affect system performance. [8] later argued that voltage-stability-based siting becomes especially important under load growth, because weak buses are not equally responsive to DG support. More recent work has preserved the same central argument while broadening the planning context. [9] showed that DG allocation must be coordinated with network-support conditions rather than treated as a standalone connection exercise. [10] confirmed that optimally allocated PV-DG can simultaneously improve voltage profile and reduce active power loss in radial networks, while [11] showed that penetration level also matters, since technical gains vary with the depth and pattern of DG integration. These studies are important because they collectively reject the simplistic assumption that any distributed generator will improve a feeder. Instead, they support the stronger and more relevant claim for this study: DG becomes technically valuable when it is treated as a network-support resource whose size and placement must respond to actual feeder weakness. Against that background, the present work contributes by applying this optimization-based logic to the Sapele 11 kV network using utility data, ETAP load-flow modelling, and Bat Algorithm-based solar DG allocation in a real Nigerian feeder context.

2. METHODS

2.1 Data Collection

Data used in this study were obtained from the Sapele 11 kV distribution network operated by the Benin Electricity Distribution Company (BEDC). The dataset comprised the network single-line diagram, feeder and load information, and solar photovoltaic (PV) system data. These inputs were used to model the existing network and to assess the effect of distributed generation (DG) integration under steady-state operating conditions.

2.2 Study Approach

The study adopted a simulation-based approach to evaluate the integration of solar PV as distributed generation in the Sapele distribution network. The methodology combined power flow analysis with optimization in order to assess the technical effect of PV penetration on the network. The main performance indicators considered were bus voltage profile, active power loss, reactive power loss, and voltage stability. In addition, the approach was used to identify suitable DG locations and sizes for improved network performance.

2.3 Network Description

The Sapele distribution network is an 11 kV medium-voltage system in Delta State, Nigeria. Power is supplied from the transmission level through step-down transformers and then distributed to residential, commercial, and industrial consumers through interconnected feeders. The single-line diagram of the existing network was used as the basis for modelling and simulation.

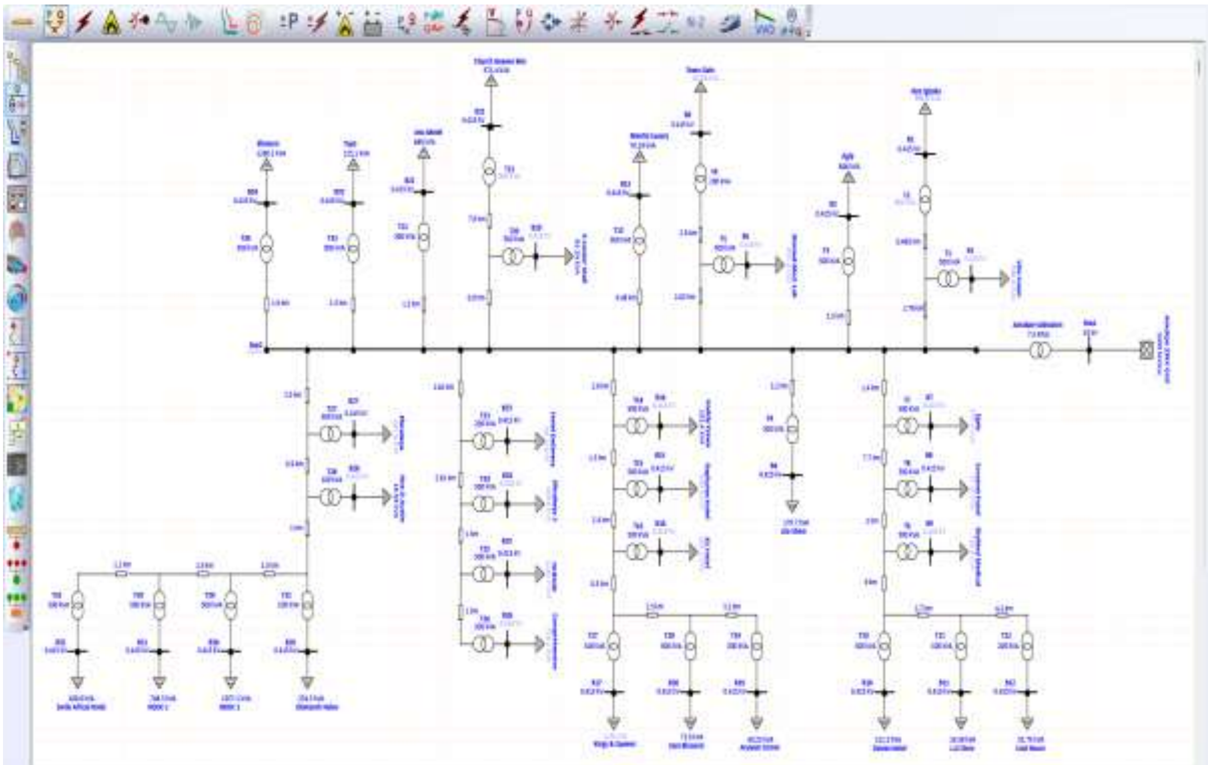

Figure 1: Single-line diagram of the existing Sapele 11 kV distribution network.

2.4 Power Flow Analysis

Power flow analysis was carried out to determine the steady-state operating condition of the network before and after DG integration. ETAP was used to model the network and compute key electrical parameters required for analysis. These included bus voltages, line flows, and network losses. The load data of the Sapele 11 kV network served as input to the model.

2.5 Newton–Raphson Solution Method

The Newton–Raphson method was used to solve the power flow problem because of its accuracy and suitability for power system studies. The method determines bus voltage magnitudes and phase angles while satisfying active and reactive power balance across the network. The results obtained from this stage formed the baseline for subsequent DG placement analysis.

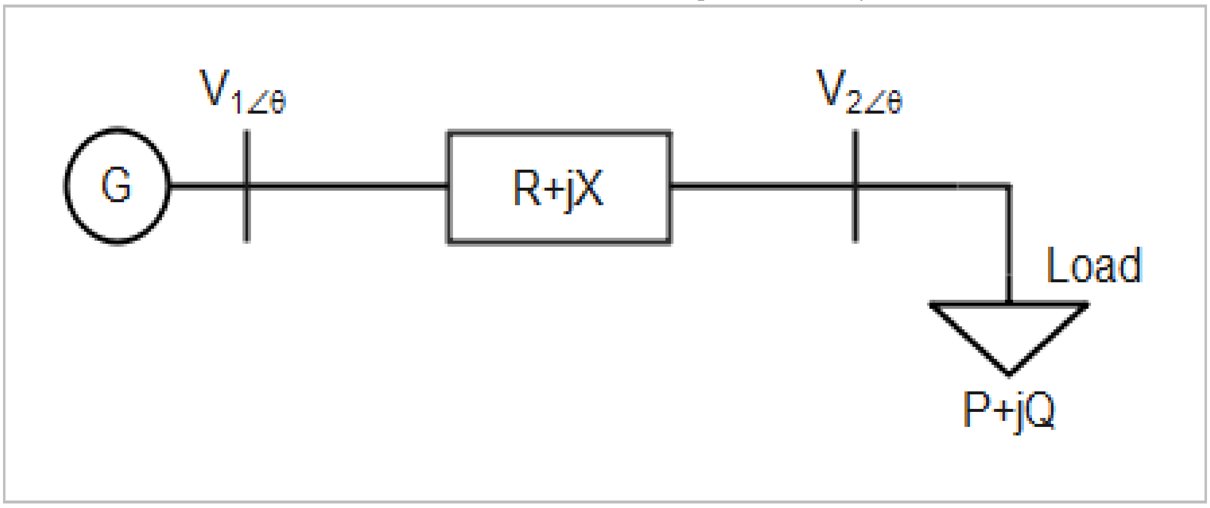

Figure 2: Simplified two-bus representation for power flow analysis.

2.6 Optimal Siting and Sizing of Solar DG

The optimal location and size of solar PV units were determined using the Bat Algorithm, a metaheuristic optimization technique inspired by the echolocation behaviour of bats. The algorithm was applied to minimize total active power loss while maintaining acceptable operating constraints for DG output and bus voltages. By iteratively searching for the best solution, the method identified the most suitable buses and corresponding DG capacities for solar PV integration.

The optimization objective is expressed as the minimization of total active power loss:

$$\text{Minimize } P_{loss} = \sum_{i=1}^{N_b} \sum_{i=j}^{N_b} g_{ij}\left[V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j)\right]$$

Subject to:

$$P_{DG} + P_{grid} = P_{demand} + P_{loss}$$

$$P_{DG}^{min} \leq P_{DG} \leq P_{DG}^{max}$$

$$V_{min} \leq V_i \leq V_{max} \quad (10)$$

Where:-

N_b: number of buses

g_{ij}: conductance between bus i and j

V_iV_j: bus voltage magnitudes

δ_i, δ_j bus voltage angles

P_{DG} is the DG output,

Vmin, Vmax are statutory voltage limits typically 0.95–1.05 p.u. for distribution networks

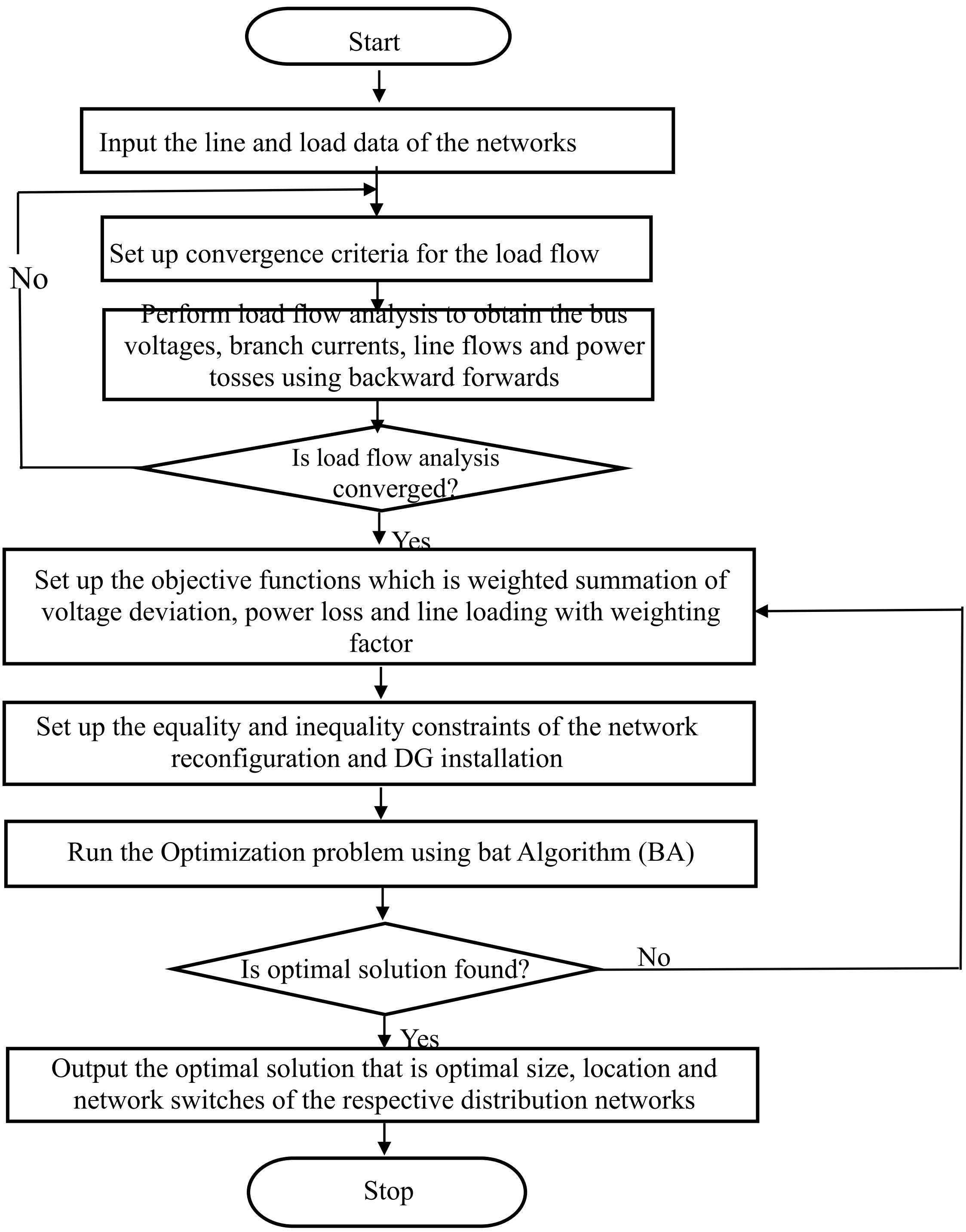

Figure 3: Flowchart of the Bat Algorithm.

2.7 Solar PV Data

The solar PV system considered in this study was based on JA Solar modules rated at 330 W. The module specifications were used in the simulation of PV-based DG integration.

Table 1: Key specifications of the JA Solar 330 W module.

Parameter	Value	Unit
Rated power per module	330	W
Modules per string	24	–
Strings per array	945	–
Module efficiency	17.2	%
Operating temperature range	–40 to +85	°C
Temperature coefficient of Pmax	–0.41	%/°C

3. RESULTS

3.1 Existing Sapele 11 kV Network without DG

The base-case load flow results show that the existing Sapele 11 kV distribution network operates with notable voltage weakness at several buses. As shown in Figure 4 and Table 2, bus voltages vary widely across the network, with the lowest value recorded at Bus 25 (87.82%) and the highest at Bus 23 (100.23%). Several buses fall below the acceptable operating range, indicating poor voltage regulation under the existing loading condition. These results confirm that the network, in its initial state, is technically stressed and requires corrective support.

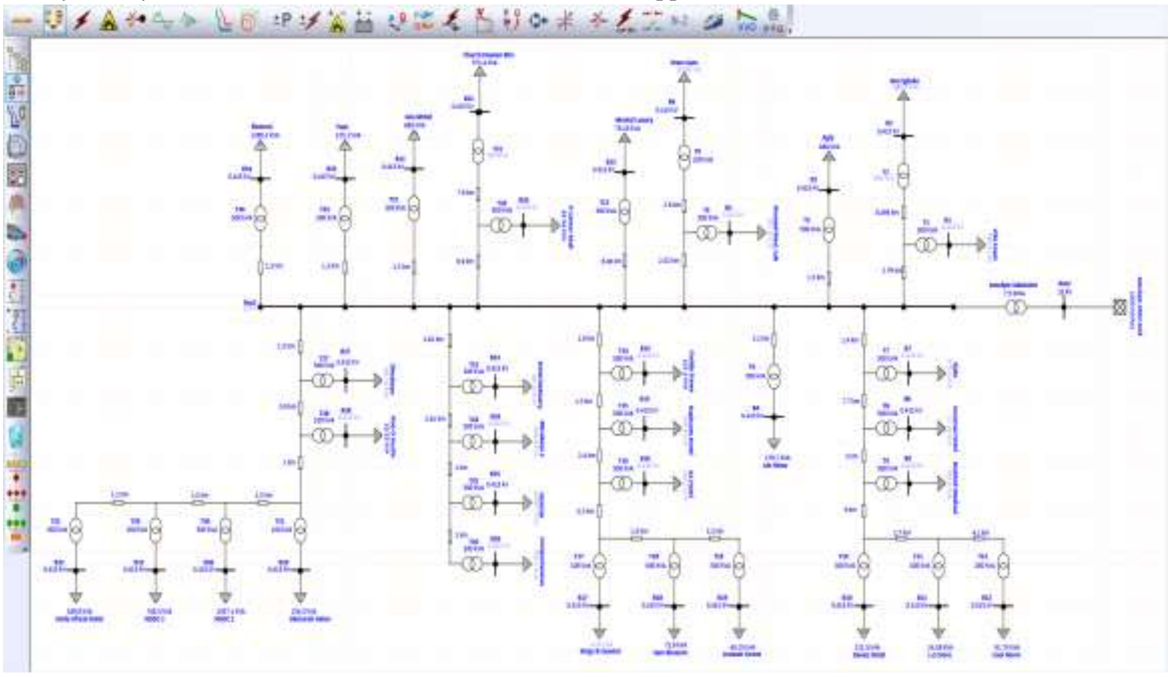

Figure 4: ETAP load flow model of the existing Sapele 11 kV distribution network.

Table 2: Voltage profile of the existing Sapele 11 kV distribution network.

Bus ID	Nominal(kV)	Operating (%)
B1	0.415	93.05
B2	0.415	91.33
B3	0.415	93.04
B4	0.415	99.72
B5	0.415	100
B6	0.415	99.04
B7	0.415	94.87
B8	0.415	99.69
B9	0.415	91.97
B10	0.415	100.15
B11	0.415	97.9
B12	0.415	100.08
B13	0.415	98.37
B14	0.415	99.17
B15	0.415	94.22
B16	0.415	99.78
B17	0.415	99.19
B18	0.415	98.78
B19	0.415	98.82
B20	0.415	98.81
B21	0.415	94.31
B22	0.415	91.18
B23	0.415	100.23
B24	0.415	90.55
B25	0.415	87.82

B26	0.415	88.58
B27	0.415	92.4
B28	0.415	99.8
B29	0.415	89.2
B30	0.415	88.02
B31	0.415	91.5
B32	0.415	99.84
B33	0.415	99.01
B34	0.415	90.44

3.2 Improved Network with DG Integration

After integrating solar PV-based DG, the network voltage profile improved considerably. Figure 5 and Table 3 show that all buses were restored to acceptable operating levels, with major improvement observed at previously weak buses. For example, Bus 25 increased from 87.82% to 97.35%, while Bus 29 improved from 89.20% to 99.26%. This confirms that DG integration provided effective voltage support and enhanced overall network performance.

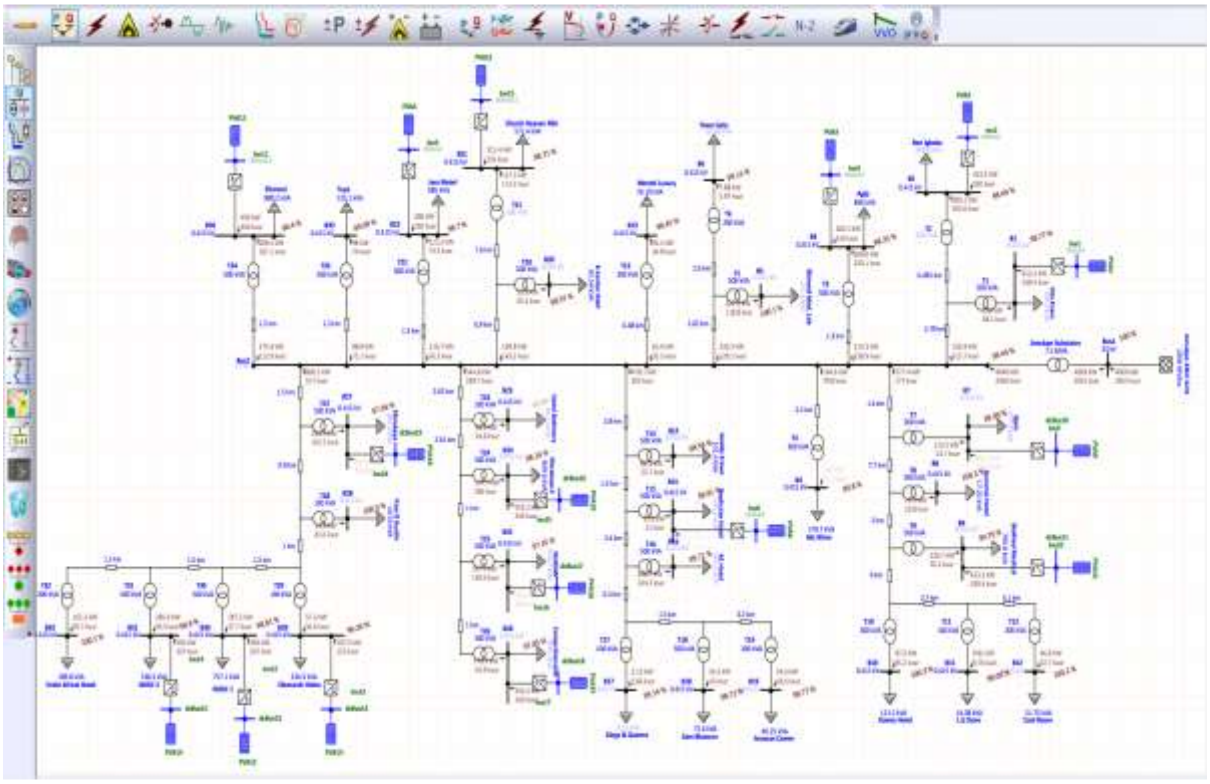

Figure 5: ETAP model of the improved Sapele 11 kV distribution network with DG.

Table 3: Voltage profile of the Sapele 11 kV distribution network after DG integration.

3.3 Line Loss Reduction

The comparison of line losses before and after DG integration shows a substantial reduction in active power loss across the network. The total real power loss decreased from 1013.84 kW to 93.11 kW, indicating a major improvement in feeder efficiency. The most significant reductions were recorded on heavily stressed lines such as Line 23, Line 24, and Line 27. This result shows that optimal DG placement reduced the burden on long feeder sections and improved overall power transfer efficiency.

Table 4: Comparison of line losses before and after DG integration.

Line	Sending End			Receiving End			Losses	
ID	From Bus	kW flow	kvar flow	To Bus	Kw Flow	kvar flow	kW	kvar
1	B1	1318.5	959.2	B2	1240.1	957.6	78.400	1.610
2	B2	672.8	581.4	B3	668.6	578.2	4.220	3.200

3	B3	577	527.9	B4	568.6	527.5	8.400	0.430
4	B4	164.3	79.66	B5	163.2	79.1	1.130	0.575
5	B5	232.9	128.9	B6	231.4	128.9	1.515	0.001
6	B6	7.88	5.98	B7	7.9	-3.1	0.003	9.050
7	B7	1094	638.4	B8	1070.3	612.6	23.750	25.800
8	B8	771	480.8	B9	703.3	474.4	67.700	6.450
9	B9	744	464.9	B10	727.1	463.5	16.950	1.355
10	B10	146	119.7	B11	142.4	119.7	3.555	0.050
11	B11	56.82	32.85	B12	56.7	32.8	0.130	0.048
12	B12	46.97	23.05	B13	46.8	22.9	0.126	0.145
13	B13	65.51	35.39	B14	65.1	20.5	0.380	14.850
14	B14	909.9	698.3	B15	871.0	692.6	38.950	5.750
15	B15	819.1	638.7	B16	804.1	636.3	15.050	2.355
16	B16	370.6	319	B17	364.4	319.0	6.200	0.017
17	B17	94.39	65.11	B18	94.3	65.0	0.043	0.076
18	B18	91.23	62.27	B19	91.0	62.2	0.199	0.021
19	B19	34.72	18.85	B20	34.7	10.1	0.054	8.750
20	B20	430.7	317	B21	407.7	315.7	23.050	1.285
21	B21	486.7	343.8	B22	483.3	341.8	3.380	2.015
22	B22	469.6	405.7	B23	464.3	338.7	5.300	67.050
23	B23	1999.8	1534.4	B24	1823.9	1470.2	175.950	64.250
24	B24	1924.9	1495.1	B25	1756.2	1483.3	168.700	11.800
25	B25	1353.6	969.7	B26	1322.6	968.0	31.050	1.655
26	B26	549.2	288.3	B27	544.9	231.0	4.340	57.350
27	B27	2575.1	1692.6	B28	2424.6	1673.7	150.550	18.950
28	B28	1897.9	1230.7	B29	1848.2	1210.0	49.700	20.700
29	B29	1873.7	1218.4	B30	1819.3	1192.6	54.400	25.800
30	B30	1720.1	1069.2	B31	1652.4	1064.5	67.700	4.675
31	B31	737	436.1	B32	724.8	435.9	12.250	0.193
32	B32	167.4	97.31	B33	166.9	97.2	0.505	0.081
33	B33	98.58	74.94	B34	98.4	66.9	0.211	8.000
							1013.84	364.333

3.4 Transformer Loading Performance

Transformer loading also improved significantly after DG installation. Several transformers that were heavily overloaded under the base case were brought closer to normal operating levels. For instance, Transformer 30 reduced from 231.0% to 38.6%, while Transformer 25 dropped from 209.6% to 45.7%. This indicates that DG integration not only improved voltage conditions but also relieved loading pressure on critical distribution transformers, thereby improving operational reliability.

Table 5: Transformer loading before and after DG integration.

Transformer ID	kW Flow	Kvar Flow	% Loading	kW Losses	Kvar Losses
T1	630	371.8	146.3	24.55	36.82
T2	671.9	581.1	177.7	36.26	54.39
T3	575.3	527.3	156.1	27.49	41.24
T4	164.1	79.58	60.8	2.37	3.56
T5	224.7	122.8	51.2	2.81	4.21
T6	7.88	5.98	4.9	0.011	0.0165
T7	318.2	155.8	118.1	9.48	14.22
T8	13.41	10.74	5.7	0.0219	0.0328
T9	594.6	343.9	137.4	22.24	33.37
T10	88.47	86.59	41.3	1.1	1.64
T11	9.82	9.79	13.9	0.044	0.066
T12	46.95	23.04	26.1	0.298	0.446

T13	65.44	35.36	24.8	0.415	0.623
T14	83.02	56.59	20.1	0.449	0.673
T15	445.5	318.6	109.5	13.75	20.63
T16	275	253.4	74.8	5.89	8.84
T17	3.16	2.84	4.2	0.0041	0.0061
T18	56.47	43.4	14.2	0.228	0.342
T19	34.71	18.85	13.2	0.117	0.176
T20	55.31	26.49	12.3	0.169	0.254
T21	426.1	315.3	106	12.89	19.33
T22	468.5	405.3	206.5	28.86	43.28
T23	39.62	25.91	23.7	0.243	0.365
T24	537.6	512.5	148.6	26.27	39.4
T25	798.2	679.1	209.6	52.69	79.03
T26	548.3	288	206.4	30.76	46.15
T27	647.1	450.4	157.7	28.52	42.78
T28	14.2	8.52	16.6	0.0604	0.0906
T29	567.1	337.9	132	20.8	31.21
T30	969.6	627.9	231	63.32	94.97
T31	142.8	145	203.5	9.69	14.54
T32	167.3	97.27	64.5	2.66	3.98
T33	98.54	74.93	24.8	0.681	1.02
T34	943.2	650.8	229.2	59.48	89.23
				484.6214	726.931

3.5 Optimal DG Allocation

The Bat Algorithm successfully identified suitable buses and corresponding DG capacities for the network. The convergence pattern in Figure 7 shows that the optimization process reached a stable solution, while Figure 6 presents the resulting PV allocation across the network. The optimized placement contributed directly to the observed reduction in losses and improvement in voltage profile.

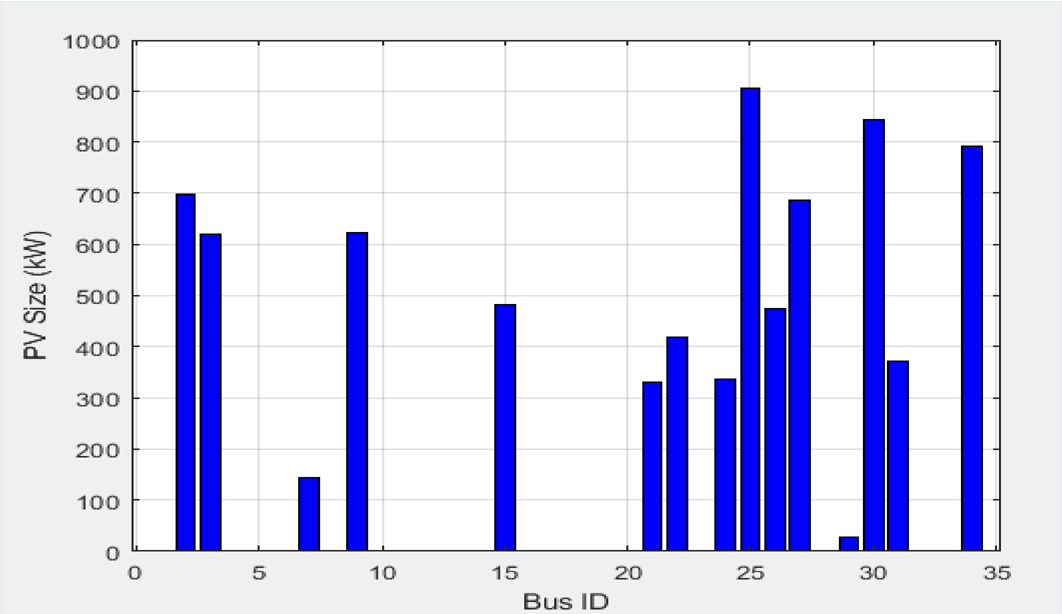

Figure 6: Optimal PV allocation using the Bat Algorithm.

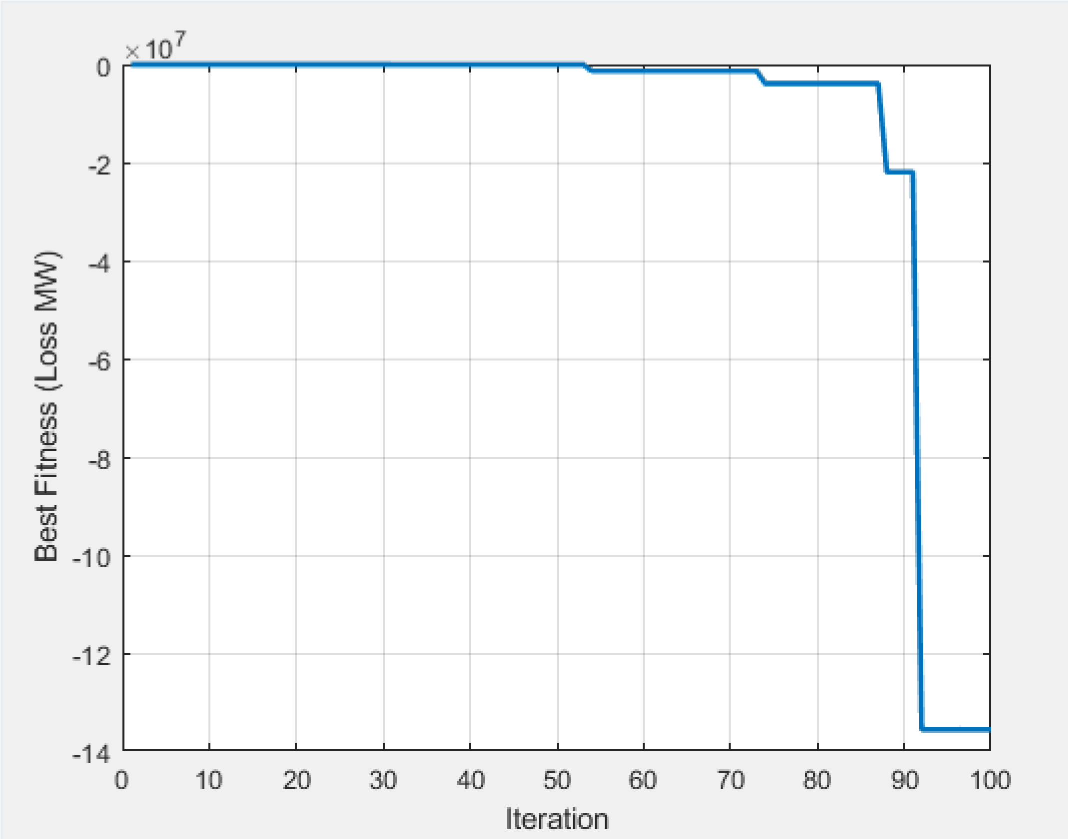

Figure 7: Bat Algorithm convergence curve.

3.6 Overall Performance Improvement

Overall, the integration of solar PV-based DG improved the technical performance of the Sapele 11 kV distribution network. Voltage deviations were corrected, real power losses were greatly reduced, and transformer overloading was minimized. These outcomes confirm that properly located DG can strengthen distribution network operation and improve service quality in radial systems.

4. DISCUSSION

The results show that integrating solar PV-based distributed generation into the Sapele 11 kV distribution network improves overall technical performance. The most visible effect was the sharp reduction in network losses, with active power loss falling from 1013.84 kW to 93.108 kW and reactive power loss reducing from 315.7 kvar to 35.448 kvar. This confirms that properly placed DG can reduce the burden on long radial feeders and improve network efficiency.

Another important outcome is the improvement in voltage profile. Buses that previously operated below acceptable limits were restored to stable operating levels after DG integration. The rise in minimum bus voltage from 87.82% to above 97% indicates that the added PV support strengthened weak sections of the network and improved voltage regulation across the system. This suggests that DG placement at critical buses can serve as an effective corrective measure in distribution networks with persistent voltage drop problems.

Transformer performance also improved after DG installation. Units that were previously overloaded experienced significant reductions in loading, showing that part of the network demand was successfully supported closer to the load points. This reduction in transformer stress has practical implications for network reliability, equipment lifespan, and operational security.

Despite these improvements, the study is limited to steady-state analysis. Dynamic operating conditions, including transient behaviour and time-varying load or solar generation patterns, were not considered. The study also depended on the available network data, which restricted the use of real-time operational profiles. These limitations mean that the findings should be interpreted as a technical assessment under modeled operating conditions rather than a full operational forecast.

5. CONCLUSION

This study has shown that solar PV-based distributed generation can improve the technical performance of the Sapele 11 kV distribution network. DG integration led to major reductions in active and reactive power losses, improved bus voltage levels, and reduced transformer loading across the network.

The results indicate that optimal placement and sizing of solar DG can strengthen weak buses, improve feeder performance, and relieve overstressed equipment. This highlights the value of distributed solar generation as a practical option for improving distribution system operation in areas affected by voltage instability and high technical losses.

Overall, the study demonstrates that renewable DG, when properly integrated, can provide meaningful support for distribution network enhancement in Nigeria.

REFERENCES

1. Begović, M., Pregelj, A., Rohatgi, A., & Novosel, D. (2001). Impact of renewable distributed generation on power systems. *Proceedings of the 34th Annual Hawaii International Conference on System Sciences*.
2. Ehsan, A., & Yang, Q. (2018). Optimal integration and planning of renewable distributed generation in the power distribution networks: A review of analytical techniques. *Applied Energy, 210*, 44–59.
3. Alele, J. O., Eni, J. N., Obuseh, E. E., Igweh, D., & Mbanuzue, C. E. (2024). Renewable energy in Nigeria: A comprehensive examination of the viability of solar energy in Nigeria. *International Journal of Innovative Research in Technology, 11*(5).
4. Obuseh, E., Eyenubo, J., Alele, J., Okpare, A., & Oghogho, I. (2025). A systematic review of barriers to renewable energy integration and adoption. *Journal of Asian Energy Studies, 9*, 26–45.
5. Eyenubo, O. J., Obuseh, E. E., Ebisine, E. E., Okpare, A. O., & Okieke, U. J. (2025). Analysis of Oria Abraka 33/11 kV power sub-station: A case for sustainable power supply. *NIPES Journal of Science and Technology Research, 7*(1), 204–218.
6. Acharya, N., Mahat, P., & Mithulananthan, N. (2006). An analytical approach for DG allocation in primary distribution network. *International Journal of Electrical Power & Energy Systems, 28*(10), 669–678.
7. Hung, D. Q., Mithulananthan, N., & Bansal, R. C. (2010). Analytical expressions for DG allocation in primary distribution networks. *IEEE Transactions on Energy Conversion, 25*(3), 814–820.
8. Murty, V. V. S. N., & Kumar, A. (2015). Optimal placement of DG in radial distribution systems based on new voltage stability index under load growth. *International Journal of Electrical Power & Energy Systems, 69*, 246–256.
9. Karunarathne, E., Pasupuleti, J., Ekanayake, J., & Almeida, D. (2021). The optimal placement and sizing of distributed generation in an active distribution network with several soft open points. *Energies, 14*(4), 1084.
10. Ayanlade, S. O., Ariyo, F. K., Jimoh, A., Akindeji, K. T., Adetunji, A. O., Ogunwole, E. I., & Owolabi, D. E. (2023). Optimal allocation of photovoltaic distributed generations in radial distribution networks. *Sustainability, 15*(18), 13933.
11. Salimon, S. A., Adepoju, G. A., Adebayo, I. G., Howlader, H. O. R., Ayanlade, S. O., & Adewuyi, O. B. (2023). Impact of distributed generators penetration level on the power loss and voltage profile of radial distribution networks. *Energies, 16*(4), 1943.