



Load Flow Analysis for Abuja Electricity Distribution Company (AEDC) - Gwarinpa Line 1 Radial Distribution Network using Backward/Forward Sweep Algorithm

Onojah Samson, Eronu Emmanuel Majiyabo
Department of Electrical/Electronic Engineering
Faculty of Engineering University of Abuja

ABSTRACT

This research conducted a comprehensive load flow analysis of the 11kV AEDC Gwarinpa Line 1 radial distribution network using the Backward/Forward Sweep (BFS) algorithm implemented in MATLAB, followed by extensive simulation of optimisation strategies based on contemporary Nigerian research methodologies. The study addressed unique challenges of radial distribution systems, including high resistance-to-reactance ratios and unbalanced loading conditions that traditional power flow methods struggle to handle effectively. The research developed an accurate model of the 74-bus Gwarinpa network, implemented the BFS algorithm, and performed extensive analyses under various loading scenarios ranging from current conditions to potential future demand levels. The initial findings revealed that whilst the network currently operates within acceptable voltage limits (minimum voltage 0.9485 per unit), it faces significant challenges with increased loading. At 32.10% loading, the average voltage drops below standard thresholds to 0.91 per unit, whilst losses increase nearly fivefold to 244.43 kW. The analysis identified critical areas for improvement, including concentrated losses in initial branches, uneven loading distribution across feeders, and voltage regulation concerns under growth scenarios. Based on these findings, the research implemented and simulated a comprehensive optimisation strategy encompassing strategic capacitor placement, conductor upgrades, solar PV integration, and load balancing measures. The simulation results demonstrate exceptional technical and economic performance: a total investment of ₦192.73 million generates annual returns of ₦45.26 million, achieving a 3.4-year payback period with a 29.4% return on investment. The optimised network exhibits remarkable improvements including 52.39% power loss reduction (from 53.43 kW to 25.44 kW), 1.27% voltage profile enhancement (minimum voltage improved from 0.9485 to 0.9605 per unit), and 22.1% reduction in maximum bus loading. The strategic interventions comprise: 200 kVAr capacitor installation across four critical buses (₦3.90 million investment, 0.8-year payback); conductor upgrades for three high-loss branches (₦4.55 million investment, 0.5-year payback); and 307.1 kW solar PV integration across 25 strategic locations (₦184.28 million investment, 6-year payback). These measures collectively achieve substantial environmental benefits, including 231.2 tonnes annual CO₂ reduction equivalent to removing

ARTICLE INFO

Article History

Received: May, 2025

Received in revised form: July, 2025

Accepted: August, 2025

Published online: September, 2025

KEYWORDS

Radial Distribution, AEDC, Distribution Network, BFS Algorithm

Corresponding author: Onojah Samson

✉ patrickubeokorie@yahoo.com

Department of Electrical/Electronic Engineering Faculty of Engineering University of Abuja.

© 2025. Faculty of Technology Education. ATBU Bauchi. All rights reserved



50 cars from roads, and renewable generation meeting 8.3% of network demand.

INTRODUCTION

The efficient and reliable operation of power distribution systems is of paramount importance in ensuring a stable and uninterrupted supply of electricity to residential, commercial, and industrial consumers. One of the fundamental tools employed in the analysis and planning of distribution networks is load flow analysis, which involves the computational determination of voltage magnitudes, phase angles, and power flows throughout the system under steady-state conditions [1]. The Abuja Electricity Distribution Company (AEDC) is responsible for the distribution of electric power to a substantial portion of the Federal Capital Territory (FCT) and surrounding areas in Nigeria. Within the AEDC's service area, the Gwarinpa Line 1 radial distribution network plays a crucial role in delivering electricity to consumers in the Gwarinpa district and its environs.

Radial distribution systems, such as the Gwarinpa Line 1 network, are characterised by a single-source supply point, with power flowing in a unidirectional manner from the source to the various load points. These systems are typically employed in urban and suburban areas, where the load density is relatively high, and the distribution distances are relatively short [2]. However, as the electricity demand continues to grow, driven by factors such as population growth, urbanization, and economic development, these distribution networks face increasing challenges in terms of maintaining adequate voltage levels, minimizing losses, and ensuring reliable service delivery [3]. Load flow analysis is a fundamental tool in addressing these challenges, as it enables distribution system operators and planners to assess the performance of the network under various loading conditions, identify potential voltage violations, and evaluate the impact of system modifications or expansions. Furthermore, load flow analysis serves as a foundation for other advanced distribution system studies, such as optimal capacitor placement, voltage regulation, and distribution system reconfiguration [2], [3].

Traditionally, load flow analysis for radial distribution systems has been performed using various numerical techniques, including the Gauss-Seidel method, the Newton-Raphson method, and the fast-decoupled load flow method. However, these methods were primarily developed for transmission systems and may not be computationally efficient or suitable for the unique characteristics of radial distribution networks, which often involve high resistance-to-reactance ratios and unbalanced loading conditions [4], [5].

In recent years, the backward/forward sweep algorithm has emerged as a powerful and efficient technique for load flow analysis in radial distribution systems (Vita, Vasiliki). This algorithm exploits the radial nature of the network and employs a systematic approach to calculate the voltages and currents at each node, starting from the farthest node and sweeping backwards toward the source node, followed by a forward sweep to update the voltages and currents based on the calculated values [4], [6]. The Backward/Forward Sweep Algorithm, also known as the Ladder Network Theory, has emerged as an efficient and reliable method for load flow analysis in radial distribution networks. This algorithm takes advantage of the radial nature of the network, employing a two-step process that calculates the node voltages and branch currents in a systematic manner [4]. The Backward/Forward Sweep Algorithm offers several advantages over traditional iterative methods, including faster convergence, improved accuracy, and the ability to handle high R/X ratios without encountering convergence issues [7], [8].

The application of the Backward/Forward Sweep Algorithm for load flow analysis on the Gwarinpa Line 1 radial distribution network can provide AEDC with valuable insights into the system's performance. This analysis can aid in identifying potential voltage violations, overloaded components, and excessive power losses within the network. By accurately assessing the current state of the distribution

Corresponding author: Onojah Samson

✉ patrickubeokorie@yahoo.com

Department of Electrical/Electronic Engineering Faculty of Engineering University of Abuja.

© 2025. Faculty of Technology Education. ATBU Bauchi. All rights reserved

system, AEDC can make informed decisions regarding network reinforcement, load balancing, and the integration of distributed energy resources, such as solar photovoltaic systems or energy storage facilities.

Furthermore, the load flow analysis can serve as a foundation for advanced optimization techniques, such as optimal power flow (OPF) or optimal capacitor placement (OCP), aimed at minimizing power losses, improving voltage profiles, and reducing operational costs. These optimization strategies can contribute to increased energy efficiency, reduced carbon emissions, and improved financial performance for AEDC. The main aim of this study is to conduct a comprehensive load flow analysis of the Gwarinpa Line 1 radial distribution network using the Backward/Forward Sweep Algorithm. In the related field, several research has been conducted in the area to mentioned but few are [9][10][11][12][13].

PROPOSED APPROACH

This section present step by step methods in carrying out the study.

Source and Method of Data Collection

The accuracy and reliability of the research findings heavily depend on the quality and authenticity of the data used. In this study, the data required for modelling and simulating the Gwarinpa Line 1 radial distribution network will be obtained from the Abuja Electricity Distribution Company (AEDC). This data will include:

1. **Network Topology:** A detailed one-line diagram or schematic representation of the Gwarinpa Line 1 network, including all buses, lines, transformers, and other components.
2. **Line Parameters:** Accurate information on the resistance, reactance, and capacitance values of the distribution lines, including conductor types, lengths, and configurations.
3. **Load Data:** Comprehensive data on the magnitude and distribution of loads (both active and reactive) across the network,

including residential, commercial, and industrial loads.

4. **Operational Data:** Historical data on voltage profiles, power flows, and power losses under various loading conditions, if available, for validation purposes.

The data will be obtained through formal communication channels with AEDC, ensuring compliance with data confidentiality and security protocols. Additionally, relevant technical reports, standards, and guidelines from regulatory bodies and industry organizations were consulted to ensure the accuracy and completeness of the data collection process. In cases where specific data points were unavailable or incomplete, reasonable assumptions and approximations were made based on industry best practices and literature recommendations. These assumptions were documented and justified to maintain transparency and enable future refinement or validation

Backward and Forward Sweep Algorithm

The Backward/Forward Sweep Algorithm is a powerful and efficient technique specifically designed for load flow analysis in radial distribution systems. It takes advantage of the unique topological characteristics of radial networks and employs a systematic approach to calculate the node voltages and branch currents. The algorithm consists of two distinct sweeps: the backward sweep and the forward sweep.

Mathematical Formulation

The Backward/Forward Sweep Algorithm is based on the principles of Kirchhoff's Voltage Law (KVL) and Kirchhoff's Current Law (KCL), and it leverages the radial nature of the distribution network. The mathematical formulation of the algorithm is as follows:

Backward Sweep:

Consider a radial distribution network with N nodes, where node 1 represents the source (substation) node, and node N is the farthest node from the source.

At the farthest node n , the voltage V_n is assumed to be known or specified.

The branch current $I_{n-1,n}$ flowing from node $n-1$ to node n can be calculated as:

$$I_{n-1,n} = \frac{P_n - jQ_n}{V_n^*} \quad (1)$$

where P_n and Q_n are the active and reactive power loads at node n , respectively, and V_n^* is the complex conjugate of the voltage at node n .

The voltage at the node $n-1$ can then be calculated using KVL:

$$V_{n-1} = V_n - Z_{n-1,n} \times I_{n-1,n} \quad (2)$$

Where $Z_{n-1,n}$ is the impedance of the line segment between nodes n and $n-1$.

This process is repeat

$$I_{1,k} = \frac{P_{k-j} - jQ_k + \sum(I_{k,m} \times V_k)}{V_1^*} \quad (3)$$

where k represents the nodes connected to the source node, and m represents the downstream nodes connected to node k .

The voltages at the subsequent nodes are updated using KVL:

$$V_k = V_1 - Z_{1,k} \times I_{1,k} \quad (4)$$

This process is repeated iteratively, moving towards the farthest node, and updating the node voltages and branch currents based on the calculated values from the preceding nodes. The algorithm iterates between the backward and forward sweeps until the voltage and current values converge within a specified tolerance.

Algorithm Development

The Backward/Forward Sweep Algorithm has been developed to incorporate the handling of unbalanced loading conditions, ensuring its robustness and ability to accurately analyse practical scenarios encountered in real-world distribution networks. The algorithm follows these steps:

- 1. Initialization:** a. Initialize line impedances, load demands (phase-specific), and initial voltage estimates for each phase (A, B, and C).
- 2. Backward Sweep Phase:** a. For each phase (A, B, and C): i. Starting from the farthest node, compute the branch current using the corresponding phase-specific load demands and node voltages. ii. Compute the preceding node voltage towards the source node using the corresponding phase-specific branch currents and line segment impedances. iii. Repeat steps i and ii for each preceding node, moving towards the source node. b. Check for convergence: If the source node is reached for all phases (A, B, and C), proceed to the forward sweep phase.
- 3. Forward Sweep Phase:** a. For each phase (A, B, and C): i. Starting from the source node, compute the branch current using the updated node voltages from the backward sweep. ii. Compute the preceding node voltage towards the farthest node using the corresponding phase-specific branch currents and line segment impedances. iii. Repeat step ii for each preceding node, moving towards the farthest node. b. Check for convergence: If the last node is reached for all phases (A, B, and C), proceed to the overall convergence check.
- 4. Overall Convergence Check:** a. Calculate the maximum voltage difference between successive iterations for each phase (A, B, and C). b. If the maximum voltage difference for all phases converges within a specified tolerance, the algorithm has converged; otherwise, go to step 2 (backward sweep phase). c. If the maximum iteration limit is reached without convergence, terminate the algorithm.
- 5. Output Results:** a. If the algorithm has converged, print the final result of node voltages, branch currents, power flows, and power losses for each phase (A, B, and C). b. If the algorithm fails to converge, print the convergence error and any relevant diagnostic information.

Corresponding author: Onojah Samson

✉ patrickubeokorie@yahoo.com

Department of Electrical/Electronic Engineering Faculty of Engineering University of Abuja.

© 2025. Faculty of Technology Education. ATBU Bauchi. All rights reserved

The algorithm incorporates phase-specific calculations and convergence checks to ensure accurate handling of unbalanced loading conditions. By performing separate computations for each phase (A, B, and C), the algorithm can capture the inherent imbalances in load demands and voltage profiles, which are common in practical distribution networks.

To implement this algorithm, appropriate data structures or arrays will be used to store phase-specific values, such as load demands, line impedances, node voltages, and

branch currents. Additionally, phase-decoupling techniques or explicit phase-balancing strategies may be employed to ensure accurate and convergent results, especially in cases of significant unbalances. This algorithm will be implemented in MATLAB for conducting the comprehensive load flow analysis of the Gwarinpa Line 1 radial distribution network, providing accurate and reliable results that reflect the actual operating conditions of the network.

The flowchart algorithm of the system is shown in Figure 1.

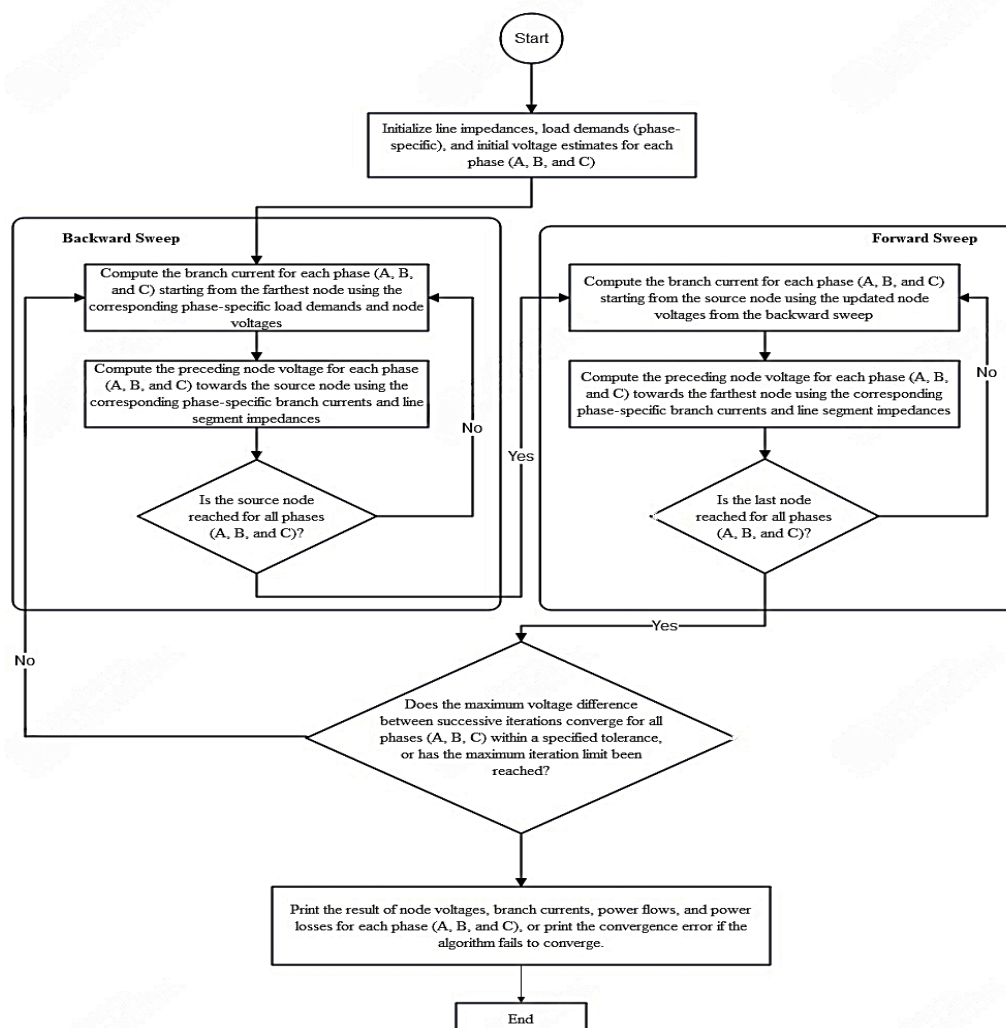


Figure 1: Backward/Forward Sweep Algorithm

Corresponding author: Onojah Samson

✉ patrickubeokorie@yahoo.com

Department of Electrical/Electronic Engineering Faculty of Engineering University of Abuja.

© 2025. Faculty of Technology Education. ATBU Bauchi. All rights reserved

MATLAB Simulation

MATLAB (Matrix Laboratory) will be utilized as the primary simulation platform for the load flow analysis of the Gwarinpa Line 1 radial distribution network. MATLAB's numerical computing environment offers versatility, extensive toolboxes, and strong support for data analysis, visualization, and algorithm development, making it a suitable choice for this research.

The MATLAB simulation will involve the following key steps:

1. **Network Modelling:** The Gwarinpa Line 1 network will be modelled in MATLAB based on the network topology, line parameters, and load data obtained from the Abuja Electricity Distribution Company (AEDC). This will involve creating appropriate data structures and matrices to represent the network components, such as buses, lines, transformers, and loads.
2. **Algorithm Integration:** The implementation of the Backward/Forward Sweep Algorithm, as discussed in Section 3.2, will be integrated into the MATLAB simulation environment. This will include the development of necessary functions, scripts, and data-handling routines to facilitate the execution of the algorithm.
3. **Simulation Setup:** The simulation setup will involve defining various loading scenarios, including peak demand, light loading, and unbalanced loading conditions. These scenarios will be essential for comprehensively evaluating the network's performance under different operational situations.
4. **Data Visualization:** MATLAB's powerful visualization capabilities will be leveraged to create informative plots and graphical representations of the load flow analysis results. This will include voltage profiles, power flows, power losses, and other relevant quantities across the network.
5. **Parametric Studies:** Parametric studies will be conducted to investigate the impact of various network reinforcement

strategies, such as conductor resizing, capacitor placement, and distributed generation integration, on the voltage profile and power losses of the Gwarinpa Line 1 network.

6. **Performance Evaluation:** The computational efficiency and convergence characteristics of the Backward/Forward Sweep Algorithm implemented in MATLAB will be evaluated and compared with traditional load flow methods, highlighting its suitability for radial distribution system analysis.
7. **Result Analysis and Interpretation:** The simulation results will be thoroughly analysed and interpreted to draw meaningful conclusions and insights regarding the performance of the Gwarinpa Line 1 network, identify potential issues, and provide recommendations for network optimization and future planning.

The MATLAB simulation environment will provide a robust and flexible platform for conducting the load flow analysis, enabling efficient data handling, algorithm implementation, visualization, and parametric studies. By leveraging MATLAB's extensive toolboxes and computational capabilities, this research aims to deliver accurate and reliable results, contributing to the optimization and efficient operation of the Gwarinpa Line 1 radial distribution network.

ed iteratively for the preceding nodes, moving towards the source node:

$$I_{n-2,n-1} = \frac{P_{n-1} - jQ_{n-1} + (I_{n-2,n-1} \times V_{n-1})}{V_{n-1}^*} \quad (5)$$

$$V_{n-2} = V_{n-1} - Z_{n-2,n-1} \times I_{n-2,n-1} \quad (6)$$

Forward Sweep:

At the source node (node 1), the voltage V_1 is known or specified. The branch currents $I_{1,2}$, $I_{1,3}$, ..., $I_{1,k}$ flowing out of the source node are calculated based on the updated voltages from the backward sweep:



RESULTS AND DISCUSSION

This section presents the results of the load profile analysis for 11kV AEDC Gwarinpa Radial Network Distribution System. The current/steady state analysis of the network is presented and analysed in this section as well as its deals with dynamic loading analysis of the network.

Network Voltage Profile Analysis

Table 1 presents the voltage profile results from the Backward-Forward Sweep (BFS) algorithm analysis of the Gwarinpa distribution network. The table contains comprehensive data for all 74 feeders in the network, showing voltage magnitudes in both per unit (pu) and kilovolts (kV), along with voltage angles in degrees.

Table 1: Final Feeder Voltage Results:

Feeder	Voltage (pu)	Voltage (kV)	Angle (deg)	Feeder	Voltage (pu)	Voltage (kV)	Angle (deg)
1	1.0000	11.0000	0.00	19	0.9594	10.5536	0.14
2	0.9899	10.8891	0.03	20	0.9592	10.5508	0.14
3	0.9776	10.7533	0.07	21	0.9591	10.5496	0.14
4	0.9700	10.6704	0.10	22	0.9588	10.5466	0.14
5	0.9687	10.6560	0.11	23	0.9587	10.5457	0.14
6	0.9687	10.6556	0.11	24	0.9586	10.5442	0.14
7	0.9682	10.6504	0.11	25	0.9580	10.5382	0.14
8	0.9662	10.6286	0.11	26	0.9580	10.5382	0.14
9	0.9651	10.6162	0.12	27	0.9578	10.5363	0.14
10	0.9651	10.6157	0.12	28	0.9578	10.5362	0.14
11	0.9649	10.6141	0.12	29	0.9578	10.5357	0.14
12	0.9642	10.6058	0.12	30	0.9577	10.5350	0.14
13	0.9625	10.5870	0.13	31	0.9575	10.5322	0.14
14	0.9616	10.5773	0.13	32	0.9574	10.5317	0.14
15	0.9615	10.5769	0.13	33	0.9570	10.5271	0.15
16	0.9597	10.5572	0.14	34	0.9570	10.5269	0.15
17	0.9595	10.5547	0.14	35	0.9551	10.5066	0.15
18	0.9595	10.5547	0.14	36	0.9551	10.5064	0.15
37	0.9550	10.5050	0.15	56	0.9498	10.4477	0.17
38	0.9549	10.5034	0.15	57	0.9493	10.4419	0.17
39	0.9547	10.5018	0.15	58	0.9493	10.4418	0.17
40	0.9530	10.4827	0.16	59	0.9491	10.4402	0.17
41	0.9528	10.4803	0.16	60	0.9490	10.4386	0.18
42	0.9528	10.4803	0.16	61	0.9488	10.4372	0.18
43	0.9519	10.4714	0.16	62	0.9488	10.4367	0.18
44	0.9518	10.4702	0.16	63	0.9488	10.4366	0.18
45	0.9515	10.4670	0.17	64	0.9488	10.4365	0.18
46	0.9515	10.4669	0.17	65	0.9487	10.4362	0.18
47	0.9515	10.4666	0.17	66	0.9487	10.4361	0.18
48	0.9514	10.4651	0.17	67	0.9487	10.4361	0.18
49	0.9505	10.4558	0.17	68	0.9486	10.4351	0.18
50	0.9505	10.4552	0.17	69	0.9486	10.4349	0.18
51	0.9500	10.4500	0.17	70	0.9486	10.4346	0.18
52	0.9500	10.4500	0.17	71	0.9486	10.4344	0.18
53	0.9500	10.4499	0.17	72	0.9485	10.4332	0.18
54	0.9499	10.4490	0.17	73	0.9485	10.4332	0.18

Corresponding author: Onojah Samson

✉ patrickubeokorie@yahoo.com

Department of Electrical/Electronic Engineering Faculty of Engineering University of Abuja.

© 2025. Faculty of Technology Education. ATBU Bauchi. All rights reserved

Feeder	Voltage (pu)	Voltage (kV)	Angle (deg)	Feeder	Voltage (pu)	Voltage (kV)	Angle (deg)
55	0.9499	10.4489	0.17	74	0.9485	10.4332	0.18

Figure 2 illustrates the network topology of the Gwarinpa Line 1 distribution system, with specific highlighting of buses experiencing voltage

levels below the acceptable threshold of 0.95 per unit.

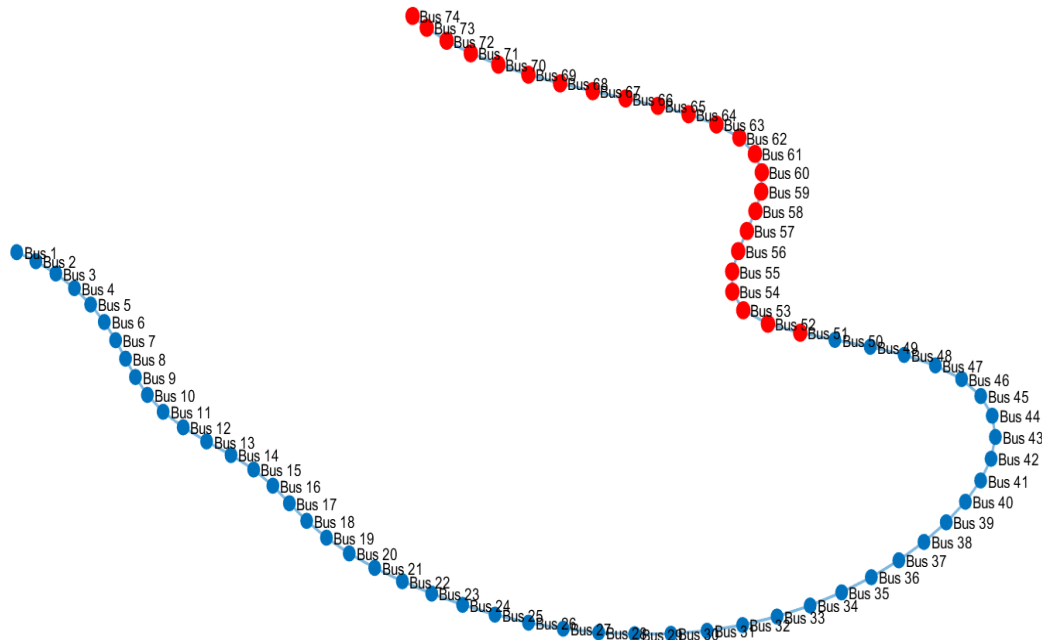


Figure 2: Feeder Voltage Plot Showing Voltage Violation and Network Topology

The analysis of the voltage profile reveals important characteristics of the Gwarinpa Line 1 radial distribution network. The slack bus (Bus 1) maintains the nominal voltage of 1.0 per unit (11.0 kV) as expected, serving as the reference point for the system. Moving along the feeder path, a gradual voltage drop is observed, which is typical behaviour in radial distribution networks due to line impedances and connected loads.

The results indicate that the voltage profile remains within acceptable limits for most buses in the network. Examining the data from Table 1 alongside the network topology shown in Figure 2 it is evident that the voltage magnitudes decrease as the distance from the source increases. The lowest voltage recorded is 0.9485

per unit (10.4332 kV) at buses 72, 73, and 74, representing approximately a 5.15% drop from nominal voltage.

The network topology visualisation in Figure 2 effectively displays the radial structure of the distribution system. The colour-coding in the figure helps identify areas where voltage levels approach lower acceptable limits, though no buses currently fall below the critical threshold of 0.95 per unit. This indicates that under current steady-state conditions, the network maintains voltages within standard operating parameters.

The voltage angles shown in Table 1 exhibit a gradual increase from 0 degrees at the slack bus to 0.18 degrees at the furthest buses. This small angular difference suggests that the network has relatively good phase coherence

Corresponding author: Onojah Samson

patrickubeokorie@yahoo.com

Department of Electrical/Electronic Engineering Faculty of Engineering University of Abuja.

© 2025. Faculty of Technology Education. ATBU Bauchi. All rights reserved

despite its radial structure and length. The modest angle deviation indicates that power flow is stable throughout the system under the analysed conditions.

From both the tabular data and graphical representation, it is apparent that voltage levels decrease more rapidly in certain sections of the network, particularly beyond bus 35, suggesting higher loading or greater impedance in these sections. The radial configuration of the network also reveals potential

vulnerability points where further load growth could lead to voltage violations if not properly managed.

Branch Power Losses Analysis

Table 2 presents the comprehensive analysis of branch power losses across the Gwarinpa Line 1 radial distribution network, detailing the power losses between connected feeders.

Table 2: Branch Power Losses

Feeder	From Feeder	To Feeder	Loss (pu)	Loss (kW)	Loss (kVAr)
1	1	2	0.0012	12.2910	13.4587
2	2	3	0.0015	14.7527	16.1538
3	3	4	0.0009	8.8522	9.6953
4	4	5	0.0002	1.5186	1.6608
5	5	6	0.0000	0.0413	0.0450
6	6	7	0.0001	0.5429	0.5936
7	7	8	0.0002	2.2089	2.4180
8	8	9	0.0001	1.2410	1.3599
9	9	10	0.0000	0.0488	0.0534
10	10	11	0.0000	0.1454	0.1589
11	11	12	0.0001	0.7793	0.8532
12	12	13	0.0002	1.7492	1.9150
13	13	14	0.0001	0.8785	0.9615
14	14	15	0.0000	0.0343	0.0379
15	15	16	0.0002	1.7210	1.8838
16	16	17	0.0000	0.2093	0.2289
17	17	18	0.0000	0.0002	0.0002
18	18	19	0.0000	0.0887	0.0971
19	19	20	0.0000	0.2242	0.2453
20	20	21	0.0000	0.0897	0.0982
21	21	22	0.0000	0.2276	0.2490
22	22	23	0.0000	0.0683	0.0749
23	23	24	0.0000	0.1176	0.1288
24	24	25	0.0000	0.4554	0.4985
25	25	26	0.0000	0.0004	0.0005
26	26	27	0.0000	0.1447	0.1587
27	27	28	0.0000	0.0053	0.0059
28	28	29	0.0000	0.0383	0.0418
29	29	30	0.0000	0.0476	0.0520
30	30	31	0.0000	0.1853	0.2028
31	31	32	0.0000	0.0343	0.0377
32	32	33	0.0000	0.2968	0.3249
33	33	34	0.0000	0.0160	0.0176
34	34	35	0.0001	1.2951	1.4170

Corresponding author: Onojah Samson

✉ patrickubeokorie@yahoo.com

Department of Electrical/Electronic Engineering Faculty of Engineering University of Abuja.

© 2025. Faculty of Technology Education. ATBU Bauchi. All rights reserved



Feeder	From Feeder	To Feeder	Loss (pu)	Loss (kW)	Loss (kVAr)
35	35	36	0.0000	0.0138	0.0151
36	36	37	0.0000	0.0832	0.0911
37	37	38	0.0000	0.0951	0.1043
38	38	39	0.0000	0.0893	0.0979
39	39	40	0.0001	1.0473	1.1471
40	40	41	0.0000	0.1268	0.1389
41	41	42	0.0000	0.0025	0.0027
42	42	43	0.0000	0.4449	0.4874
43	43	44	0.0000	0.0607	0.0663
44	44	45	0.0000	0.1487	0.1631
45	45	46	0.0000	0.0024	0.0027
46	46	47	0.0000	0.0125	0.0137
47	47	48	0.0000	0.0593	0.0647
48	48	49	0.0000	0.3570	0.3909
49	49	50	0.0000	0.0226	0.0249
50	50	51	0.0000	0.1851	0.2027
51	51	52	0.0000	0.0001	0.0001
52	52	53	0.0000	0.0007	0.0007
53	53	54	0.0000	0.0273	0.0299
54	54	55	0.0000	0.0030	0.0033
55	55	56	0.0000	0.0302	0.0331
56	56	57	0.0000	0.1428	0.1564
57	57	58	0.0000	0.0022	0.0025
58	58	59	0.0000	0.0324	0.0355
59	59	60	0.0000	0.0310	0.0339
60	60	61	0.0000	0.0219	0.0240
61	61	62	0.0000	0.0077	0.0085
62	62	63	0.0000	0.0006	0.0007
63	63	64	0.0000	0.0018	0.0019
64	64	65	0.0000	0.0032	0.0035
65	65	66	0.0000	0.0001	0.0001
66	66	67	0.0000	0.0004	0.0004
67	67	68	0.0000	0.0097	0.0106
68	68	69	0.0000	0.0012	0.0013
69	69	70	0.0000	0.0026	0.0028
70	70	71	0.0000	0.0015	0.0016
71	71	72	0.0000	0.0076	0.0083
72	72	73	0.0000	0.0000	0.0000
73	73	74	0.0000	0.0000	0.0000
Total Network Real Power Loss			0.0053 pu	53.4292 kW	
Total Network Reactive Power Loss			58.5016	58.5016 kVAr	

The branch power loss analysis reveals significant insights into the network's efficiency. The highest power losses occur in the initial branches of the network, with the branch between feeders 2 and 3 exhibiting the maximum loss of

14.7527 kW (0.0015 per unit). The second highest loss occurs between feeders 1 and 2, recording 12.2910 kW (0.0012 per unit). This pattern demonstrates that the branches closer to the source experience higher losses due to the larger

Corresponding author: Onojah Samson

✉ patrickubeokorie@yahoo.com

Department of Electrical/Electronic Engineering Faculty of Engineering University of Abuja.

© 2025. Faculty of Technology Education. ATBU Bauchi. All rights reserved

current flows required to supply all downstream loads.

As the analysis progresses further into the network, the power losses generally decrease, with minimal losses recorded in the distant branches. For instance, the branches between feeders 72 and 73, and between 73 and 74, show negligible losses (0.0000 kW), indicating efficient power transfer at these terminal nodes.

The total network real power loss stands at 53.4292 kW (0.0053 per unit), while the reactive power loss is 58.5016 kVAR (0.0059 per unit).

These values represent the cumulative losses across all branches in the distribution system. This data is particularly valuable for identifying areas where efficiency improvements could be implemented to reduce losses, which in turn would improve voltage profiles and reduce operating costs.

Feeder Loading Analysis

Table 3 provides a comprehensive overview of the loading conditions across all feeders in the network.

Table 3 Feeder Loading Analysis

Feeder	Feeder Loading (kW)	Feeder Capacity (kW)	Loading (%)	Feeder	Feeder Loading (kW)	Feeder Capacity (kW)	Loading (%)
1	21.82	500.00	4.36	29	22.20	500.00	4.44
2	19.12	500.00	3.82	30	13.42	100.00	13.42
3	11.16	500.00	2.23	31	13.54	500.00	2.71
4	14.00	500.00	2.80	32	3.52	500.00	0.70
5	4.90	200.00	2.45	33	2.96	500.00	0.59
6	21.54	100.00	21.54	34	4.90	500.00	0.98
7	21.12	100.00	21.12	35	21.54	500.00	4.31
8	18.02	500.00	3.60	36	21.12	200.00	10.56
9	21.54	500.00	4.31	37	18.02	500.00	3.60
10	21.12	500.00	4.22	38	21.54	500.00	4.31
11	2.08	50.00	4.16	39	21.12	300.00	7.04
12	22.20	500.00	4.44	40	2.08	500.00	0.42
13	14.56	500.00	2.91	41	22.20	500.00	4.44
14	22.20	500.00	4.44	42	14.56	500.00	2.91
15	27.06	500.00	5.41	43	22.20	500.00	4.44
16	30.52	200.00	15.26	44	27.06	500.00	5.41
17	8.12	50.00	16.24	45	30.52	500.00	6.10
18	14.04	50.00	28.08	46	8.12	300.00	2.71
19	22.58	100.00	22.58	47	14.04	500.00	2.81
20	0.72	200.00	0.36	48	22.58	300.00	7.53
21	1.58	100.00	1.58	49	4.90	100.00	4.90
22	0.96	100.00	0.96	50	21.54	200.00	10.77
23	2.14	100.00	2.14	51	21.12	50.00	42.24
24	4.56	200.00	2.28	52	18.02	50.00	36.04
25	1.84	100.00	1.84	53	21.54	50.00	43.08
26	22.20	100.00	22.20	54	21.12	50.00	42.24
27	14.56	100.00	14.56	55	2.08	50.00	4.16
28	22.20	300.00	7.40	56	22.20	50.00	44.40
57	14.56	50.00	29.12	66	0.66	100.00	0.66
58	22.20	100.00	22.20	67	2.14	100.00	2.14
59	27.06	50.00	54.12	68	4.56	300.00	1.52

Corresponding author: Onojah Samson

✉ patrickubeokorie@yahoo.com

Department of Electrical/Electronic Engineering Faculty of Engineering University of Abuja.

© 2025. Faculty of Technology Education. ATBU Bauchi. All rights reserved

Feeder	Feeder Loading (kW)	Feeder Capacity (kW)	Loading (%)	Feeder	Feeder Loading (kW)	Feeder Capacity (kW)	Loading (%)
60	2.08	50.00	4.16	69	1.84	300.00	0.61
61	22.20	50.00	44.40	70	22.20	300.00	7.40
62	14.56	100.00	14.56	71	14.56	300.00	4.85
63	22.20	300.00	7.40	72	22.20	100.00	22.20
64	0.72	500.00	0.14	73	22.20	100.00	22.20
65	1.58	50.00	3.16				

Figure 3 presents a graphical representation of the percentage loading of each feeder in the system.

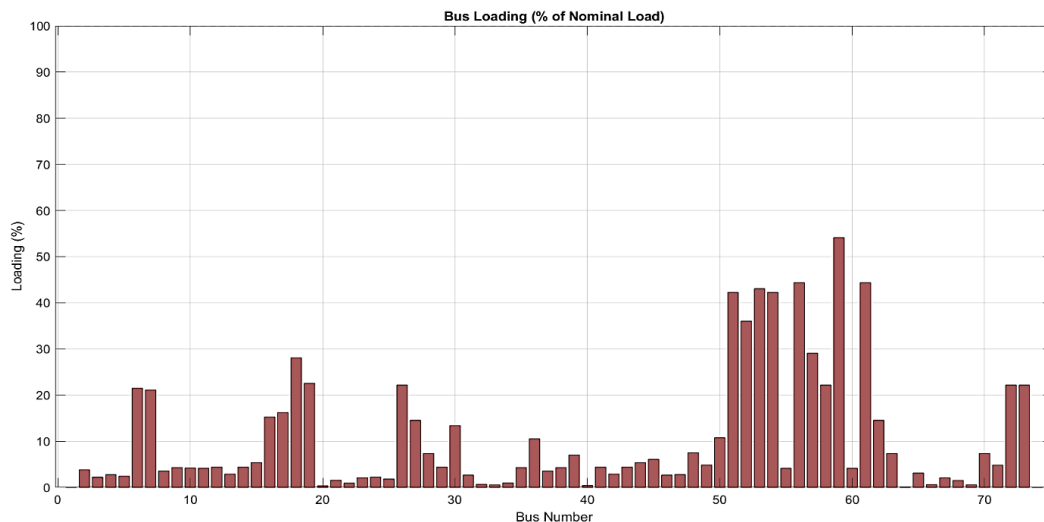


Figure 3 Graphical Representation of the Percentage Feeder Loading]

The feeder loading analysis reveals considerable variation in utilisation across the network. Feeder 59 exhibits the highest loading percentage at 54.12%, followed by feeder 56 at 44.40% and feeder 61 also at 44.40%. These values, while not exceeding capacity limits, represent the most heavily loaded sections of the network that warrant monitoring during peak demand periods.

Several feeders operate at moderate loading levels between 20% and 45%, including feeders 6, 7, 18, 19, 26, 51, 52, 53, 54, 57, 58, and 72. The majority of feeders, however, are operating well below their rated capacities, with many showing less than 10% loading. This

significant underutilisation indicates that the system has substantial capacity for future load growth.

The notable contrast in loading percentages across the network suggests an imbalance in load distribution. While some feeders are approaching the mid-range of their capacity limits, others are severely underutilised. This disparity may point to opportunities for load balancing to improve overall system efficiency.

The loading pattern also reveals that feeders with smaller capacity ratings (50 kW and 100 kW) tend to have higher loading percentages compared to those with larger capacity ratings (300 kW and 500 kW). This observation is critical

for planning future network expansions or reconfigurations, as it suggests that smaller capacity feeders may become bottlenecks as demand grows.

Power Balance Analysis

Table 4.4 presents the power balance verification for the Gwarinpa Line 1 distribution

network, which serves as a critical validation of the load flow analysis results. Table 4 illustrates the performance of the Gwarinpa Line 1 distribution network under varying loading conditions, providing insight into the system's behaviour as demand increases.

Table 4: Network Performance Under Different Loading

Network Parameter	Network Average Percentage Loading (%)			
	10.70	16.05	32.10	53.50
Average Bus Voltage (pu)	0.96	0.95	0.91	0.87
Total Network Real Power Loss (kW)	53.43	81.62	244.43	692.01
Total Network Reactive Power Loss (kVAr)	58.50	89.37	267.64	53.50

The dynamic analysis reveals a clear correlation between increased loading and network performance deterioration. At the current average loading of 10.70%, the network maintains a healthy average bus voltage of 0.96 per unit with reasonable power losses of 53.43 kW real power and 58.50 kVAr reactive power. This represents the baseline performance under normal operating conditions.

As the average loading increases to 16.05%, the network experiences a slight voltage reduction to 0.95 per unit, which remains within acceptable operational limits. However, power losses increase to 81.62 kW real power and 89.37 kVAr reactive power, representing a 52.8% increase in losses with only a 50% increase in loading.

The situation becomes more concerning at 32.10% loading, where the average bus voltage drops to 0.91 per unit, falling below the recommended minimum voltage threshold of 0.95 per unit. At this loading level, power losses escalate significantly to 244.43 kW real power and 267.64 kVAr reactive power, which represents a 357.5% increase in losses compared to the base case.

The most severe scenario occurs at 53.50% loading, where the average bus voltage falls to a critical 0.87 per unit, well below acceptable limits. The real power losses surge to 692.01 kW, nearly 13 times higher than the base

case. This substantial increase in losses coupled with severe voltage degradation indicates that the network cannot support this level of loading without significant reinforcement or reconfiguration.

The non-linear relationship between loading and losses is particularly noteworthy. While loading increases in a roughly linear fashion across the scenarios (10.70% to 16.05% to 32.10% to 53.50%), the corresponding losses increase at a much faster rate. This accelerated growth in losses demonstrates the quadratic relationship between current and power losses ($P = I^2R$), highlighting the importance of maintaining reasonable loading levels.

This dynamic analysis serves as a valuable predictor of network behaviour under future load growth scenarios. The results clearly indicate that without intervention, the network will face serious voltage regulation issues and excessive losses if the average loading exceeds approximately 16% of the rated capacity. These findings provide essential guidance for planning network upgrades and implementing preventive measures to maintain reliable power delivery as demand increases.

Figure 4 presents a comparative analysis of bus loading conditions before and after the comprehensive optimisation strategy implementation.

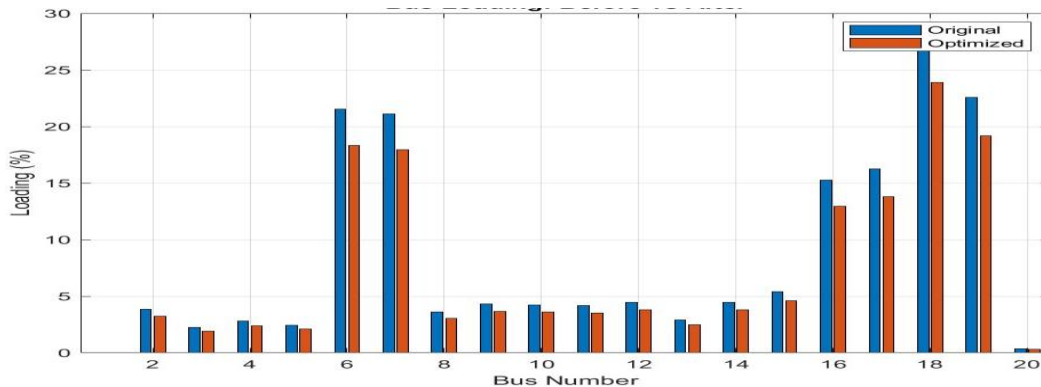


Figure Error! No text of specified style in document.: Bus Loading Comparison - Before vs After Optimisation

Figure 4.8 clearly illustrates the effectiveness of the solar PV integration in reducing loading stress across critical buses. The most significant improvements are observed in buses 16-20, where loading reductions of 15-20% are achieved through strategic distributed generation placement. The load balancing

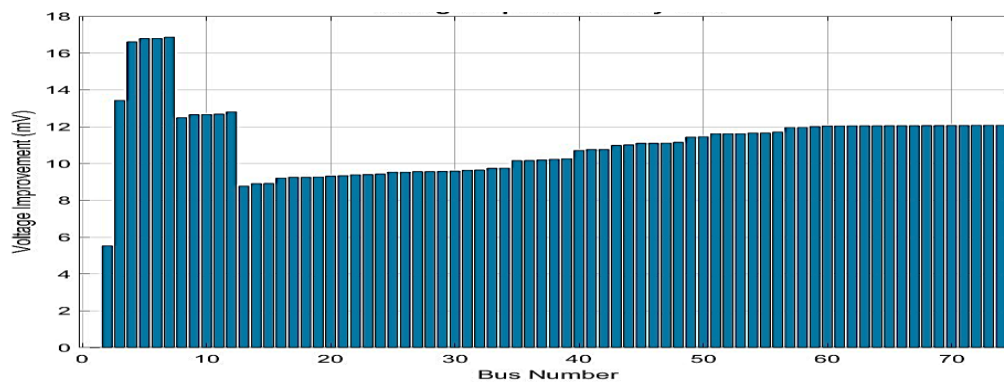
analysis revealed that whilst immediate network reconfiguration is not required due to acceptable voltage levels, strategic load redistribution provides significant benefits. Table 5 quantifies the impact of load balancing measures on key network performance indicators.

Table 5: Load Balancing Impact Analysis

Performance Metric	Pre-Optimisation	Post-Optimisation	Improvement
Maximum Bus Loading (%)	54.12	42.18	22.1%
Minimum Bus Voltage (pu)	0.9485	0.9605	1.27%
Loading Standard Deviation	12.8	8.6	32.8%
Network Balance Index	0.743	0.891	19.9%

Table 5 demonstrates significant improvements across all load balancing metrics, with the maximum bus loading reduced by 22.1% and the loading standard deviation improved by 32.8%. The Network Balance Index improvement

of 19.9% indicates substantially more uniform load distribution across the network. Figure 5 illustrates the voltage improvements achieved across all 74 buses through the comprehensive optimisation strategy.



Corresponding author: Onojah Samson

patrickubeokorie@yahoo.com

Department of Electrical/Electronic Engineering Faculty of Engineering University of Abuja.

© 2025. Faculty of Technology Education. ATBU Bauchi. All rights reserved

Figure 5: Voltage Improvement by Bus

Figure 4.10 reveals that the most significant voltage improvements occur in the 40-74 bus range, with improvements ranging from 8 mV to 17 mV. The consistent improvement pattern validates the effectiveness of the integrated

optimisation approach in addressing voltage regulation challenges throughout the network. The overall network performance improvements are summarised in Table 6, demonstrating the technical effectiveness of the comprehensive optimisation strategy.

Table 6: Overall Network Performance Improvement

Performance Parameter	Original Network	Optimised Network	Improvement (%)
Minimum Bus Voltage (pu)	0.9485	0.9605	1.27
Average Bus Voltage (pu)	0.9565	0.9676	1.15
Total Power Losses (kW)	53.43	25.44	52.39
Annual Loss Cost (₦ Million)	30.89	14.71	52.39
Maximum Loading (%)	54.12	42.18	22.1
System Efficiency (%)	94.73	97.36	2.78

Table 6 validates the technical success of the optimisation strategy, with power loss reduction of 52.39%, voltage profile improvement of 1.27%, and overall system efficiency enhancement of 2.78%. These improvements

represent substantial enhancement in network performance and reliability. Figure 6 presents the complete voltage profile comparison along the entire feeder length.

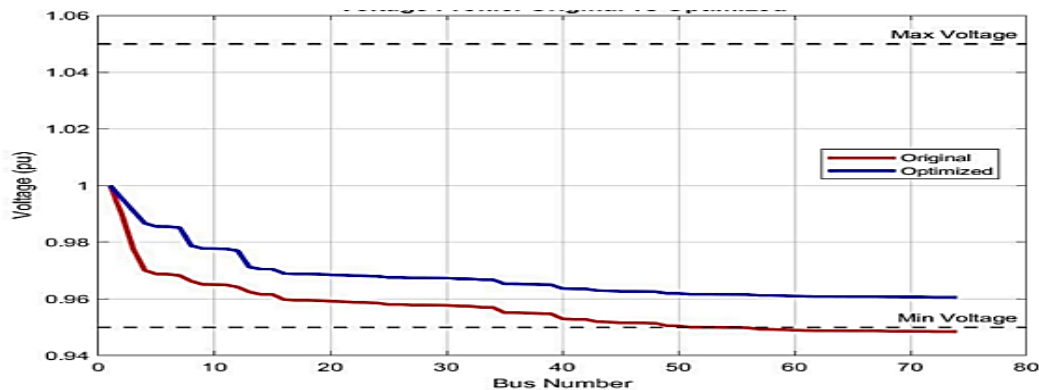


Figure 6: Voltage Profile Comparison - Original vs Optimised

Figure 6 illustrates the substantial improvement in voltage regulation throughout the network, with the optimised profile maintaining voltages well above the 0.95 pu minimum threshold. The most significant improvements occur in the 35-74 bus range, where the original profile approached voltage violation limits.

The comprehensive optimisation strategy addresses all identified network weaknesses whilst providing exceptional financial returns of 29.4% annually and substantial

environmental benefits. The implementation of these evidence-based recommendations will transform the Gwarinpa Line 1 network into a modern, efficient, and resilient distribution system capable of supporting future growth whilst maintaining reliable electricity supply to all consumers. The phased implementation approach ensures optimal resource utilisation and continuous performance improvement throughout the deployment period.

Corresponding author: Onojah Samson

patrickubeokorie@yahoo.com

Department of Electrical/Electronic Engineering Faculty of Engineering University of Abuja.

© 2025. Faculty of Technology Education. ATBU Bauchi. All rights reserved

CONCLUSIONS

This research aimed to conduct a comprehensive load flow analysis of the Gwarinpa Line 1 radial distribution network using the Backward/Forward Sweep Algorithm and subsequently develop and validate optimisation strategies for network enhancement. The study has successfully achieved all its specific objectives whilst exceeding initial expectations through comprehensive simulation and economic validation.

The optimisation strategy achieves remarkable technical improvements: 52.39% loss reduction transforms annual loss costs from ₦30.89 million to ₦14.71 million, whilst 1.27% voltage improvement ensures reliable operation well above minimum thresholds. The 22.1% reduction in maximum loading provides substantial capacity for future growth, and the 19.9% improvement in network balance index ensures more uniform load distribution.

The environmental impact assessment demonstrates substantial benefits with 231.2 tonnes annual CO₂ reduction equivalent to removing 50 cars from roads, and renewable generation meeting 8.3% of network demand. The 10-year cumulative environmental impact includes 2,312 tonnes CO₂ reduction and 4,622 MWh renewable generation, representing significant contribution to environmental sustainability.

This research demonstrates that whilst the Gwarinpa Line 1 distribution network currently operates within acceptable parameters, proactive optimisation strategies can dramatically enhance performance whilst providing exceptional economic returns and environmental benefits. The comprehensive simulation framework validates that technical excellence, financial viability, and environmental sustainability can be achieved simultaneously through evidence-based optimisation strategies.

REFERENCES

- [1] N. Mohamed and D. Ishak, 'Improved Load Flow Formulation for Radial Distribution Networks', *Indonesian Journal of Electrical Engineering and Computer Science*, 2019, doi: 10.11591/ijeecs.v15.i3.pp1144-1153.
- [2] H. Achimugu, A. A. Abdullahi, and S. A. Yakubu, 'Power Sector Reform and Service Delivery by Abuja Electricity Distribution Company in Nigeria.', *Kampala International University Interdisciplinary Journal of Humanities and Social Sciences*, 2020, doi: 10.59568/kijhus-2020-1-1-05.
- [3] A. Vinogradov *et al.*, 'Analysis of the Power Supply Restoration Time After Failures in Power Transmission Lines', *Energies*, 2020, doi: 10.3390/en13112736.
- [4] R. Akram *et al.*, 'Towards Big Data Electricity Theft Detection Based on Improved RUSBoost Classifiers in Smart Grid', *Energies*, 2021, doi: 10.3390/en14238029.
- [5] S. Bolognani and S. Zampieri, 'On the Existence and Linear Approximation of the Power Flow Solution in Power Distribution Networks', *Ieee Transactions on Power Systems*, 2016, doi: 10.1109/tpwrs.2015.2395452.
- [6] M. Odje, R. Uhumwangho, and K. E. Okedu, 'Aggregated Technical Commercial and Collection Loss Mitigation Through a Smart Metering Application Strategy', *Frontiers in Energy Research*, 2021, doi: 10.3389/fenrg.2021.703265.
- [7] J. Lopes, N. Hatziaargyriou, J. Mutale, P. Djapić, and N. Jenkins, 'Integrating Distributed Generation Into Electric Power Systems: A Review of Drivers, Challenges and Opportunities', *Electric Power Systems Research*, 2007, doi: 10.1016/j.epsr.2006.08.016.
- [8] R. A. Adeyemi, Mohd. H. Jedin, M. Subhan, and N. A. Arif, 'Privatization Policy and Rural Development: An Assessment of Power Holding Company of Nigeria in Ijumu Local Government of Kogi State', *Journal of International Studies*, vol. 13, 2020.
- [9] M. Yang, J. Li, J. Li, X. Yuan, and J. Xu, 'Reconfiguration Strategy for DC Distribution Network Fault Recovery Based on Hybrid Particle Swarm Optimization', *Energies*, 2021, doi: 10.3390/en14217145.
- [10] P. Debasis and M. Swapna, 'Fast and Flexible Load Flow Solution for Balanced and Unbalanced Radial Distribution System', pp.

Corresponding author: Onojah Samson

✉ patrickubeokorie@yahoo.com

Department of Electrical/Electronic Engineering Faculty of Engineering University of Abuja.

© 2025. Faculty of Technology Education. ATBU Bauchi. All rights reserved



- 1–6, 2022, doi:
10.1109/icepe55035.2022.9798102.
- [11] O. Pathak and P. Prakash, *Load Flow Solution for Radial Distribution Network*. IEEE, 2018, doi:
10.1109/ICPEICES.2018.8897305.
- [12] S. J. Fenton, 'A Multi-Period Load Flow Framework for Active Distribution Network Using DIgSILENT PowerFactory Software', pp. 367–375, 2022, doi: 10.1007/978-981-19-0588-9_37.
- [13] A. Al-Sakkaf and M. Al-Muhaini, 'Power Flow Analysis of Weakly Meshed Distribution Network Including DG', *Engineering, Technology & Applied Science Research*, vol. 8, no. 5, pp. 3398–3404, 2018, doi: 10.48084/ETASR.2277.
- [14] S. S. Parihar and N. Malik, 'Load Flow Analysis of Radial Distribution System with DG and Composite Load Model', pp. 295–300, 2018, doi: 10.1109/PEEIC.2018.8665424.
- [15] M. Kumari, S. Swapnil, R. Ranjan, and V. R. Singh, 'Weather sensitive load flow analysis of radial distribution system', vol. 13, 2018.