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Research Paper

Power Loss Minimization and Voltage Profile Improvement on Nigeria Distribution Network Using Whale Optimization Algorithm

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ABSTRACT

The power grid has significant power losses, unstable voltage, and large voltage drops during high demand due to its high resistance. One way to reduce power loss is by strategically placing and sizing Distributed Generation (DG) within the distribution network. However, improper installation of DG can increase power loss. To address this issue, various optimization techniques have been used, but finding the best solution and dealing with complex issues has been challenging. It is important to make efforts to optimally place and size DG in the distribution network to minimize power loss. To this end, a research study aimed to minimize power loss and improve the voltage profile on the DG network using the Whale Optimization Algorithm (WOA) was done. Objective functions were formulated and integrated into WOA, and power flow analysis on the standard IEEE 33-bus and 33-bus Ilorin industrial distribution feeder with and without DG was conducted using the forward and backward sweep distribution load flow algorithm. The optimal size and location of DG for power network loss reduction using sensitivity analysis (SA) and the whale optimization algorithm were determined. The results of the power flow analysis indicated that the total active losses and reactive power losses were reduced to varying extents with the integration of DG using both SA and WOA. The validation results showed that WOA is more efficient and provides high-quality solutions in terms of system loss reduction and best placement for DG in power systems compared to the application of SA. Additionally, WOA was found to offer accurate and high-quality solutions for power loss reduction compared to other existing techniques such as Loss Sensitivity Analysis (LSA), Grey Wolf Optimizer (GWO), Adaptive Shuffled Frogs Leaping Algorithm (ASFLA), and One Rank Cuckoo Search Algorithm (ORCSA).

Keywords: Optimization, Distributed Generation (DG), Whale Optimization Algorithm (WOA), Sensitivity Analysis (SA)

1. INTRODUCTION

The distribution network plays a vital role in ensuring the efficient and reliable delivery of electricity to end-users [1]. It is the utilities' most widely distributed and frequently monitored system for investment, maintenance, and operational management [2]. However, due to its extensive reach and complex structure, the network is susceptible to significant power losses, primarily due to its high resistance-to-impedance ratio, leading to energy dissipation in the form of heat [3, 4]. These losses directly impact the power quality delivered to consumers, a concern for utility providers and regulatory authorities [5].

Challenges in managing these losses include the unpredictable nature of events contributing to them, such as load complexity and the continuous expansion of power networks [6, 7]. As the load varies, especially in modern urban settings, the network experiences stress that increases power losses [8]. The ongoing growth and expansion of distribution networks further exacerbate the issue by introducing longer transmission distances and more components susceptible to inefficiencies, resulting in even higher losses [9].

Electric utilities are under pressure to keep power losses within specified limits due to factors such as environmental concerns, population growth, and unscheduled loading [10]. Increased global focus on environmental sustainability makes energy efficiency a central concern, as excessive power losses result in higher greenhouse gas emissions [11]. The rising power demand due to growing populations and unscheduled loading also adds unpredictability to the networks and can lead to service interruptions or degraded power quality [12].

Economic and ecological restrictions make power loss reduction an urgent objective. From an economic perspective, power losses directly translate to financial losses for utilities, as they need to compensate for the energy that is generated but never reaches the consumer [13]. Additionally, these inefficiencies increase operational costs, impacting the profitability and sustainability of utility companies [14]. Ecologically, reducing power losses aligns to reduce the carbon footprint of energy systems, and contribute to a more sustainable energy supply chain [15].

The reduction of power losses in distribution networks is widely recognized as a significant achievement in modern power system operations [16]. Power system management has made significant advancements aimed at minimizing these losses to enhance overall network performance [17]. The focus on loss minimization has become increasingly crucial as distribution networks expand and loads become more complex [18]. Implementing strategies and technologies to reduce losses, such as through more efficient network design, advanced monitoring, or optimization algorithms, can lead to substantial improvements in system reliability, energy efficiency, and sustainability [19].

It's important to note that while power loss in distribution networks cannot be eliminated, it can be controlled and minimized [20]. Factors such as the types of linked loads, network structure, system voltage, current conditions, and the characteristics of electrical devices all influence distribution power losses, as well as parameters of transmission lines such as length, type, size, and material of cables, among others [21]. As a result, power system engineers are growing interested in significantly reducing power loss.

Various analytical approaches have been utilized to minimize power loss in distribution networks, including network reconfiguration, installation of energy storage systems, Distributed Resources (DR) installation, and capacitor placement [22]. Among these approaches, the strategic sizing and location of Distributed Generation (DG) in the distribution network is widely regarded as a feasible choice for minimizing power loss [23]. Distributed Resources, electrical power resources connected directly to the network, encompass a wide range of energy sources, such as turbines, fuel cells, Photovoltaic (PV), and storage devices, with capacities ranging from 1 kW to 10 MW [24]. Installing these resources on distribution networks enhances network power quality, improves the network voltage profile, and reduces network power loss.

However, improper installation of DR on distribution networks can lead to increased network power loss and have undesirable effects on the network [25]. Furthermore, selecting the best sizing and location for installing DR in distribution networks is considered an optimization problem. Thus, implementing an optimization approach that can determine the optimal size and placement of these resources to minimize distribution network power loss can be more beneficial for system planning engineers.

Several evolutionary, swarm intelligent-based optimization techniques and new metaheuristic optimization algorithms, such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Whale optimization algorithm (WOA), Cuckoo Search Algorithm (CSA), Firefly Algorithm (FA), and Salp Swarm Algorithm (SSA), among others, are reported to have excelled in solving power loss minimization on distribution networks through optimal DR sizing and location in terms of computational time, convergence, and quality of solution [26]. These techniques offer the benefit of identifying a set of non-dominated solutions in just one run since they can perform multi-point searches. Additionally, they are less susceptible to issues related to dimensionality.

The research aims to address the issue of power loss in the Nigerian distribution network by focusing on the optimal sizing and location of Distribution Resources (DRs) with the following specific objectives viz; to perform power flow analysis on the standard IEEE 33-bus and 33-bus Ilorin industrial distribution feeder without and with the inclusion of DG using the Forward and Backward Sweep distribution load flow algorithm, to optimally size and locate DG for network power loss reduction using Sensitivity Analysis (SA) and Whale Optimization Algorithm (WOA), to simulate DG model with SA and WOA using MATLAB R2019a, and to validate the simulation results of IEEE 33-bus and compare with other optimization techniques such as Grey Wolf Optimizer (GWO), Adaptive Shuffled Frogs Leaping Algorithm (ASFLA) and One Rank Cuckoo Search Algorithm (ORCSA) and evaluate on 33-bus Ilorin Industrial distribution Network using active power loss.

Power loss in distribution networks, particularly in developing countries like Nigeria, is a concern due to ageing infrastructure, growing demand, and inefficient system design. By strategically deploying DRs, this research aims to improve the efficiency and reliability of electricity distribution across the country.

Distribution Resources (DRs), such as Distributed Generation (DG) units, capacitors, and energy storage systems, play a crucial role in modern power systems. Properly sized and optimally located DRs can help mitigate power losses by reducing the distance electricity must travel from generation points to consumers, minimizing resistive losses in transmission lines. Additionally, DRs can support voltage regulation, improve power quality, and provide backup during outages. However, if DRs are not appropriately sized or placed, they can introduce inefficiencies, increase operational costs, and exacerbate power losses. Therefore, an optimization-based approach is essential to ensure that the DRs provide the maximum benefit.

The research proposes the Whale Optimization Algorithm (WOA) as the optimization technique due to its proven ability to avoid common pitfalls in traditional optimization methods, such as being trapped in local optima. WOA is a bio-inspired algorithm that mimics the hunting behaviour of humpback whales, particularly their bubble-net feeding strategy, to find optimal solutions in complex search spaces. The algorithm's capacity to search both globally and locally allows it to explore a broad range of potential solutions before refining its search to find the most optimal one. This makes WOA particularly suitable for solving multi-dimensional optimization problems, like those found in power distribution networks, where multiple variables (such as DR size, location, and network configuration) need to be considered simultaneously.

Problem Formulation

The primary objective of this research is to determine the optimal size and location of a DG unit within a radial distribution network to minimize power loss. The network power losses would be considered as indices in identifying the optimal sites for DG placement, highlighting areas with the most and least significant impact on enhancing loss reduction efficiency. Mathematically, the objective function for this research is given in terms of total active power losses:

$$F = Min(P_{TLoss}) \qquad 1$$

$$Min \quad P_{TLoss} = \sum_{i=1}^{n} I_i^2 \times R_i \qquad 2$$

1. where;
2. F is the objective function
3. n number of branches
4. i is branch number
5. P_{Loss} is the total real power loss
6. I_i is the branch current at bus i
7. R_i is the resistance of network at bus i

a. The minimization problem is subjected to the following constraints:

8. The power load flow constraints as:

$$P_i + P_{DGi} - P_{Di} + P_{Loss} = 0 \qquad 3$$

$$Q_i + Q_{DGi} - Q_{Di} + Q_{Loss} = 0 \qquad 4$$

where,

Pi is real power flow at bus i

Qi is reactive power flow at bus i

P_{DGi} is real power generation from DG placed at bus i

Q_{DGi} is reactive power generation from DG placed at bus i

P_{Di} is real power demand at bus i

Q_{Di} is reactive power demand at bus i

The constraints on generator voltages, real power outputs, and reactive power outputs are confined by their respective lower and upper limits as follows:

$$V_{Gi}^{Min} \le V_{Gi} \le V_{Gi}^{Max} \qquad 5$$

$$P_{Gi}^{Min} \le P_{Gi} \le P_{Gi}^{Max} \qquad 6$$

$$Q_{Gi}^{Min} \le Q_{Gi} \le Q_{Gi}^{Max} \qquad 7$$

$$P_{DGi}^{Min} \le P_{DGi} \le P_{DGi}^{Max} \qquad 8$$

$$Q_{DGi}^{Min} \le Q_{DGi} \le Q_{DGi}^{Max} \qquad 9$$

The power balance constraints:

$$\sum_{i=1}^{n} P_{DGi} = \sum_{i=1}^{n} P_{Di} + P_{Loss} \qquad 10$$

where,

V_i, $V_i^{\min}$ and $V_i^{\max}$ are the magnitude, minimum and maximum value of voltage at bus i

P_{Gi}, P_{Gi}^{Min} and P_{Gi}^{Max} are the real power load, minimum and maximum real power at bus i

Q_{Gi}, Q_{Gi}^{Min} and Q_{Gi}^{Max} are the reactive power load, minimum and maximum reactive power at bus i

P_{DGi}, P_{DGi}^{Min} and P_{DGi}^{Max} are the DG real power load, minimum and maximum real power generation from DG capacity
at bus i

Q_{DGi}, Q_{DGi}^{Min} and Q_{DGi}^{Max} are the DG reactive power load, minimum and maximum reactive power generation from DG capacity at bus i.

2. MATERIALS & METHODS

The work commences with load flow studies of the 33-bus Ilorin industrial distribution feeder using the Fast-Decoupled Load Flow Technique, without incorporating Distribution Generation (DG). Subsequently, load flow studies are conducted with the optimal placement of DG to determine the active and reactive components of the power flow in the network, as well as the losses. A sensitivity analysis for the optimal placement of DG is performed. The global optimal location for DG is determined using the Whale Optimization algorithm, and the performance of the algorithm is thoroughly evaluated and validated. Figure 1a shows the single line diagram of 33-bus Ilorin industrial distribution feeder. The Flowchart of Distribution Load Flow without and with DG is shown in Figure 1b

IBEDC, the local utility responsible for managing the distribution network in the Ilorin area, supplied real-world data regarding the specific load points, substations, and distribution lines relevant to the 33-bus feeder under investigation. This data was crucial for accurately reflecting the actual operating conditions of the industrial feeder and ensuring that the simulation was based on up-to-date and precise information.

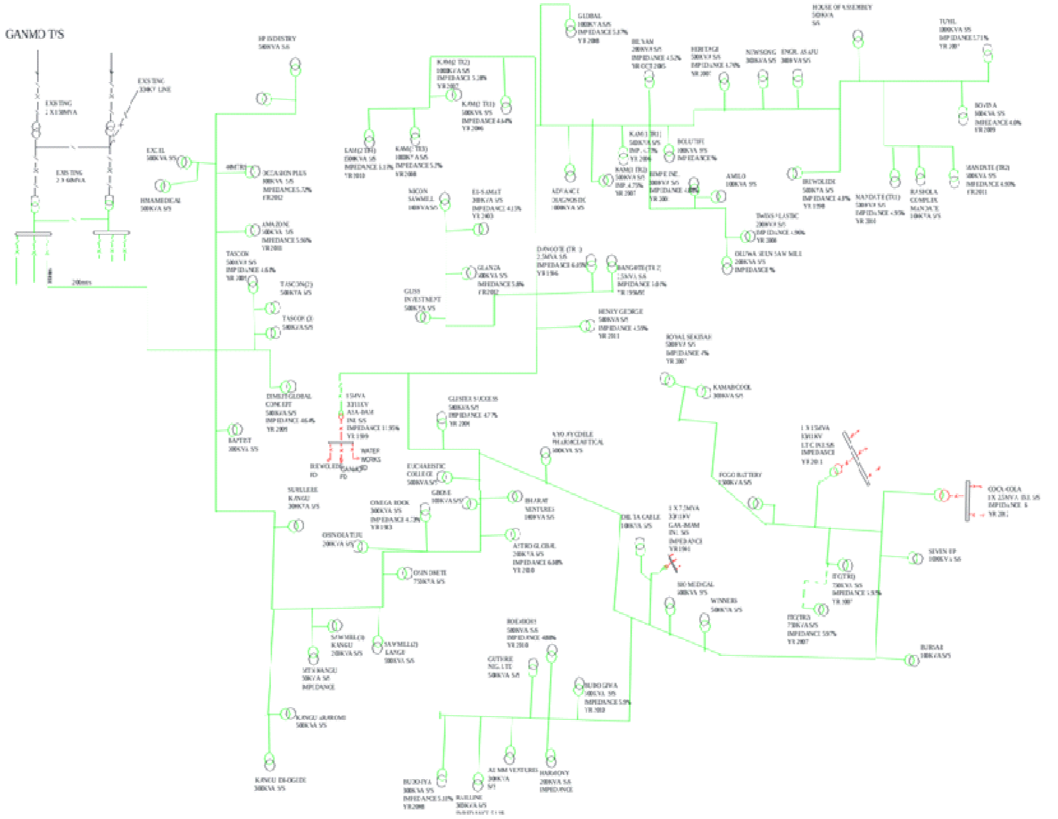

Figure 1a: The single line diagram of 33-bus Ilorin industrial distribution feeder

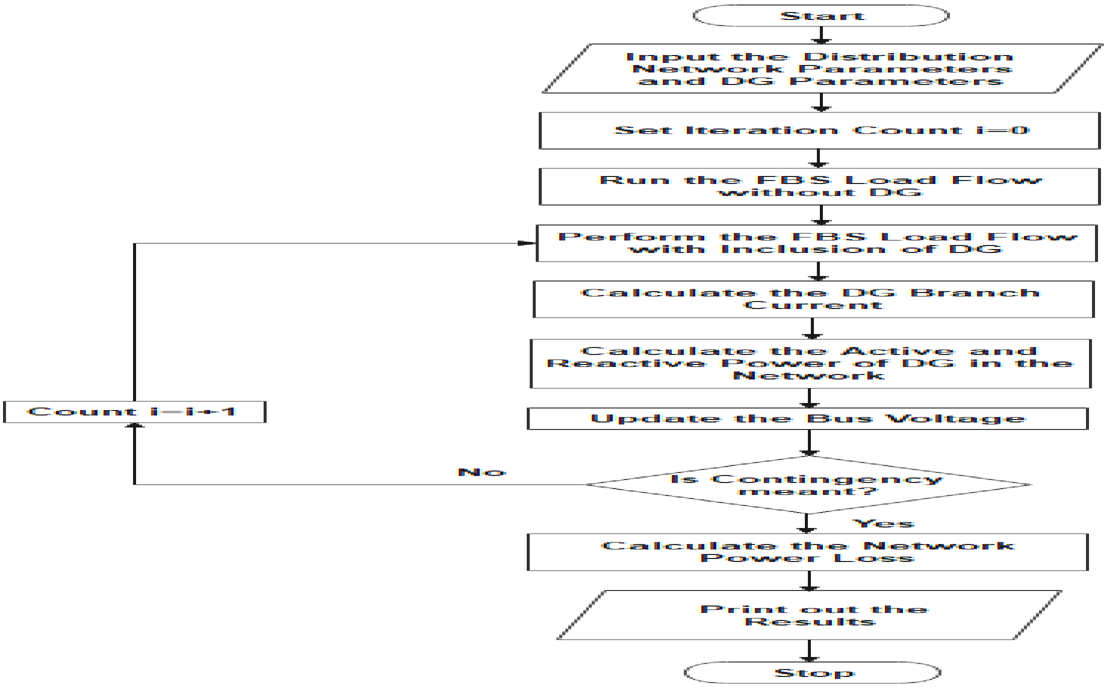

Figure 1b: The Flowchart of Distribution Load Flow without and with DG

2.1 Implementation and Simulation of Sensitivity Analysis for Optimal DG Placement

Based on minimizing loss, the Sensitivity Analysis (SA) method was used to identify the most effective candidates for Demand Response (DR) allocation. This approach offered the benefit of expediting the convergence of the optimization algorithm. The resulting optimization was implemented using MATLAB (R2019b). To address operational constraints, the optimization problem is formulated as:

Optimize $$f(x)=\sum_{i=1}^{n} I_i^2 \times R_i \qquad 11$$

where; $x = [\ V_i, P_{DGi},\ Q_{DGi}, n_{bus}]$ is the vector of variables or particles

The following steps were followed to obtain the desired optimization result.

Step 1: The initial values of the particles, sizes of the DG (P_{DR} and Q_{DR}), and the bus voltage limits (V_i) in the initial population are randomly generated.

Step 2: Distribution load flow without and with inclusion of DR are performed using Forward and Backward load flow technique.

Step 3: The sensitivity factors at each bus are evaluated. All the bus locations (n_{bus}) except the slack bus, will be tried for optimal location for DR placement one by one by the Sensitivity factors.

Step 4: The iteration count is increased. Step 3 is repeated if iteration count has not reached maximum. Else, go to step 5.

Step 5: A priority list is formed by ranking the buses in descending order of the values of sensitivity factors accordingly and stop.

The buses with the best sensitivity factors were identified as the most suitable for DG placement. The flowchart of the sensitivity analysis algorithm for distribution loss minimization based on optimal sizing and location of DR is shown in Figure 2.

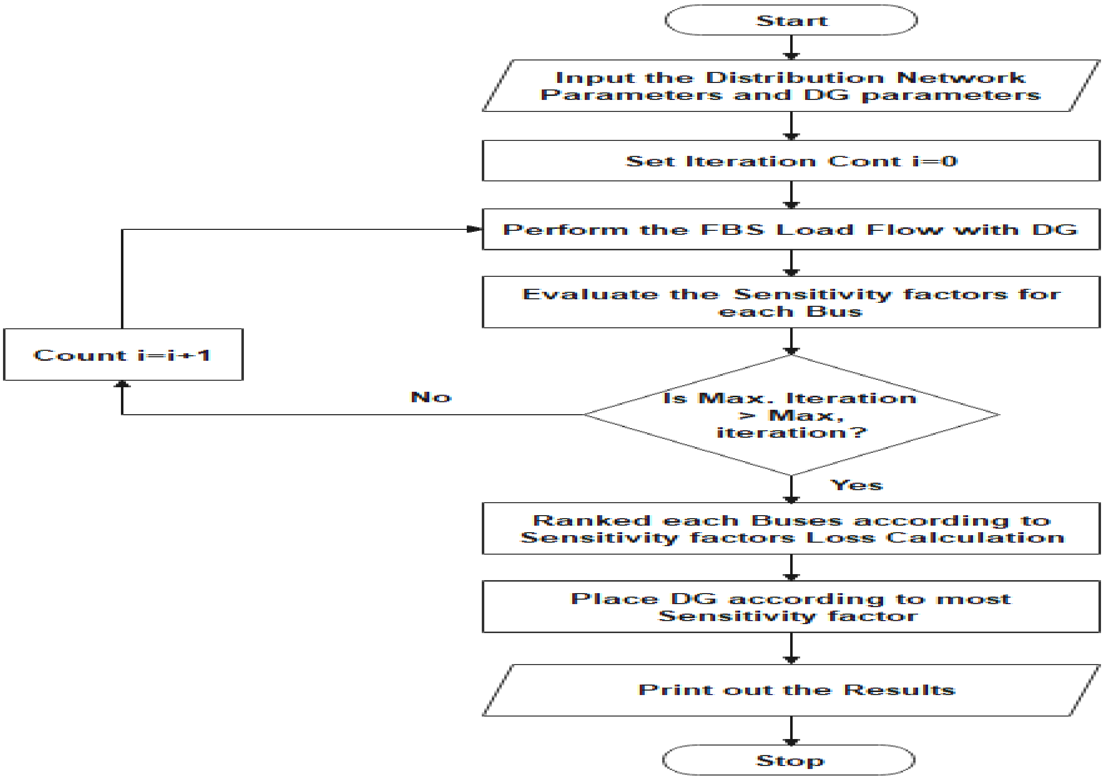

Figure 2: Flowchart of Sensitivity Analysis for Optimal DG Placement

2.2 Implementation and Simulation of WOA for Optimal DG Placement

The Whale Optimization Algorithm (WOA) was utilized to determine the global optimal placement of Distributed Resources (DR) for minimizing power loss in distribution networks.

The optimization process will take into account the following parameters:

The first step will be determining the optimal location for DG within the network, considering network variables like voltage changes, power loss, and system balance conditions within the optimization algorithm.

The DG capacity will be established based on the operational range of the network in which the shunt voltage source inverter voltage range was determined.

The power flow model of DG will be examined, and the stability of the system will be evaluated.

The whale Optimization Algorithm would be implemented and the encircling prey location, spiral bubble-net feeding updating position and global search updating position would be calculated.

The humpback whales encircling prey location is calculated as:

$$D = \left| \vec{C}.\vec{X}^*(t) - X(t) \right| \qquad 12$$

The spiral bubble-net feeding updating the position of whales during optimization was calculated as:

$$\vec{X}(t+1) = \begin{cases} \vec{X}^*(t) - \vec{A}.D \\ \vec{D}.e^{bl}.\cos(2\pi l) + \vec{X}^*(t) & p \leq 0.5 \end{cases} \qquad 13$$

Whale Optimization Algorithm global search updating position is calculated as:

$$D = \left| \vec{C} X_{rand} - \vec{X} \right| \qquad 14$$

$$\vec{X}(t+1) = X_{rand} - \vec{A}.\vec{D} \qquad 15$$

The fitness function of the Whale Optimization Algorithm for maximum loss reduction in this research is the objective function given in equation (3). The fitness function is computed as:

$$FF = P_L - P_{L,DR} \qquad 16$$

where;

$\overline{A}$ and $\overline{C}$ are coefficient vectors

t indicates the current iteration,

b is a constant for defining the shape of the logarithmic spiral

p is a random number in the range [0,1]

l is a random number in the range [-1,1]

X_{rand} is a random position vector chosen from the current population

a is linearly decreased from 2 to 0 over the course of iterations

X is the position vector

$\overline{X}$ is the position vector of the best solution obtained

D is the i^{th} whale to the prey (best solution obtained)

P_L is the system power loss?

FF is the fitness function

The following are the stepwise procedure for the simulation of the Whale Optimization Algorithm (WOA) for optimal DG placement.

Step 1: Read the system data while satisfying different equality and inequality constraints.

Step 2: The whale population $X_i \left(i = 1,2.......n\right)$ are initialize and the maximum number of iterations are set.

Step 3: The FBS load flow for initial network status and Sensitivity Analysis was performed

Step 4: The mathematical representation of the objective function in equation (16) is used in evaluating the fitness value of each search agent for maximum loss reduction and the best search candidate solution without violating the constraints are identified.

Step 5: For each search agent, the values of a, A, C, l and p are updated

Step 6: The position of the current search agent is updated using equation (12)

Step 7: A random search agent (X_{rand}) is selected and the new positions of the current search agent are updated using equation (15).

Step 8: Check if there is any boundary violation of search space, then, amend accordingly and go to step 2

Step 9: The new fitness function of each search agent is calculated.

Step 10: The new position X^* is updated, if there is a better solution, otherwise go to step (8)

Step 11: Output the optimal solution.

The flowchart of the Whale Optimization Algorithm for the Optimal Solution of DR is shown in Figure 3.

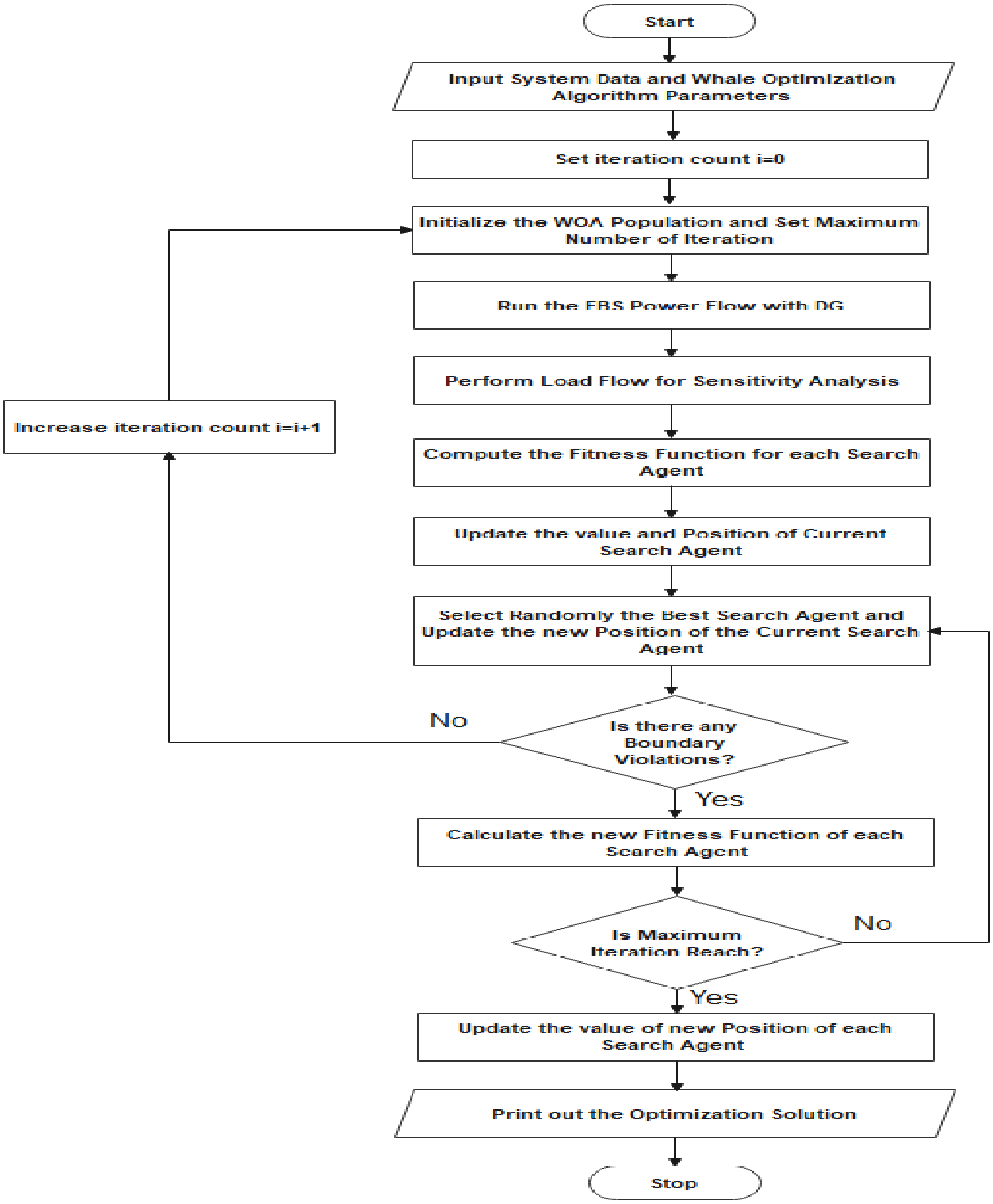

Figure 3: Flowchart of Whale Optimization Algorithm for Optimal Solution of DG

3. RESULT AND DISCUSSION

The Table 1 shown the simulation data of the IEEE 33-bus power system for the base case, indicated the bus voltages, line flow, and line loss, respectively. It was observed from Table 1 that the lowest active line flow was along line connecting buses, 13 to 14, 14 to 15, 15 to 16, 19 to 20 and 31 to 32 with active power values of 1.90, 1.77, 1.59, 1.91 and 1.91 MW, respectively. It was also observed that the line with the highest active power loss is line connecting buses 5 to 6 and 4 to 5, respectively. The total active and reactive power loss in the system is 195.51 MW and 136.34 MVar, respectively.

The Figure 4 simulation results of IEEE 33-bus power system for the base case. It is observed that buses 5, 11, and 23 have voltage magnitudes of 0.9303 p.u., 1.0558 p.u., and 1.0571 p.u., respectively. These values fall outside the ±5% tolerance margin of the voltage criterion, indicating that these buses are potential candidates for DG integration.

The Table 2 shown the simulation data of the IEEE 33-bus power system for DG integration using SA, indicated the bus voltage, line flow, and line loss, respectively. With the integration of DG unit, the active power flow from base case was redistributed and the result deduced an increase in active power flow along the line. The lowest active line flow was along line connecting buses, 13 to 14, 14 to 15, 15 to 16, 19 to 20, 31 to 32 and 32 to 33 with active power values of 1.95, 1.79, 1.64, 1.95, 1.95 and 3.62MW respectively. Also, the lines with the highest active power loss were line connecting buses 5 to 6 and 4 to 5, with active power loss values of 52.49 and 25.54 MW respectively. With the integration of DG unit, the power losses along the line were minimized compared to base case and the total active and reactive power loss in the system were reduced to 163.30 MW and 122.18 MVar, respectively.

Table 1: Bus Voltage, Line Flow and Line Loss of IEEE 33-Bus System for Base Case

From Bus	To Bus	Power MW	Power MVar	Line Flow (MW)	Line Loss (MVar)
1	2	41.32	21.01	17.68	9.61
2	19	2.58	2.46	1.41	1.40
3	23	8.41	5.72	5.38	4.06
4	5	24.11	12.18	26.28	13.99
5	6	19.03	17.18	63.38	46.36
6	26	11.34	5.72	4.41	2.85
7	8	9.28	2.02	7.85	3.41
8	9	5.12	4.42	6.80	5.23
9	10	5.56	3.95	6.01	4.61
10	11	5.64	2.01	0.76	0.25
11	12	5.44	1.84	0.49	-0.33
12	13	3.86	2.65	3.01	2.20
13	14	1.90	2.77	0.03	0.30
14	15	1.77	1.67	-0.35	-0.40
15	16	1.59	1.15	-0.40	-0.51
16	17	6.66	8.21	-0.53	-0.43
17	18	5.56	8.96	0.08	0.58
18	19	-7.33	-5.83	0.48	0.58
19	20	1.91	1.72	1.08	1.08
20	21	7.81	1.34	0.38	0.40
21	22	2.44	5.90	0.31	0.32
22	23	-4.40	-6.08	0.28	0.31
23	24	7.30	5.78	7.40	5.90
24	25	3.69	2.91	2.05	1.66
25	26	-3.51	-2.35	2.25	1.46
26	27	10.81	5.53	4.26	2.29
27	28	8.22	8.14	15.65	13.83
28	29	8.67	7.56	10.81	9.45
29	30	8.14	4.19	4.55	2.44
30	31	3.26	3.38	2.28	2.26
31	32	1.91	2.21	0.50	0.54
32	33	3.35	6.32	0.42	0.32
33	4	-2.97	-4.95	0.52	0.32
Total				195.51	136.34

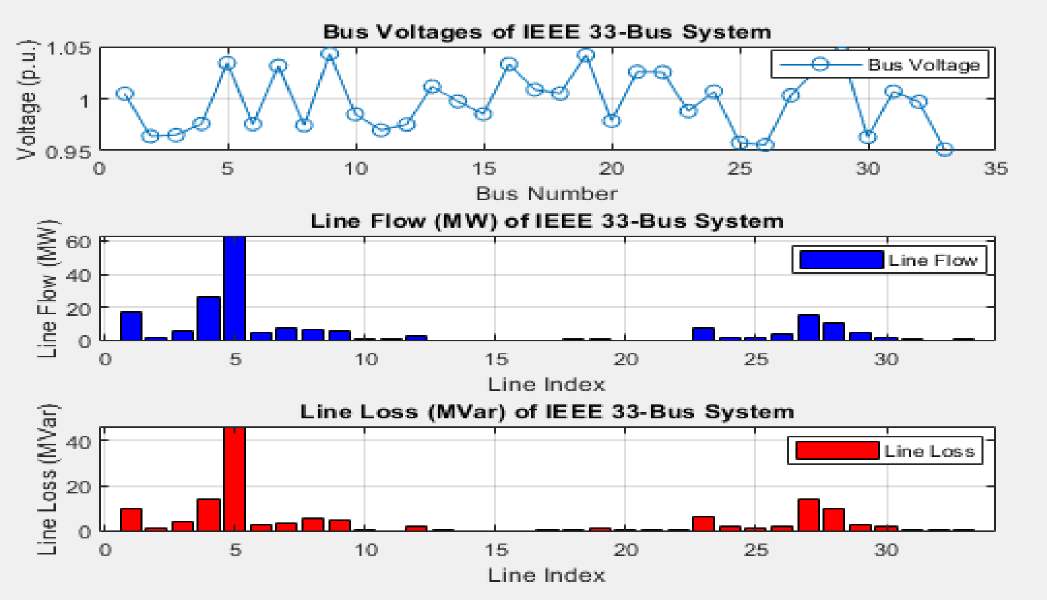

Figure 4: Simulation Result of IEEE 33-Bus System for Base Case

Table 2: Bus Voltage, Line Flow and Line Loss of IEEE 33-Bus System for DG with SA

From Bus	**To Bus**	**Power MW**	**Power MVar**	**Line Flow (MW)**	**Line Loss (MVar)**
1	2	42.37	21.69	16.10	8.70
2	19	2.60	2.52	0.92	1.31
3	23	8.82	5.75	4.85	3.74
4	5	24.50	12.95	25.54	13.57
5	6	19.41	17.89	52.49	45.61
6	26	11.58	5.76	3.89	2.54
7	8	9.47	2.88	7.29	3.10
8	9	5.88	4.56	6.27	4.90
9	10	5.62	3.98	5.47	4.29
10	11	5.70	2.88	0.56	-0.24
11	12	5.51	1.92	-0.38	-0.23
12	13	3.86	2.92	2.84	2.14
13	**14**	**1.95**	**2.84**	**-0.02**	**-0.31**
14	**15**	**1.79**	**1.76**	**-0.33**	**-0.32**
15	16	1.64	1.54	-0.36	-0.48
16	17	-7.21	8.79	-0.46	-0.36
17	18	5.64	9.96	-0.06	-0.46
18	19	7.61	-6.79	0.47	0.57
19	**20**	**1.95**	**1.75**	**0.53**	**0.93**
20	21	8.40	1.35	0.38	0.38
21	22	3.17	5.91	-0.23	-0.26
22	23	-5.58	-7.10	-0.23	-0.28
23	24	7.33	5.82	6.80	5.52
24	25	3.69	2.97	1.50	1.33
25	26	3.73	-2.81	1.89	1.32
26	27	10.87	5.67	3.73	2.07
27	28	8.92	8.55	15.01	13.40
28	29	8.67	7.58	10.22	9.36
29	30	8.86	4.24	-3.85	-2.11
30	31	-3.91	3.58	2.17	2.04
31	**32**	**1.95**	**2.29**	**0.41**	**0.47**
32	33	3.62	6.51	0.37	0.21
33	4	-3.16	-5.90	-0.48	-0.27
Total				**163.30**	**122.18**

The Figure 5 showed the simulation results of IEEE 33-bus standard system for DG integration using SA. The result was presented according to bus voltages, line flow power loss, and DG placement with Sensitivity Analysis (SA) factor. Three (3) DGs were placed at buses 5, 11 and 23 under base case to control the voltage magnitude to acceptable working range. With DG incorporated at these buses, it was observed that the bus voltage limits were violated under the base case were rectified by having voltage magnitude at all the buses within voltage limit of ±5% tolerance.

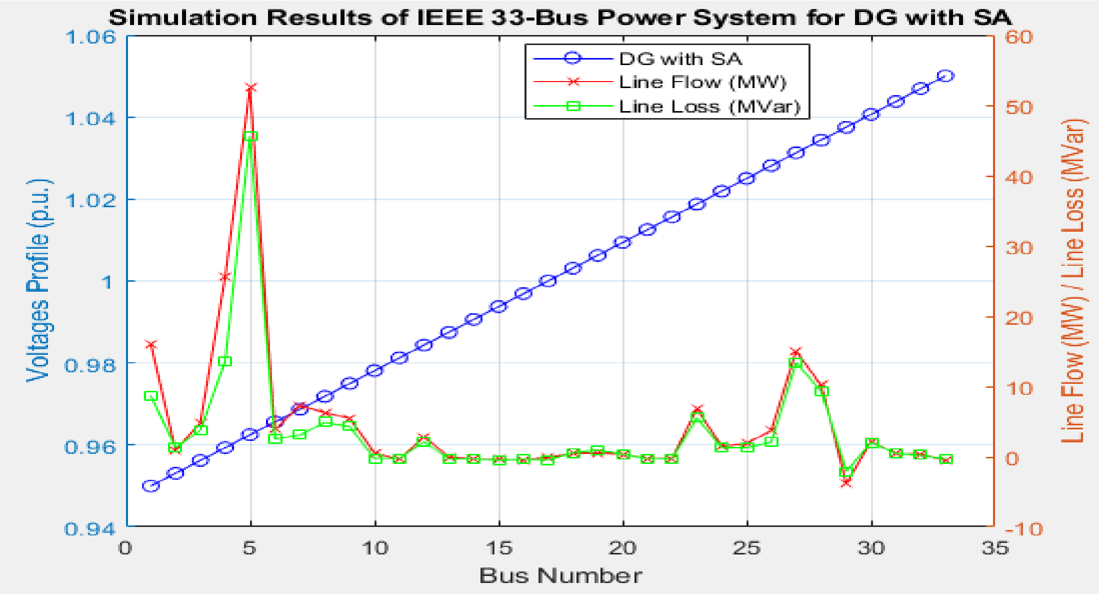

Figure 5: Simulation Result of IEEE 33-Bus System for DG with SA

The simulated results of IEEE 33-bus power system for DG integration using WOA are presented according to bus voltages, line flow and power loss, and with optimal DG placement using Whale Optimization Algorithm (WOA). Whale Optimization Algorithm was implemented to rectify the problem of voltage violations, regulate the power losses, and optimally locate the best placement and size of DG unit in the system.

The Figure 6 illustrated the comparison of voltage magnitude with the bus number of the system with inclusion of DG and WOA. With application of WOA, all the bus voltages were maintained within their voltage limit of ±5% tolerance. Also, the simulation data of the IEEE 33-bus power system for DG with WAO, indicated the bus voltage, line flow, and line loss, respectively are shown in Table 3. With application of WOA all the active power flow was further redistributed and the result indicates an increase in active power flow along the lines. In addition, the power loss along the line were further reduced compared to base case and the total active and reactive power loss in the system were reduced to 153.30 MW and 114.49 MVAr, respectively.

Figure 7 shows the comparison of total active power loss of IEEE 33-Bus System

Table 3: Bus Voltage, Line Flow and Line Loss of IEEE 33-Bus System for DG with WOA

From Bus	To Bus	Power MW	Power MVar	Line Flow (MW)	Line Loss (MVar)
1	2	45.42	22.74	16.01	8.50
2	19	2.85	2.77	-0.54	-1.25
3	23	8.97	5.90	4.65	3.70
4	5	25.56	13.00	23.54	13.37
5	6	19.56	17.95	50.05	43.16
6	26	11.64	5.81	3.09	2.34

7	8	9.52	2.94	7.09	3.09
8	9	5.93	4.62	5.82	3.45
9	10	5.85	3.99	5.37	4.19
10	11	5.72	2.90	0.52	-0.20
11	12	5.63	1.94	-0.32	-0.23
12	13	3.98	2.94	2.24	2.13
13	14	1.97	2.96	-0.01	-0.29
14	15	1.84	1.88	-0.30	-0.28
15	16	1.68	1.82	-0.31	-0.41
16	17	-7.74	8.96	-0.41	-0.30
17	18	5.71	8.97	-0.06	-0.36
18	19	7.68	-7.32	0.37	0.47
19	20	1.99	1.85	0.49	0.89
20	21	8.87	1.94	0.28	0.30
21	22	3.64	6.01	-0.20	-0.23
22	23	-6.15	-7.67	-0.21	-0.26
23	24	7.97	5.86	6.70	5.48
24	25	3.73	2.99	0.98	1.31
25	26	3.76	-2.86	1.88	1.29
26	27	10.90	5.81	3.63	1.97
27	28	8.93	8.87	14.54	12.93
28	29	8.83	7.75	9.75	9.30
29	30	8.89	5.05	-3.55	-2.01
30	31	-3.93	3.67	1.99	2.00
31	32	1.97	2.48	0.38	0.41
32	33	3.88	6.67	0.21	0.20
33	4	-4.30	-5.97	-0.37	-0.17
Total				153.30	114.49

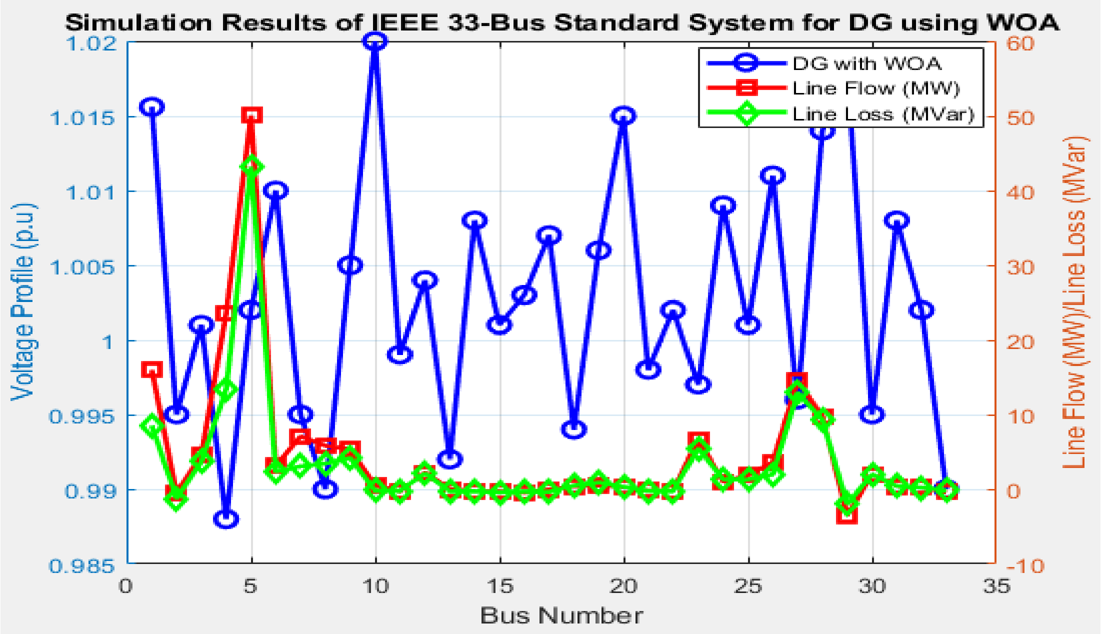

Figure 6: Simulation Result of IEEE 33-Bus System for DG with WOA

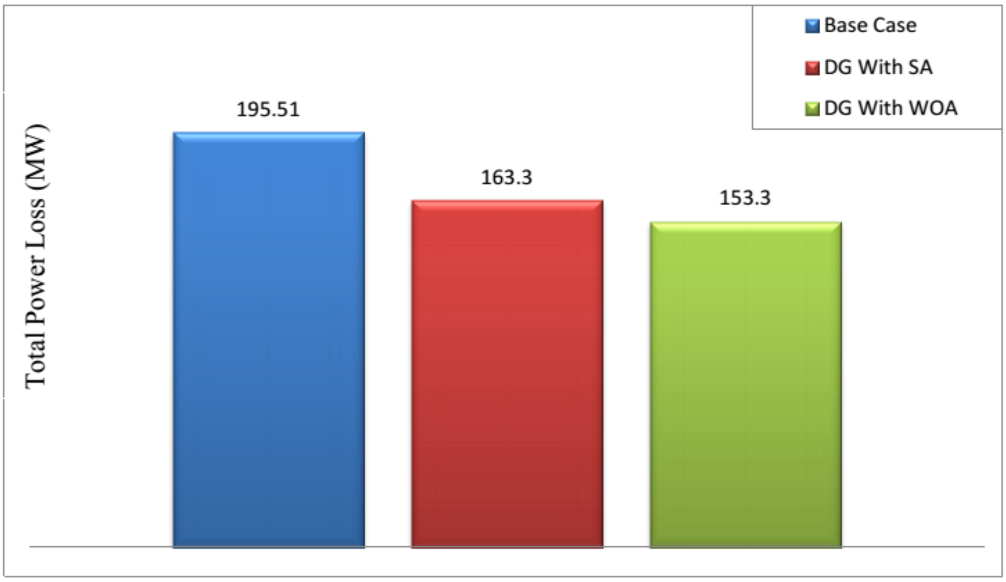

Figure 7: Comparison of Total Active Power Loss of IEEE 33-Bus System

The Comparative Analysis of Total Active Power Loss for the Three Cases provides an insightful look into the effectiveness of Distributed Generation (DG) placement for minimizing power losses in a distribution network. In this study, three distinct scenarios are analyzed to compare the overall reduction in total active power loss: Base Case (Without DG), DG Placement Using Sensitivity Analysis (SA), DG Placement Using Whale Optimization Algorithm (WOA).

In the base case, the distribution network operates without any DG units integrated. The total active power loss recorded in this scenario is 195.51 MW, representing the starting point and benchmark for comparison. This high level of power loss is typical in distribution networks due to factors like long distances between generation points and loads, resistive losses in the lines, and inefficient power distribution without local generation.

When DG units are incorporated into the network based on Sensitivity Analysis (SA), the total active power loss is significantly reduced to 163.30 MW, which corresponds to a 16.5% reduction from the base case. Sensitivity Analysis identifies the most effective buses for DG placement by determining how variations in system parameters affect the network's power losses. This technique allows the placement of DG at strategic points, reducing losses and improving overall network performance.

Further improvements are achieved when the Whale Optimization Algorithm (WOA) is employed to determine the optimal DG placement. The total active power loss is minimized to 153.30 MW, resulting in a 21.5% reduction from the base case. WOA, as a metaheuristic algorithm, outperforms SA by efficiently searching the solution space for the global optimum, avoiding local minima traps that could limit the potential loss reduction. The greater reduction achieved with WOA highlights its superior capability in optimizing DG placement for power loss minimization compared to traditional approaches like SA.

3.1 Location and Size of DG Units

Table 4 presents the optimal locations and sizes of the DG units as determined by the Whale Optimization Algorithm. The selected buses for DG integration are:

Bus 4 with a DG size of 8.5 MW
Bus 5 with a DG size of 5.5 MW
Bus 27 with a DG size of 5.25 MW

These buses were identified as critical points in the network where the integration of DG would yield the greatest reduction in power loss. The DG sizes are optimized to match the power demand and minimize losses, contributing to more efficient energy distribution and lower operational costs.

Table 5 provides a comparison between the results achieved using WOA and those reported by other optimization methods. This comparison demonstrates that WOA not only provides accurate and high-quality solutions but also yields superior results in power loss reduction. Other methods, while effective, often struggle to consistently achieve the same level of optimization that WOA delivers, especially when it comes to balancing local generation with the overall network load. This positions WOA as a highly reliable tool for solving complex power system optimization problems.

Table 4: Optimal Placement and Sizing of DG for IEEE 33-Bus System

From Bus	To Bus	SA Factor	Voltage Profile (p.u)	DG Size (MW)
10	11	0.9705	1.0156	6.55
27	28	0.9074	1.0115	10
28	29	0.9091	0.9763	8.55
29	30	0.9584	0.9856	5.25
4	**5**	**0.3453**	**1.0354**	**8.5**
5	**6**	**0.4992**	**1.0000**	**5.5**
27	**28**	**0.9074**	**1.0000**	**10**

Table 5: Performance Evaluation for Active Power Losses for IEEE 33-Bus Tests System

Techniques	Active Power Loss (%)	Reactive Power Loss (%)	Authors
DG with SA	**16.5**	**10.4**	**----**
DG with WOA	**21.5**	**16.1**	**----**
DG with LSA	19.4	10	[27]
DG with GWO	10.7	11.1	[28]
DG with ORCSA	21.2	10.6	[29]
DG with ASFLA	20.2	14.5	[30]

The comparison of voltage magnitudes across the 33 buses of the system reveals specific buses that fall outside the acceptable voltage tolerance range. In power distribution systems, maintaining bus voltages within a ±5% tolerance margin is crucial for ensuring voltage stability and the efficient functioning of electrical equipment. The bus voltage magnitudes are measured in per unit (p.u.), a normalized unit in power systems.

From the simulation results, it is observed that buses 5, 14, 19, and 31 exhibit voltage magnitudes of:

Bus 5: 1.0556 p.u.
Bus 14: 0.9239 p.u.
Bus 19: 0.9314 p.u.
Bus 31: 1.0546 p.u.

While the voltage magnitudes for some buses are slightly outside the desired range, buses 14 and 19, with values of 0.9239 p.u. and 0.9314 p.u., are notably below the tolerance margin. This indicates voltage drops that could lead to instability or inefficiency in the distribution network. These buses, along with bus 5 and bus 31, are identified as potential candidates for DG integration. DG units placed at these points could help raise the voltage levels, improving overall network voltage stability and reducing power losses by injecting active and reactive power locally.

The line flow in a distribution network represents the amount of power transferred between different buses. In this case, the simulation shows that the lowest active power flows occur along the lines connecting the following buses:

Line from bus 21 to bus 22: 1.10 MW
Line from bus 20 to bus 21: 1.12 MW
Line from bus 23 to bus 24: 1.13 MW

These low active power flow values indicate sections of the network where power transfer is minimal, suggesting possible inefficiencies or areas of underutilization. Such lines may benefit from load redistribution or the integration of DG to optimize power flow and reduce losses in these regions.

The simulation identifies the lines with the highest active power losses, which are found in the connections between the following buses:

Line from bus 1 to bus 2

Line from bus 4 to bus 5

These lines exhibit significant losses due to factors such as high resistances, long line lengths, or heavy load demands. Power losses in distribution networks typically arise from the resistive nature of the lines, and these losses can escalate when the lines are heavily loaded or have inefficient power flow. Integrating DG units strategically along these lines can reduce the power that must be supplied from the grid, decreasing the overall losses by supplying power closer to the load centers.

For the base case, the total active power loss in the system is 247.29 MW, while the reactive power loss is 393.04 MVAr. These high losses highlight the inefficiencies in the current system configuration without DG integration. Active power losses directly impact the energy efficiency of the network, while reactive power losses affect the voltage regulation and stability of the system. Reducing both types of losses is crucial for improving the overall performance and reliability of the distribution network.

The simulation results for the 33-bus Ilorin industrial distribution feeder reveal several key insights that are critical for optimizing the network:

Voltage deviations at buses 5, 14, 19, and 31 indicate the need for corrective actions, such as DG integration, to stabilize voltage levels and improve the overall efficiency of the network.

Low line flow values between buses 21-22, 20-21, and 23-24 suggest underutilized areas where power flow could be improved, potentially through strategic DG placement.

High active power losses along the lines connecting buses 1-2 and 4-5 point to areas of inefficiency that could benefit from DG integration or network reconfiguration.

The total active and reactive power losses in the system emphasize the need for optimization techniques to minimize these losses and improve energy efficiency.

By identifying critical buses and lines for DG placement, the study lays the groundwork for more efficient power distribution. Integrating DG units at the optimal locations will not only enhance voltage stability but also significantly reduce power losses, leading to a more reliable and sustainable energy system. Table 6 shows the bus voltage, line flow and line loss of 33-bus Ilorin industrial distribution feeder system

Table 6: Bus Voltage, Line Flow and Line Loss of 33-Bus Ilorin Industrial Distribution Feeder System

From Bus	To Bus	Power MW	Power MVar	Line Flow (MW)	Line Loss (MVar)
1	**2**	**29.56**	**49.07**	**120.15**	**206.86**
2	4	26.64	42.86	9.23	15.87
3	2	-1.56	-2.58	0.06	0.11
4	**5**	**24.50**	**40.18**	**54.97**	**94.64**
5	6	20.32	33.99	2.83	4.87
6	8	19.67	32.87	2.66	4.57
7	6	-5.57	-8.28	0.01	0.03
8	10	33.57	5.58	10.07	1.73
9	8	-1.54	-2.45	0.01	0.02
10	11	14.79	24.46	6.06	10.43
11	12	14.41	23.81	5.80	9.99
12	13	11.97	20.40	3.02	5.20
13	15	9.11	15.07	1.39	2.39
14	13	-1.03	-1.67	0.02	0.04
15	17	8.53	13.69	3.10	5.33

16	15	-7.24	-1.15	0.01	0.03
17	33	10.15	11.77	8.68	10.12
18	26	2.35	3.04	0.03	0.52
19	20	2.18	3.46	0.35	0.60
20	**21**	**1.12**	**1.72**	**0.08**	**0.13**
21	**22**	**1.10**	**1.79**	**0.02**	**0.06**
22	21	-1.11	-1.89	0.03	0.02
23	**24**	**1.13**	**1.95**	**0.05**	**0.04**
24	23	-1.14	-1.85	0.04	0.06
25	23	-1.17	-1.95	0.03	0.01
26	27	3.42	2.54	0.04	8.68
27	29	2.28	3.27	8.68	0.05
28	27	2.25	3.24	0.03	0.35
29	30	4.18	3.28	0.35	0.08
30	31	-1.95	2.17	0.08	0.02
31	32	2.54	2.15	0.60	0.04
32	33	3.27	2.18	0.13	0.03
33	17	-10.87	-12.67	8.68	10.12
Total				**247.29**	**393.04**

Figure 8 shows the simulation result of 33-bus Ilorin distribution system for base case

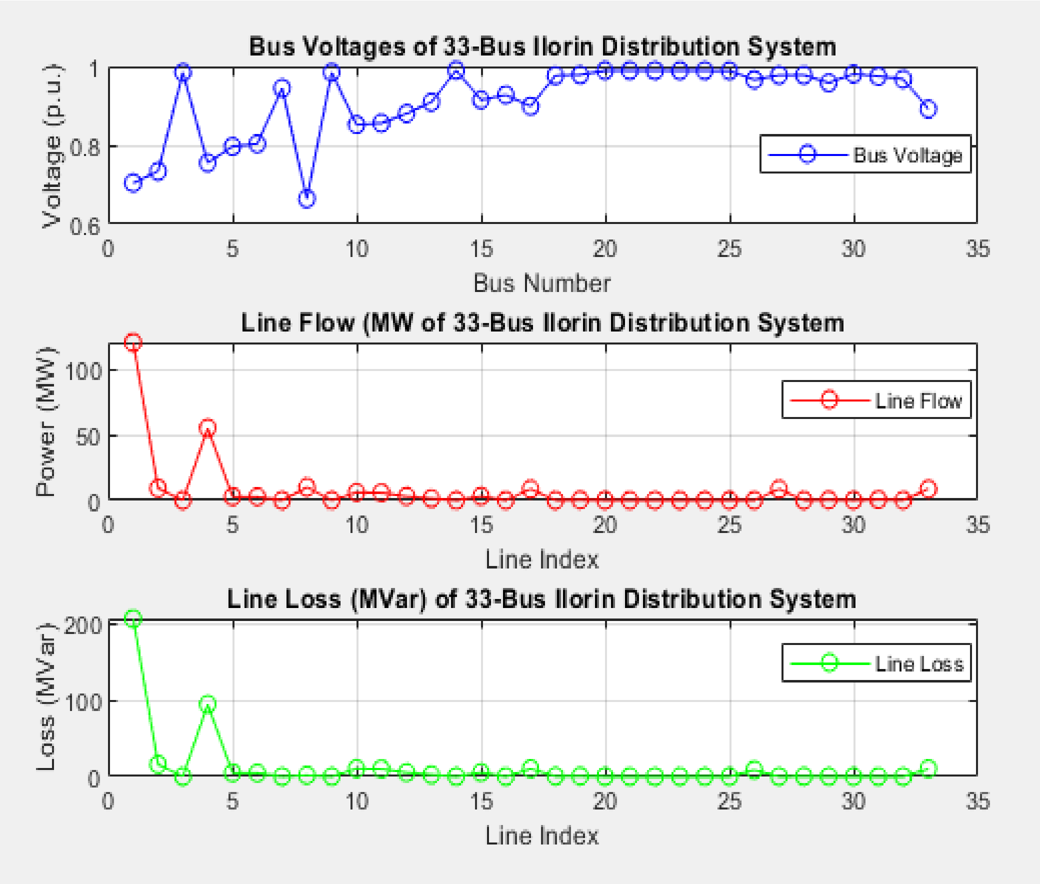

Figure 8: Simulation Result of 33-Bus Ilorin Distribution System for Base Case

The Table 7 showed simulation data of the 33-bus Ilorin industrial distribution feeder for the DG with SA. The integration of the DG unit led to a redistribution of active power flow from the base case, resulting in an increase in active power flow along the lines. The lines with the lowest active power flow were those connecting buses 23 to 24, 21 to 22, and 20 to 21. Additionally, the lines with the highest active power loss were those connecting buses 1 to 2 and 4 to 5, with active power losses of 115.59 MW and 53.55 MW, respectively. With the integration of the DG unit, the power losses along the lines were minimized compared to the base case, reducing the total active and reactive power losses in the system to 234.51 MW and 376.50 MVAr, respectively.

The simulated results of the 33-bus Ilorin industrial distribution feeder for integration of DG with SA in Figure 9. The Figure 9 illustrates the comparison of voltage magnitude across the bus number with DG inclusion. Four DGs were placed at buses 5, 14, 19, and 31 in the base case to maintain the voltage magnitude within an acceptable operating range. With DGs incorporated at these buses, the voltage limits that were violated in the base case were corrected, resulting in voltage magnitudes at all buses within a ±5% tolerance limit.

Whale Optimization Algorithm (WOA) was implemented on 33-bus Ilorin distribution feeder to regulate the problem of voltage violations in the system, reduce the power losses, and optimally locate possible buses for the placement of DG unit within the system.

Table 7: Bus Voltage, Line Flow and Line Loss of 33-Bus Ilorin for DG with SA

From Bus	**To Bus**	**Power MW**	**Power MVAr**	**Line Flow (MW)**	**Line Loss (MVar)**
1	**2**	**29.68**	**50.59**	**115.59**	**200.17**
2	**4**	**26.78**	**44.58**	**8.40**	**14.66**
3	2	-1.65	-2.66	0.05	0.11
4	5	24.85	41.93	53.55	92.41
5	6	20.50	34.58	2.79	3.81
6	8	19.85	33.66	2.52	3.51
7	6	-5.64	-9.22	0.01	0.01
8	10	33.86	5.74	9.04	1.67
9	8	-1.73	-2.64	0.01	0.02
10	11	14.90	25.31	5.58	10.20
11	12	14.63	24.67	5.43	8.86
12	13	11.99	20.78	2.66	4.62
13	15	9.22	15.87	1.20	2.19
14	13	-1.54	-1.74	0.02	0.03
15	17	8.93	14.36	2.75	5.26
16	15	-7.73	-1.21	0.01	0.02
17	33	10.29	12.07	8.27	9.42
18	26	2.69	3.76	0.03	0.46
19	20	2.23	3.50	0.24	0.54
20	**21**	**1.24**	**1.79**	**0.06**	**0.12**
21	**22**	**1.22**	**1.86**	**0.01**	**0.04**
22	21	-1.16	-1.90	0.02	0.01
23	24	1.14	1.96	0.03	0.03
24	23	-1.19	-1.91	0.03	0.04
25	23	-1.24	-1.96	0.02	0.01
26	27	3.57	2.61	0.03	8.38
27	29	2.45	3.33	8.08	0.03
28	27	2.32	3.30	0.02	0.34
29	30	4.23	3.34	0.34	0.06
30	31	-1.97	2.25	0.05	0.01
31	32	2.59	2.18	0.49	0.03
32	33	3.33	2.22	0.10	0.02
33	17	-10.93	-12.70	7.08	9.41
Total				**234.52**	**376.50**

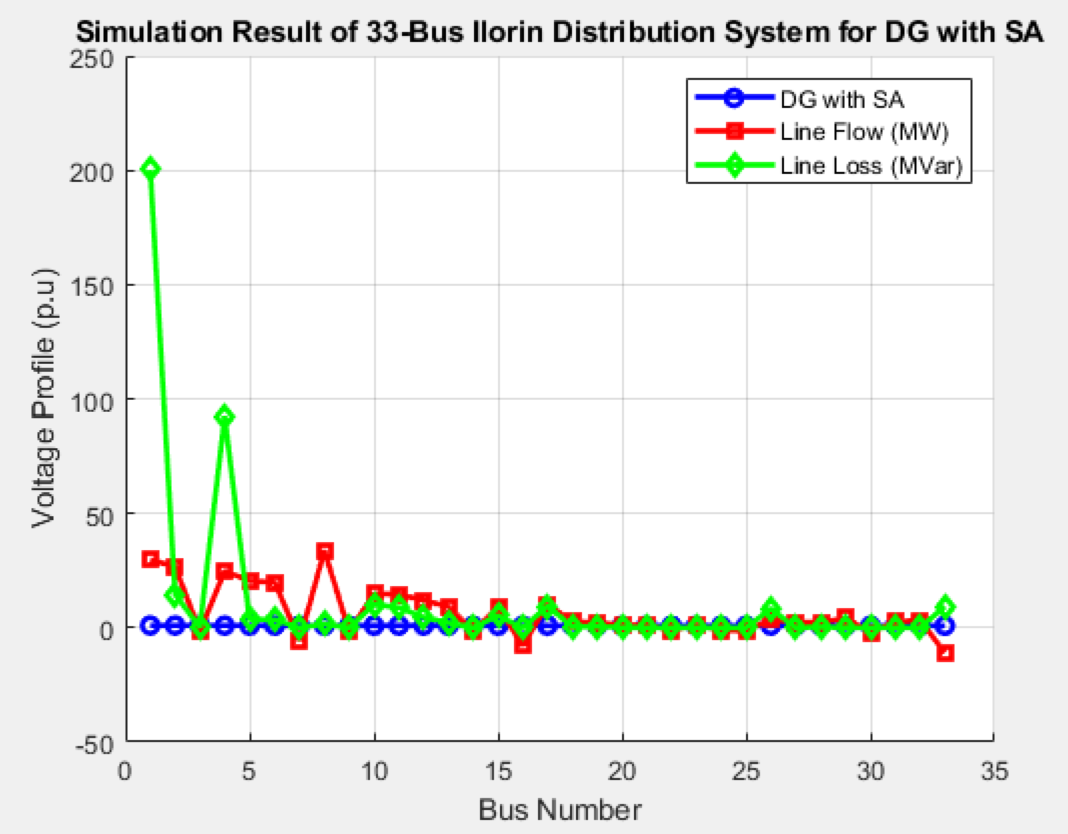

Figure 9: Simulation Result of 33-Bus Ilorin Distribution System for DG with SA

The voltage magnitude compared to the bus number in the system with DG and WOA integration for the Industrial 33-bus distribution system is depicted in Figure 10. The application of WOA ensured all bus voltages remained within the ±5% tolerance limits. The Table 8 showed the simulation data of the 33-bus Ilorin industrial distribution feeder for the DG with WOA. It provided the line flow and line loss results, showing that WOA redistributed active power flows from the base case, leading to increased active power flow along the lines. Moreover, the power loss along the lines was further reduced compared to the base case, with total active and reactive power losses reduced to 201.97 MW and 343.09 MVAr, respectively.

In a similar fashion, The Figure 10 presents the total active power loss comparison across the three cases. The total active power loss was 247.29 MW for the base case, 243.51 MW for DG with SA (representing a 5.2% reduction), and 201.97 MW for DG with WOA (representing an 18.3% reduction). Moreover, Table 9 outlines the optimal DG unit locations and sizes using WOA, highlighting buses 4, 8, and 17 with DG sizes of 12.5 MW, 10.5 MW, and 10.0 MW, respectively.

Moreover, Table 10 presents a comparison of power loss results with other optimization methods, showing that WOA provides accurate and high-quality solutions for power loss reduction compared to existing techniques reported by other authors.

Thus, application of WOA in the system resulted in further improvement in the overall system voltage magnitude, improved the line flow and the total power loss in the system was reduced to minimum compared to base case result and with DG incorporated. Also, the results clearly showed that WOA is more efficient and produce high quality solution in terms of system loss reduction and best placement for DG in power system compared with the application of SA.

Table 8: Bus Voltage, Line Flow and Line Loss of 33-Bus Ilorin for DG with WOA

From Bus	To Bus	Power MW	Power MVar	Line Loss (MW)	Line Loss (MVar)
1	**2**	**29.90**	**52.07**	**110.03**	**178.05**
2	**4**	**26.98**	**45.22**	**7.62**	**12.19**
3	2	-1.70	-2.98	0.04	0.10
4	5	24.98	42.67	51.63	90.40
5	6	20.83	34.74	2.51	3.26
6	8	19.97	33.85	2.34	3.18
7	6	-5.87	-9.95	0.01	0.01
8	**10**	**34.06**	**5.97**	**8.44**	**1.46**
9	8	-1.99	-2.86	0.01	0.01
10	11	15.03	25.55	5.30	9.68
11	12	14.90	24.93	4.55	7.56
12	13	12.03	21.90	2.19	3.41
13	15	9.86	16.08	1.15	2.07
14	13	-1.92	-1.96	0.01	0.02
15	17	8.99	14.62	2.38	5.16
16	15	-8.00	-1.29	0.01	0.01
17	33	10.90	12.30	8.03	8.67
18	26	2.94	3.99	0.02	0.35
19	20	2.69	3.73	0.20	0.53
20	**21**	**1.52**	**1.95**	**0.04**	**0.11**
21	**22**	**1.32**	**1.93**	**0.01**	**0.02**
22	21	-1.28	-1.96	0.01	0.01
23	24	1.18	2.02	0.02	0.01
24	23	-1.21	-1.97	0.01	0.02
25	23	-1.31	-1.99	0.02	0.01
26	27	3.93	2.95	0.02	7.41
27	29	2.70	3.46	7.41	0.03
28	27	2.47	3.45	0.01	0.27
29	30	4.45	3.48	0.27	0.03
30	31	-2.09	2.32	0.03	0.01
31	32	2.71	2.20	0.29	0.02
32	33	3.49	2.33	0.09	0.01
33	17	-11.09	-13.01	5.27	9.01
Total				**201.97**	**343.09**

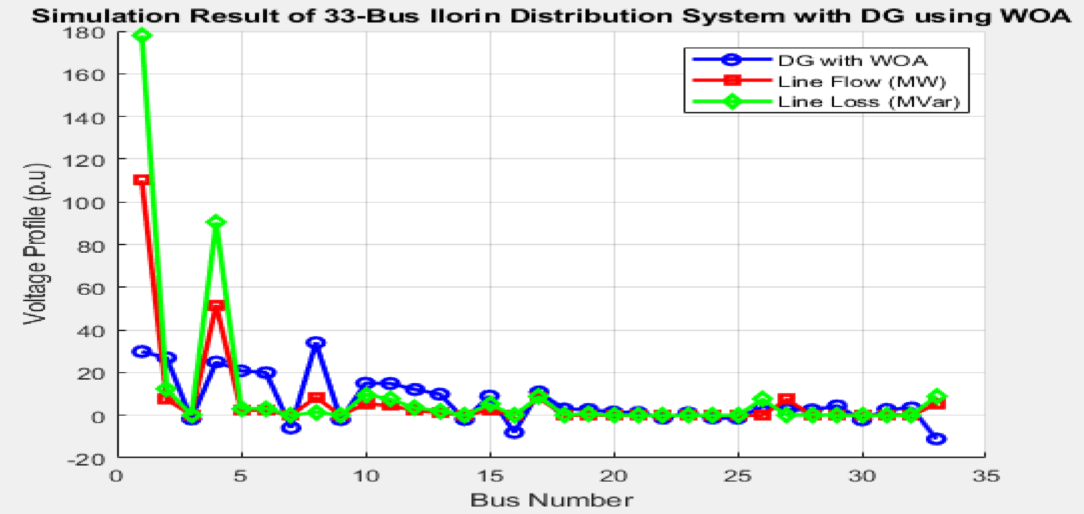

Figure 10: Simulation Result of 33-Bus Ilorin Distribution System for DG with WOA

Table 9: Optimal Sizing of DG for 33-bus Ilorin Industrial Distribution Feeder

From Bus	To Bus	SA Factor	Voltage Profile (p.u)	DG Size (MW)
5	6	0.9402	0.9552	10
14	13	0.7250	0.9793	12.5
20	21	0.6929	1.0127	10.5
27	29	0.8518	1.0335	15
28	27	0.9590	1.0315	10
4	**5**	**0.3768**	**1.0228**	**12.5**
8	**10**	**0.3569**	**1.0464**	**10.5**
17	**33**	**0.1052**	**1.0279**	**10**

Table 10: Performance Evaluation for Active Power Losses for 33-bus Ilorin Industrial Distribution Feeder

Techniques	Active Power Loss (%)	Reactive Power Loss (%)	Authors
DG with SA	**5.20**	**4.20**	**Nil**
DG with WOA	**18.30**	**12.70**	**Nil**
DG with LSA	19.4	10	[27]
DG with GWO	10.7	11.1	[28]
DG with ORCSA	21.2	10.6	[29]
DG with ASFLA	20.2	14.5	[30]

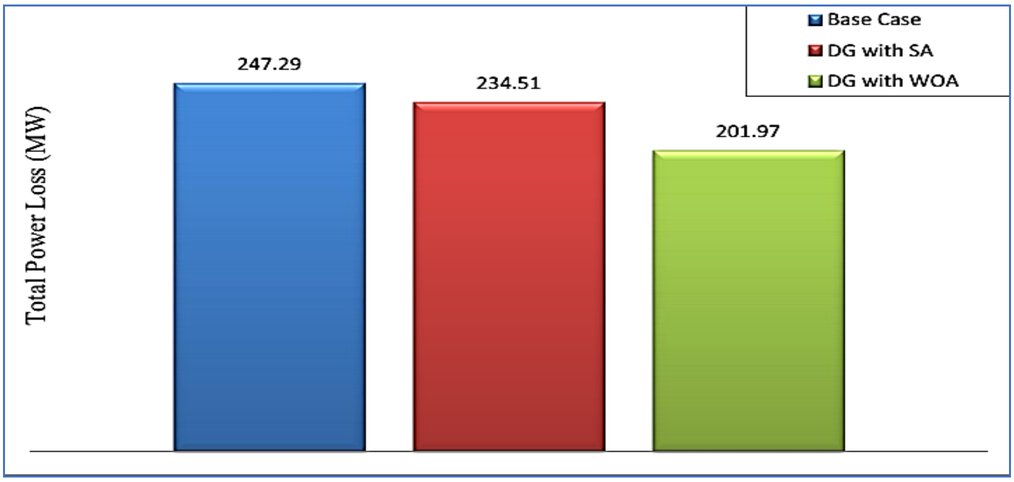

Figure 10: Comparison of Total Active Power Loss of 33-Bus Ilorin Distribution System

CONCLUSION

The study successfully explored and presented the application of the Whale Optimization Algorithm (WOA) for minimizing power losses in distribution networks through the optimal integration of Distributed Resources (DR), including Distributed Generation (DG). The Forward and Backward Sweep (FBS) load flow technique was used for both the steady state and the DG-integrated network. Sensitivity Analysis (SA) was conducted to identify the most sensitive buses for DG allocation based on power loss findings. WOA was implemented as an optimization technique to solve voltage violations, reduce power losses, and determine the optimal placement and size of DG units. The effectiveness of these methods was demonstrated on the IEEE 33-bus standard system and the 33-bus Ilorin industrial distribution feeder of the Ibadan Electricity Distribution Company (IBEDC), using total active power loss and the optimal location and size of DG as performance metrics.

Declaration by Authors

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