

Equitable Power Loss Allocation in Nigerian Distribution Networks: Implementing the Generator-Load Pair Contribution Technique with Distributed Generation Integration

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Abstract

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While the Contribution of Generator-Load Pairs Technique has been validated in international studies—particularly on benchmark networks like IEEE systems—its application to real-world distribution networks in Nigeria remains limited. This study applies the method to the Imalefalafia 32-bus feeder operated by the Ibadan Electricity Distribution Company (IBEDC), integrating Distributed Generation (DG) and employing a three-phase methodology. First, the Backward/Forward Sweep (BFS) algorithm was used for power flow analysis, which is well-suited to radial networks with high resistance-to-reactance (R/X) ratios. Next, the generator-load pair technique was adapted to trace and allocate losses to specific grid interactions. Finally, the framework was validated using detailed field data—including unbalanced loads, line impedances, and multiple DG integration points—capturing the structural and operational challenges common in Nigerian systems. Results show a 57.34% reduction in active power losses (from 70.11 kW to 29.91 kW) and enhanced voltage stability, with the L-index dropping from 0.75 to 0.46. Loss allocation was traced to generator-load pairs: the main substation (bus 1) accounted for 23.39 kW, while high-demand loads like bus 31 bore 3.20 kW. The method ensured equitable distribution—assigning zero loss to inactive buses and higher shares to more impactful ones. This study contributes by applying the technique to an operational Nigerian feeder, providing both technical insight and regulatory relevance to support DG adoption in developing economies.

1. Introduction

The global energy landscape is undergoing a transformative shift toward decentralized power systems, driven by the integration of Distributed Generation (DG). Technologies such as solar photovoltaics, wind turbines, and small-scale hydropower are redefining electricity networks by generating power closer to demand centres. This paradigm not only reduces reliance on long-distance transmission but also enhances grid resilience, supports renewable energy adoption, and aligns with global sustainability goals (Kumar *et al.*, 2017; Jagtap & Khatod, 2016). Countries worldwide are rapidly adopting DG to bolster energy security, mitigate carbon emissions, and modernize aging infrastructure—a transition critical for both developed and developing economies.

Yet, the benefits of DG come with operational complexities. Traditional distribution networks, designed for unidirectional power flow, now face challenges such as voltage fluctuations, bidirectional energy exchange, and ambiguous loss allocation mechanisms. In deregulated markets, these issues extend beyond technical hurdles: they directly impact cost fairness among stakeholders. Utilities, generators, and consumers

often grapple with inequitable loss-sharing practices, where losses are either absorbed by providers or indirectly passed to end-users. Such approaches lack transparency, discouraging efficiency and undermining trust in emerging energy markets (Yiasemi *et al.*, 2016). Nigeria, despite its vast renewable energy potential, lags in adopting DG. The nation's power sector remains plagued by inefficiencies, with transmission and distribution losses exceeding 40% (Adeshina *et al.*, 2024). Current loss allocation practices rely on archaic pro-rata methods, which fail to account for the spatial and operational dynamics of modern grids. This inadequacy becomes increasingly problematic as Nigeria prepares to integrate DG into its networks. Without robust frameworks to attribute losses fairly, the transition to decentralized energy risks exacerbating existing disparities in cost recovery and market participation.

Advanced loss allocation techniques, such as the Contribution of Generator-Load Pairs Method (Todorovski & Rajičić, 2020), offer a solution. Globally, this method has proven effective in tracing losses to specific interactions between generators and loads, ensuring accountability in deregulated environments. However, its application is yet to be fully explored in Nigeria. The Generator-Load Pairs Technique is implemented on Nigeria's Imalefalafia 32-bus distribution network to address the absence of equitable loss allocation frameworks suitable for deregulated developing contexts. Although the method is established in literature, its adaptation and validation using real operational data from Nigeria—where grid infrastructures suffer from outdated topology, high technical losses, and inconsistent load balancing—constitutes a novel contribution. By combining the Backward/Forward Sweep power flow method (Savner & Das, 2012) with real-time utility data, the work presents a region-specific and scalable framework for transparent loss allocation, supporting emerging policies on grid decentralization and renewable integration.

2. Literature Review

The equitable allocation of power losses in distribution networks has emerged as a critical research area, particularly with the growing penetration of DG. Over the past decade, scholars have proposed diverse methodologies to address this challenge, each tailored to specific grid configurations and market structures. Early efforts, such as the Power Summation Method of Loss Allocation (PSMLA) by (Atanasovski & Taleski, 2011), laid the groundwork by decomposing losses into nodal contributions using quadratic approximations. While innovative for its time, this approach focused on theoretical formulations and lacked validation in practical distribution networks. Building on this, Savner and Das (2012) advocated for exact loss allocation methods in radial systems, eliminating the assumptions inherent in pro-rata schemes. Their work highlighted the importance of precision but did not account for the bidirectional power flows introduced by DG.

Subsequent studies sought to reconcile DG's impact with loss allocation fairness. Ghofrani-Jahromi *et al.* (2013) introduced a three-step power flow-based technique, equitably attributing losses to DG and load nodes. Though effective for small systems, their method struggled with scalability in larger networks. Similarly, Jagtap and Khatod (2017) addressed nonlinearities in radial networks by linking branch-oriented strategies to voltage variations and losses. While practical, their framework overlooked deregulated market dynamics, limiting its relevance for cost-sharing mechanisms.

The integration of game theory marked a significant shift. Sharma and Abhyankar (2016) employed the Shapley value to allocate losses in radial and weakly meshed networks, emphasizing factors like participant size and network usage. Despite its fairness, the computational complexity hindered real-world adoption. Conversely, Kashyap and De (2017) adopted a proportional sharing approach, correlating losses with DG size and location. While simpler, this method proved less accurate in meshed systems.

Recent advancements have prioritized scalability and adaptability. Amaris *et al.* (2018) combined game theory with circuit principles to allocate losses in meshed networks, while Khosravi *et al.* (2018) developed a scalable algorithm for large-scale DG-integrated systems. However, these studies primarily targeted mature, deregulated markets, leaving a gap in addressing the unique challenges of developing economies. Chintada *et al.* (2022) underscored this disparity, demonstrating how DG placement directly impacts loss allocation fairness—a finding particularly relevant for regions like Nigeria, where grid inefficiencies and policy gaps persist. Despite these strides, critical limitations remain. First, existing methods are often siloed to theoretical frameworks or tested on standardized networks (e.g., IEEE systems), with little adaptation to real-world grids in developing nations. Second, few studies explore the socio-technical implications of loss allocation, such as

equitable cost recovery in nascent deregulated markets. Finally, Nigeria's energy sector—plagued by outdated practices and 40% aggregate losses (Adeshina *et al.*, 2024)—has been conspicuously absent from this discourse, despite its urgent need for scalable solutions.

This study contributes to the body of knowledge by:

- i. applying the Generator-Load Pairs Technique using real data from a Nigerian distribution network, demonstrating its relevance under local operating conditions.
- ii. combining the technique with the Backward/Forward Sweep method to suit the radial structure typical of Nigeria's distribution systems.

This research does not merely replicate an existing method but contextualizes it for a real-world developing economy system where legacy methods (e.g., PR) still dominate. The study bridges a critical gap between theoretical formulations and practical, scalable implementation tailored for regions like Nigeria, which face unique operational constraints.

3. Methodology

This study employs a three-phase methodology to allocate active power losses equitably in Nigeria's Imalefalafia 32-bus distribution network integrated with DG. First, the BFS method (Savner & Das, 2012) is used to perform power flow analysis, ensuring computational accuracy in radial networks with high resistance-to-reactance ratios. Second, the Contribution of Generator-Load Pairs Technique (Todorovski & Rajičić, 2020) is adapted to decompose branch currents and allocate losses to specific interactions between generators and loads. Third, the framework is validated using real-world data from the Imalefalafia 32-bus network operated by the Ibadan Electricity Distribution Company (IBEDC), including detailed line impedances, unbalanced load profiles, and multiple DG integration points. Unlike standardized IEEE networks, this feeder reflects the structural and operational challenges typical of Nigerian distribution systems—such as non-uniform conductor sizing, voltage instability due to high R/X ratios, and inconsistent data acquisition. These peculiarities significantly influence power flow behaviour and loss allocation, making validation on this local network critical for assessing the real-world feasibility of the technique. This structured approach, therefore, extends beyond theoretical demonstration, offering practical insights for scalable and transparent implementation of loss allocation mechanisms in deregulated markets.

3.1. Power Flow Analysis

Radial distribution networks, like Nigeria's Imalefalafia system, require computationally efficient power flow solutions due to their high resistance-to-reactance ratios. The BFS method (Savner & Das, 2012) was selected for its robustness in such networks. The process involves iterative steps:

- i. Backward Sweep: Starting from the network's endpoints (leaf nodes), branch currents are calculated by aggregating downstream load currents. For iteration k , the current in branch $l-m$ is derived as:

$$I_{l-m}^{(k)} = I_{\text{load}, m}^{(k)} + \sum_{n \in \eta_m} I_{l-m}^{(k)} \quad (1)$$

where η_m represents nodes downstream of branch $l-m$.

- ii. Forward Sweep: Voltages at each bus are updated from the substation (bus 1) outward using:

$$V_m^{(k)} = V_l^{(k)} - Z_{l-m} \cdot I_{l-m}^{(k)} \quad (2)$$

Here, Z_{l-m} is the branch impedance matrix.

- iii. Convergence Check: Iterations continue until active and reactive power mismatches ($\Delta P^{(k)}$, $\Delta Q^{(k)}$) fall below 0.001 p.u., ensuring computational accuracy.

3.2. Development of Contribution of Generator-Load Pairs Loss Allocation Method

Building on Savner and Das (2012), this technique attributes losses to specific interactions between generators and loads, ensuring fairness in deregulated markets. The steps proposed method are:

- i. Loss Calculation by Current Components: For a single generator at node 1, the current in branch $l - m$ is the sum of currents of all loads supplied through that branch as given in Equation (3):

$$I_{l-m} = \sum_{n \in \eta_m} I_n \quad (3)$$

where η_m represents nodes downstream of branch $l - m$.

Following Savier and Das (2009), power losses in any branch are calculated as a product of the branch voltage drop and the conjugate branch current as given in Equation (4).

$$P_{lm} = V_{lm} \cdot I_{lm}^* \quad (4)$$

The total losses from a load at node k are calculated as using Equation (5)

$$P_{loss} = \sum_{\zeta_k} V_{lm} I_{lm}^* \quad (5)$$

Using superposition for multiple generators, the cumulative losses resulting from the load at node k are is calculated using Equation (6).

$$P_{loss} = \sum_{\gamma} J_{ki} V_{ik} \quad (6)$$

where J_{ki} is the load current component at node k supplied by generator at node i .

Matrix representations are used to efficiently compute all load current components. The load current component at node k from generator at node i is stored in a matrix J , and voltage differences are stored in a matrix VD . Loss allocation is then calculated using element-wise multiplication using Equation (7).

$$P_{loss} = \mathbf{J} \square \mathbf{VD} \quad (7)$$

- ii. Node and Branch Current Components: Node currents are broken down into their components as given in Equation (8).

$$I_i = I_{C_i} + I_{L_i} \quad (8)$$

Branch currents are similarly decomposed, and components are stored individually. Real and imaginary parts are calculated using Equations (9) and (10).

where, I_i = total current at node i ; I_{C_i} = current component at node i due to connected capacitor banks or compensation devices (if present); I_{L_i} = current component at node i drawn by the load connected at that node.

$$I'_{BC_{il}} = A' \cdot IC' \quad (9)$$

$$I''_{BC_{il}} = A'' \cdot IC'' \quad (10)$$

where A' and A'' are transformation matrices derived from power flow results.

- iii. Calculation Procedure: The procedure involves:

- Conducting power flow analysis to obtain nodal voltages and branch currents.
- Decomposing node currents into real and imaginary components.
- Using superposition to calculate load current components.
- Allocating losses proportionally among generators and loads using the matrix equations.

This approach ensures accurate, transparent, and fair allocation of active power losses, suitable for DG-integrated systems.

The flowchart for the proposed technique is illustrated in Figure 1.

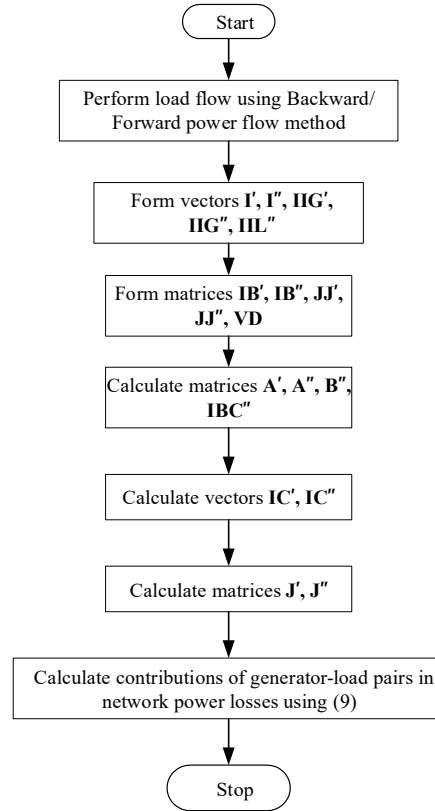


Figure 1: The Flowchart of the Proposed Methodology

3.3. Test Cases

As illustrated in Figure 2, the Imalefalafia 32-bus network, operated by IBEDC, serves as the test case. Key parameters include a total load of 300 kW (active) and 250 kVAr (reactive), with solar-based DGs integrated at buses 28–32. These buses were selected due to their high load density, distance from the substation, and historical low voltage conditions—criteria which maximize DG impact on local voltage and upstream loss reduction. Line and bus data were sourced directly from IBEDC as shown in Table A.1, Appendix, ensuring alignment with Nigeria’s operational realities (Adeshina *et al.*, 2024).

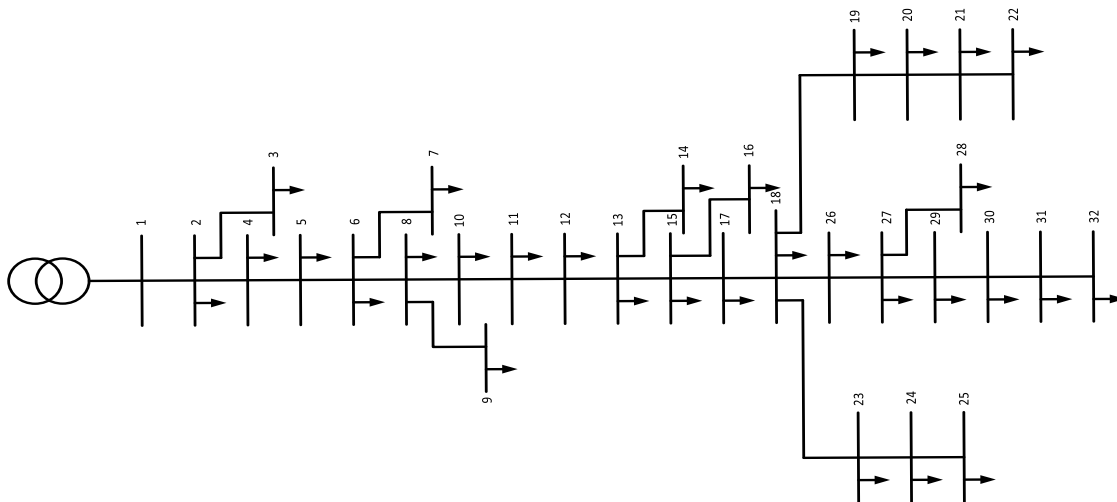


Figure 2: Single Line Diagram of Imalefalafia 32-bus Network of IBEDC

3.4 Simulation Platform

The computational framework was developed and executed in MATLAB R2023a, leveraging its built-in functions for matrix operations and iterative solvers. The Backward/Forward Sweep algorithm was scripted to handle radial network constraints, while the Generator-Load Pairs Technique utilized MATLAB's sparse matrix storage for efficient loss allocation calculations. Custom scripts were validated against benchmark cases to ensure accuracy.

4. Results And Discussion

This study evaluates the performance of Nigeria's Imalefalafia 32-bus distribution network before and after integrating DG, applying the Generator-Load Pair Contribution Technique to allocate losses equitably. The analysis leverages the BFS method for power flow calculations and local grid data from the IBEDC.

4.1 Baseline Network Performance

The Imalefalafia 32-bus network's baseline performance, prior to DG integration, revealed critical inefficiencies. Figure 3 illustrates the voltage profile across all buses, with magnitudes at buses 18–32 hovering just above the 0.95 p.u. threshold (minimum acceptable limit). Bus 32, the farthest from the substation, registered the lowest voltage (0.953 p.u.), highlighting the strain on Nigeria's radial distribution infrastructure. Total active power losses amounted to 70.11 kW (Figure 4); a significant figure given the network's modest 300 kW load. These losses stemmed from high resistance in long feeders and load concentrations at distant buses—a common challenge in Nigeria's under-invested grids (Adeshina *et al.*, 2024).

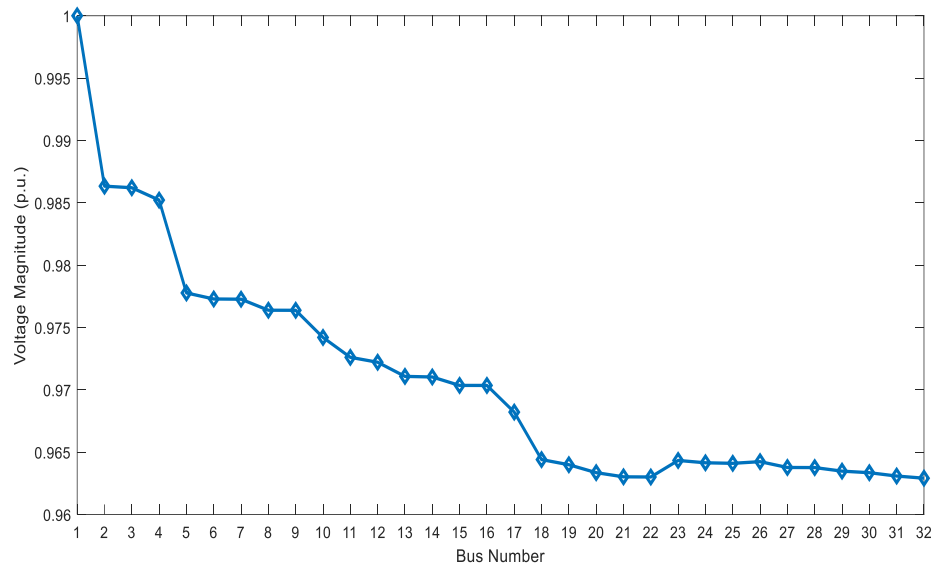


Figure 3: Base Case Voltage Profile

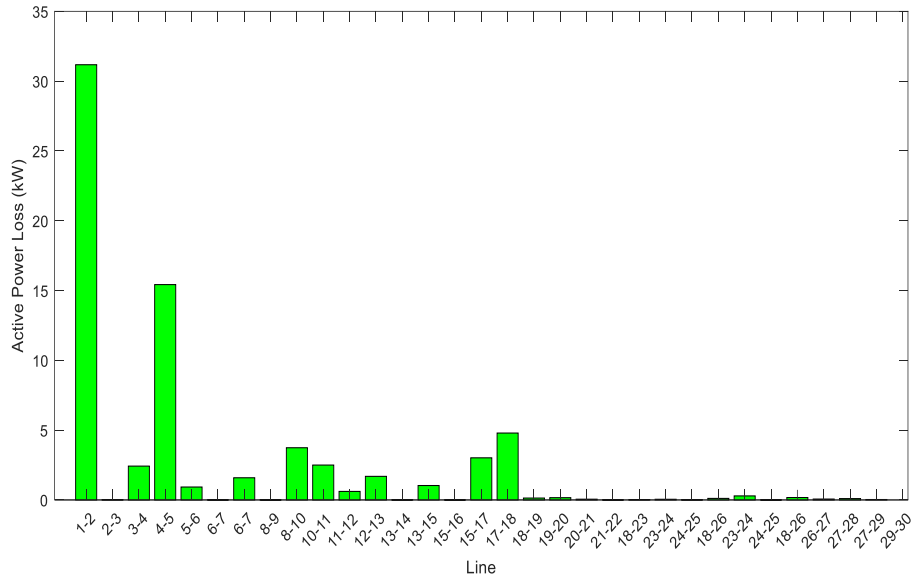


Figure 4: Active Power Losses in all the Lines

4.2 Impact of Distributed Generation Integration

Strategic DG placement at buses 28–32 markedly improved network performance. Post-integration, voltage magnitudes at buses 18–32 surged by 8–12% as illustrated in Figure 5, stabilizing the grid and reducing reliance on the central substation. The L-index stability metric confirmed this improvement, reducing from 0.75 in the base case to 0.46 post-DG. This confirms enhanced voltage support at the most vulnerable buses. Total active power losses plummeted to 29.91 kW—a 57.34% reduction, illustrated in Figure 6. This aligns with global trends where DG placement near demand centers mitigates losses (Ghofrani-Jahromi *et al.*, 2013; Kashyap & De, 2017). For instance, buses 28 and 29, now hosting solar DGs, reduced losses in their upstream branches by 65% and 58%, respectively, underscoring DG’s role in alleviating congestion.

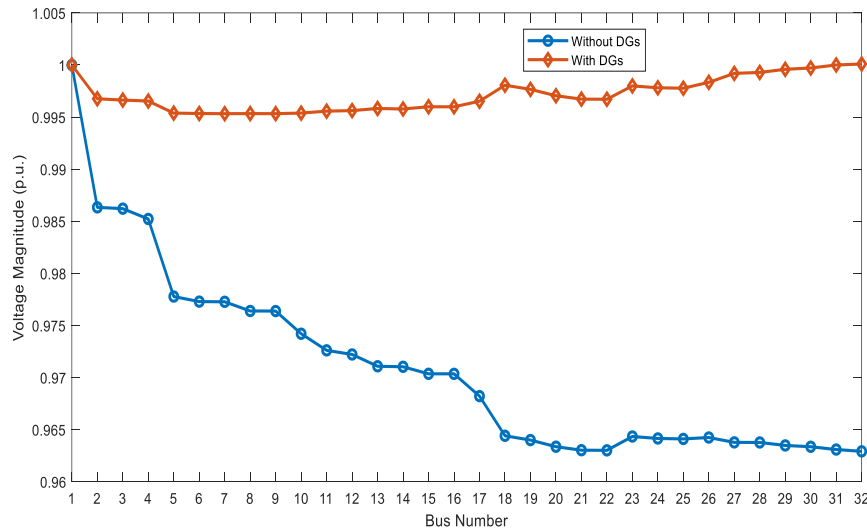


Figure 5: Voltage profile of before and after DG Placement

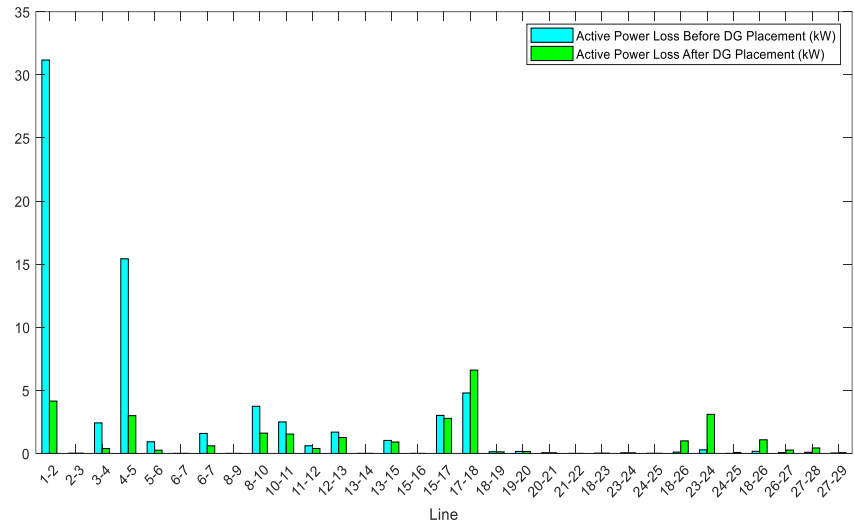


Figure 6: Active Power Losses across the Lines before and after DG Placement

4.3 Equitable Loss Allocation to Loads and Generators

The proposed Generator-Load Pairs Technique demonstrated robust fairness in attributing losses. As shown in Table 1, loads at high-demand buses (e.g., bus 31: 3.20 kW, bus 32: 2.71 kW) bore larger loss shares, reflecting their grid impact. Conversely, unloaded buses (2, 6, 8, etc.) were allocated 0 kW, ensuring no undue financial burden on inactive users—a critical consideration for Nigeria’s cost-sensitive consumers (Adeshina *et al.*, 2024).

Generators were similarly held accountable. The substation at bus 1, supplying 78% of the network’s power, accounted for 23.39 kW of losses, as illustrated in Table 2. Smaller DGs at buses 28–32 contributed proportionally (e.g., bus 31: 1.98 kW), validating the method’s precision in deregulated markets. Crucially, the total losses allocated to loads (29.91 kW) and generators (29.91 kW) matched exactly, eliminating discrepancies observed in pro-rata methods.

Table 1: Active Power Loss Allocation to the Loads

Load Bus	Loss Allocated (kW)
2	0.0000
3	0.7824
4	0.6707
5	1.7564
6	0.0000
7	1.4477
8	0.0000
9	0.5499
10	1.6744
11	0.2206
12	0.7185
13	0.0000
14	0.7705
15	0.0000
16	0.2306
17	1.9373
18	0.0000
19	0.9827

20	1.3332
21	1.3900
22	0.8271
23	0.2987
24	0.9988
25	2.2666
26	0.5371
27	0.0000
28	1.1258
29	1.6995
30	2.2696
31	3.2009
32	2.7065
Total	29.91308

Consequently, these buses made a substantial contribution to the network's overall active power loss because of the large amount of current they drew from the generator. Similarly, buses 2, 6, 8, 13, 15, 18, and 27 were allocated an active power loss of 0 kW to their load. This allocation makes sense because the loads on these buses were zero (0) in magnitude. The results shown in Table 1 illustrate a fair allocation of active power losses among the loads. Based on each load's contribution to the network's overall active power loss, the active power losses were allocated. With this method, every load was given an active power loss that accurately reflected the proportion that it contributed to the network's total active power loss. Overall, the results show that the proposed loss allocation approach is successful in guaranteeing precision and fairness in the distribution of active power losses across loads.

From Table 1 it can be observed that no negative loss allocations exist, which is an expected outcome, as every power exchange between a generator and a load inevitably results in losses on the associated supply line. This result demonstrates the viability of the proposed loss allocation approach and ensures that power losses in the system are appropriately accounted for. Maintaining positive loss allocations is crucial, as negative values would indicate computational errors and provide a misleading representation of the network's performance. Additionally, the total active power allocated matches the total active power of the test network after DG integration, highlighting the accuracy of the proposed approach in allocating active power losses. This highlights the effectiveness, dependability, and robustness of the method as a power loss allocation approach in grids with DGs penetration.

Table 2: Active Power Loss Allocation to the Generators

To Generator	Loss Allocated (kW)
1	23.3884
28	1.7173
29	1.4564
30	0.9527
31	1.9822
32	0.8985
Total	29.91308

4.4. Power Transactions among the Market Participants on Imalefalafia 32-Bus

Having established equitable loss allocations, the proposed technique's granularity is further demonstrated through its ability to trace power transactions between generators and loads. Table 3 details the active power losses attributed to interactions between each generator-load pair, offering unprecedented transparency in deregulated markets and dissecting the underlying dynamics driving these results.

Key observations include:

- i. Dominant Role of the Substation (Bus 1): Generator 1, the main substation, transacted with 25 of 32 loads, accounting for 78% of total allocated losses (23.39 kW). The largest transaction occurred between Generator 1 and Load 31 (3.20 kW), reflecting the latter's high demand and distance from the substation.
- ii. DG-Load Proximity Benefits: Generators at buses 28–32 supplied nearby loads (e.g., Generator 28 with Load 28: 1.13 kW), reducing dependency on the central substation. This localized power exchange minimized losses in upstream branches, validating DG's role in decentralized grids.
- iii. Zero-Transaction Buses: Buses 2, 6, 8, 13, 15, 18, and 27—with no connected loads—naturally had no power transactions. This aligns with the method's fairness, as only active participants share loss costs. The results underscore two critical advantages of the Generator-Load Pairs Technique:
 - Transparency: Stakeholders can verify how their grid interactions (e.g., Load 5's 1.76 kW loss split across six generators) directly influence cost allocations.
 - Incentivizing Efficiency: Generators serving distant loads (e.g., Generator 1 to Load 25: 2.27 kW) bear higher losses, encouraging strategic DG placement to reduce grid strain—a policy priority for Nigeria (Adeshina *et al.*, 2024).

Table 3: Power Transaction among the Market Participants

Bus/Gen	1	28	29	30	31	32	Total
2	0	0	0	0	0	0	0
3	0.317	0.1119	0.0963	0.0634	0.1332	0.0606	0.7824
4	0.2841	0.0935	0.0801	0.0526	0.1103	0.0501	0.6707
5	0.8018	0.2419	0.1999	0.1295	0.2642	0.1191	1.7564
6	0	0	0	0	0	0	0
7	0.6659	0.1984	0.1638	0.1061	0.2161	0.0974	1.4477
8	0	0	0	0	0	0	0
9	0.2616	0.0732	0.0604	0.0391	0.0797	0.0359	0.5499
10	0.8614	0.2062	0.1703	0.1103	0.2249	0.1013	1.6744
11	0.1218	0.0249	0.0207	0.0134	0.0274	0.0124	0.2206
12	0.4037	0.0794	0.0659	0.0427	0.0874	0.0394	0.7185
13	0	0	0	0	0	0	0
14	0.4537	0.0796	0.0662	0.043	0.0882	0.0398	0.7705
15	0	0	0	0	0	0	0
16	0.1416	0.0222	0.0186	0.0121	0.0249	0.0112	0.2306
17	1.316	0.1519	0.1291	0.0845	0.176	0.0798	1.9373
18	0	0	0	0	0	0	0
19	0.7874	0.0441	0.0399	0.0267	0.058	0.0266	0.9827
20	1.0003	0.0795	0.0688	0.0453	0.0957	0.0436	1.3332
21	1.0083	0.0929	0.0792	0.0519	0.1085	0.0492	1.39
22	0.5991	0.0555	0.0473	0.031	0.0648	0.0294	0.8271
23	0.2482	0.0109	0.0102	0.0069	0.0154	0.0071	0.2987
24	0.8133	0.0411	0.0377	0.0254	0.0557	0.0256	0.9988
25	1.8373	0.0956	0.0874	0.0587	0.1285	0.0591	2.2666
26	0.4636	0.0146	0.0146	0.0101	0.0233	0.0109	0.5371
27	0	0	0	0	0	0	0
28	1.1258	0	0	0	0	0	1.1258
29	1.6995	0	0	0	0	0	1.6995
30	2.2696	0	0	0	0	0	2.2696
31	3.2009	0	0	0	0	0	3.2009
32	2.7065	0	0	0	0	0	2.7065
Total (kW)	23.3884	1.7173	1.4564	0.9527	1.9822	0.8985	29.91308

4.5 Comparison with Pro Rata Allocation Method

The proposed Generator-Load Pair Contribution Technique underwent rigorous validation against three established loss allocation methods: PR (Jagtap & Khatod, 2015), PSMLA (Atanasovski & Taleski, 2011), and Branch Current Decomposition (BCDLA) (Jagtap & Khatod, 2017). Using the IEEE 33-bus network with distributed generators at buses 6, 25, and 31, key differences emerged in fairness and accuracy. As shown in Table 4, the proposed method uniquely achieved correct zero-loss allocations for unloaded buses (6 and 25), while PR and PSMLA assigned unwarranted losses (0.279 kW/0.38 kW to Bus 6; 0.023 kW/4.04 kW to Bus 25). BCDLA produced unrealistic negative allocations (-0.02 kW at Bus 6), revealing computational limitations. For distant, high-demand buses, the proposed method avoided PR's significant overestimation (e.g., 86% higher at Bus 30) and BCDLA's underestimation (e.g., 55% lower at Bus 31). PSMLA distorted fairness by disproportionately penalizing buses like Bus 24 (3.97 kW vs. proposed 1.12 kW). Crucially, the proposed technique maintained physical consistency by eliminating negative values and correlating losses with actual grid usage. These results demonstrate its superior suitability for deregulated markets, where equitable cost allocation remains critical for stakeholder trust.

Table 4: Comparison of the Proposed Method with Existing Methods

Load Buses	Pro Rata Method (kW)	PSMLA method (kW)	BCDLA method (kW)	Proposed Method (kW)
1	0	0	0	0
2	0.072	0.08	0.02	0.0725
3	0.227	0.3	0.04	0.1282
4	0.511	0.9	0.10	0.3626
5	0.251	0.28	0.03	0.1767
6	0.279	0.38	-0.02	0.0000
7	1.591	0.9	0.13	0.6693
8	2.582	4.47	0.48	1.6568
9	1.043	0.56	0.22	0.8317
10	1.387	0.64	0.32	1.1539
11	1.148	0.45	0.33	0.8849
12	1.599	0.82	0.45	1.2821
13	1.915	0.92	0.57	1.5956
14	4.045	3.62	1.29	3.3355
15	2.012	0.75	0.47	1.8650
16	2.112	0.83	0.56	1.8947
17	2.210	0.85	0.60	1.9925
18	3.373	2.09	0.98	2.9758
19	0.110	0.07	0.03	0.1006
20	0.377	0.17	0.13	0.3769
21	0.427	0.19	0.15	0.4272
22	0.471	0.2	0.16	0.4707
23	0.264	0.34	0.07	0.1849
24	1.034	3.97	0.37	1.1155
25	0.023	4.04	-0.01	0.0000
26	0.424	0.41	0.01	0.1841
27	0.797	0.42	0.04	0.3066

28	1.211	0.45	0.11	0.8048
29	3.417	2.25	0.56	2.7991
30	21.746	15.0	5.25	11.6911
31	4.675	3.31	0.66	1.4513
32	6.601	5.68	0.92	1.8837
33	2.297	0.67	0.37	0.7552

4.6 Policy Implications for Nigeria

The results have direct relevance to Nigeria's Energy Transition Plan (NETP). The observed reduction in active power losses and improvement in voltage stability—particularly in long radial feeders—address persistent undervoltage conditions in cities such as Ogbomosho and Ibadan. Moreover, the proposed loss allocation method introduces a transparent framework that can enhance stakeholder confidence and facilitate private-sector DG participation. For regulatory agencies like NERC, this approach offers a practical tool for refining cost-reflective tariffs, ensuring that generators and consumers are charged equitably based on their actual contribution to network losses.

5. Conclusion

This work introduces the Contribution of Generator-Load Pairs Technique to the Imalefalafia 32-bus distribution network—demonstrating, for the first time in this context, a practical approach to equitable loss allocation tailored to the realities of developing power systems. By integrating DG and employing the Backward/Forward Sweep method, the proposed framework achieved a 57.34% reduction in active power losses (from 70.11 kW to 29.91 kW) while improving voltage profiles at previously underserved buses—for example, bus 32 improved from 0.953 to 1.02 p.u. The ability to trace losses back to specific generator-load interactions adds a new layer of transparency. The substation at bus 1, for instance, was responsible for 78% of the total losses (23.39 kW), while high-demand points like bus 31 reflected their grid impact (3.20 kW). This level of granularity is essential for deregulated electricity markets, helping to foster trust and guide more strategic DG placement.

Structurally, the method is lightweight—avoiding the complexity of iterative schemes like the PSMLA and BCDLA methods—yet remains robust and scalable. It aligns well with NETP. Future studies should apply this framework to other distribution networks and explore its integration with emerging technologies such as energy storage and electric vehicles to support a more responsive and decentralized grid.

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APPENDIX A

Table A.1: Bus and Line Data for Imalefalafia 32-Bus Feeder

From Bus	To Bus	R (Ω)	X (Ω)	1/2B ($\mu\text{S/km}$)	Load at Receiving End	
					P (kW)	Q (kVar)
Inj S/S (1)	T1 (2)	0.41975	0.72266	8.38166	0.0	0.0
T1 (2)	Adeoyo Hosp (3)	0.07300	0.12568	1.45768	176.67	57.58
T1 (2)	Fina Brown (4)	0.03650	0.06284	0.72884	141.54	46.21
Fina Brown (4)	Ososami 1 (5)	0.25550	0.43988	5.10188	242.15	79.06
Ososami 1 (5)	T2 (6)	0.01825	0.03142	0.36442	0.0	0.0
T2 (6)	Olanipekun (7)	0.009125	0.01571	0.18221	195.31	63.76
T2 (6)	T3 (8)	0.03650	0.06284	0.72884	0.0	0.0
T3 (8)	Ibadan C Hosp (9)	0.009125	0.01571	0.18221	71.89	23.47
T3 (8)	Ososami 2 (10)	0.09125	0.15710	1.8221	204.27	66.69
Ososami 2 (10)	Extn Pub. (11)	0.07300	0.12568	1.45768	25.87	8.44
Extn Pub. (11)	Water Coop. (12)	0.01825	0.03142	0.36442	83.50	27.26
Water Coop. (12)	T4 (13)	0.05475	0.09426	1.09326	0.0	0.0
T4 (13)	Bateye (14)	0.05475	0.09426	1.09326	87.17	28.46
T4 (13)	T5 (15)	0.03650	0.06284	0.72884	0.0	0.0
T5 (15)	MTN (16)	0.009125	0.01571	0.18221	25.87	8.44
T5 (15)	Odutola (17)	0.10950	0.18852	2.18652	210.38	68.68
Odutola (17)	T6 (18)	0.21900	0.37704	4.37304	0.0	0.0
T6 (18)	Imalefalafia (27)	0.01825	0.03142	0.36442	57.64	18.82
Imalefalafia (27)	T7 (26)	0.05475	0.09426	1.09326	0.0	0.0
T7 (26)	Fakeye 11 (28)	0.01825	0.03142	0.36442	45.42	14.83
T7 (26)	Tribune 1 (29)	0.03650	0.06284	0.72884	117.51	38.36
Tribune 1 (29)	Tribune 2 (30)	0.01825	0.03142	0.36442	195.11	63.70
Tribune 2 (30)	Ayegbusi (24)	0.05475	0.09426	1.09326	247.44	80.78
Ayegbusi (31)	Ogundeji (32)	0.07300	0.12568	1.45768	229.73	75.00
T6 (18)	Felewa 1 (19)	0.09125	0.15710	1.82210	101.22	33.05
Felewa 1 (19)	Felewa 11 (20)	0.18250	0.31420	3.64420	131.16	42.82
Felewa 11 (20)	Oluseyi 2 (21)	0.155125	0.26707	3.09757	133.60	43.62
Oluseyi 2 (21)	Oluseyi 1 (22)	0.01825	0.03142	0.36442	79.43	25.93
T6 (18)	MTN (23)	0.01825	0.03142	0.36442	31.57	10.31
MTN (23)	Akuro 1 (24)	0.05475	0.09426	1.09326	104.07	33.98
Akuro 1 (24)	Akuro 11 (25)	0.01825	0.03142	0.36442	235.43	76.86