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Optimal DG Placement and Sizing in Radial Distribution Networks Using Whale Optimization for 11 KV Bypass Feeder

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Abstract

The rapid growth in electricity demand, coupled with high line losses and voltage instability in Nepal's rural distribution networks, necessitates the efficient integration of distributed generation (DG). This thesis presents a whale optimization algorithm (WOA)-based framework for the optimal placement and sizing of solar DG in the real 11 kV Bypass Feeder, Biratnagar Distribution Center, Nepal Electricity Authority (NEA). Using actual feeder data, including line parameters, load profiles, and time-varying solar irradiance (300 sunny days/year), a multi-objective optimization model was formulated to minimize active power losses and maximize the minimum bus voltage under annual load growth. Inspired by the hunting behavior of humpback whales, the WOA effectively balances global exploration and local exploitation, outperforming conventional methods in terms of convergence and solution quality. The simulation results demonstrate an over 57.77% reduction in real power losses and voltage improvement to ≥ 0.951 p.u. with optimally sized solar DG units, without requiring network reconfiguration or energy storage. The proposed approach was validated using a forward-backward sweep load flow and real operational constraints, ensuring practical implementation. This study fills a critical research gap by moving beyond standard IEEE test systems to field-level applications, providing a scalable and computationally efficient tool for distribution utilities in developing nations. This supports Nepal's national goals of renewable energy integration, grid reliability enhancement, and sustainable rural electrification.

Keywords: Distributed generation • whale optimization algorithm • radial distribution system • solar DG • power loss minimization • voltage stability

1. Introduction

The electrification of rural areas in developing nations, such as Nepal, remains a pressing challenge owing to rapid load growth, high transmission and distribution (T&D) losses, voltage instability, and limited grid expansion in remote regions. The Nepal Electricity Authority (NEA) reports that distribution losses exceed 20%, with rural 11 kV feeders experiencing voltage drops below 0.9 p.u. during peak hours and frequent outages caused by overloaded lines and long radial paths

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[NEA Annual Report, 2023]. These issues not only degrade power quality but also hinder economic development and access to reliable electric power.

Distributed Generation (DG), particularly solar photovoltaic (PV) systems, offers a viable solution by generating power near load centers, thereby reducing line losses, improving voltage profiles, and enhancing system reliability. Nepal's solar potential, averaging 300 sunny days per year with an irradiance of 4.5-5.5 kWh/m^2/day, makes solar DG an ideal candidate for rural electrification [AEPC, 2022]. However, improper placement and sizing of DG units can lead to reverse power flow, overvoltage, increased losses, or underutilization of the installed capacity, negating the intended benefits.

Traditional analytical and sensitivity-based methods for DG allocation Prakash et al. (2018); Gauli et al. (2023) rely on simplified assumptions, such as constant power loads and ideal system conditions, rendering them inadequate for real-world radial feeders characterized by high R/X ratios, unbalanced loading, and time-varying solar generation. The emergence of metaheuristic optimization algorithms, such as Genetic Algorithm (GA), particle swarm optimization (PSO), and whale optimization algorithm (WOA), has enabled the robust handling of nonlinear multi-objective problems with greater accuracy and convergence speed Biswal et al. (2021); Li et al. (2016).

Among these, the whale optimization algorithm (WOA), introduced by Mirjalili and Lewis in 2016, mimics the bubble-net hunting strategy of humpback whales and excels in balancing exploration and exploitation, making it particularly effective for complex engineering optimization tasks. Recent studies have successfully applied WOA to DG placement in standard IEEE test systems Gnanendar and Sushama (2025); Murty and Kumar (2015); Li et al. (2016), achieving significant loss reduction and voltage improvement. However, no study has implemented WOA on an actual distribution feeder using real operational data, time-varying solar irradiance, and load growth projections, which is a critical gap in translating theoretical advancements into field-level solutions.

This study addresses this gap by developing a WOA-based optimization framework for the optimal placement and sizing of solar DG in the real 11 kV Bypass Feeder, Biratnagar Distribution Center, NEA. Using the actual feeder topology, hourly load data, solar irradiance profiles, and annual load growth forecasts, the proposed model simultaneously minimizes active power losses and maximizes the minimum bus voltage under practical constraints.

2. Literature Review

Early research on Distributed Generation (DG) optimization primarily focused on analytical and sensitivity-based techniques to enhance voltage stability and reduce active power losses. Murty and Kumar Prakash et al. (2018) introduced a Voltage Stability Index (VSI) and compared it with the Power Loss Sensitivity and Power Stability Index (PSI) to determine the optimal DG placement under load growth scenarios. When applied to the IEEE 12-bus, 69-bus, and 85-bus radial systems, their approach achieved 50–70% loss reduction and prevented voltage collapse. However, these deterministic methods assume static loading and single-objective formulation, limiting their adaptability to nonlinear and multi-constrained systems.

Subsequent studies have incorporated time-varying loads and generation dynamics. Hung et al. Gauli et al. (2023) developed a multi-objective analytical expression using an Index of Multiple Objectives (IMO) to evaluate PV penetration in IEEE 33-bus and 69-bus systems. The results revealed that industrial loads could support up to 50% PV integration with a 40–60% loss reduction, underscoring the inadequacy of constant-load assumptions. Despite capturing dynamic load profiles, the study lacked metaheuristic optimization and real-time feeder validation.

The mid-2010s marked a the shift toward practical microgrid implementation. Gaonkar et al. Uniyal and Kumar (2016) experimentally validated a 10-kW hybrid microgrid (6.4 kW wind

+ 3.6 kW PV), and demonstrated its stable operation under varying inputs. However, this study was limited to isolated operations and did not address grid-connected DG placement or radial feeder integration,which are key aspects of Nepal's interconnected networks.

Metaheuristic algorithms have emerged as effective solutions for nonlinear multi-objective DG optimization. Uniyal and Kumar Biswal et al. (2021) compared Cuckoo Search (CSA), Gravitational Search (GSA), Particle Swarm Optimization (PSO), and Genetic Algorithm (GA) for IEEE 33-bus systems, with CSA showing superior convergence. However, the study excluded whale optimization algorithm (WOA) and relied on constant loads. Later, Morshidi et al. Gnanendar and Sushama (2025) applied WOA integrated with the Fast Voltage Stability Index (FVSI), achieving up to 60% loss reduction with faster convergence than the Firefly Algorithm, confirming WOA's robustnessof WOA. However, solar-specific modelling and field validation are lacking.

Further research has explored multi-objective frameworks. Prakash et al. Morshidi et al. (2018) employed a Multi-Objective Bat Algorithm (MOBA) to minimize active loss and DG cost, achieving 70 % loss reduction, while Biswal et al. Gaonkar et al. (2014) introduced the Quasi-Reflected Slime Mould Algorithm (QRSMA) for simultaneous DG/capacitor placement with reconfiguration. although effective, these models are computationally intensive and unsuitable for fixed-topology rural feeders. Comparative studies by Hamad et al. Murty and Kumar (2015) validated WOA's strong convergence performanceof the WOA, while Gnanendar and Sushama Li et al. (2016) achieved a 79% loss reduction using the WOA on IEEE 33-bus, reinforcing its potential.

Research Gaps and Contribution

Despite proven algorithmic advances, major research gaps persist.

1. **Real-world validation**–Existing works rely solely on IEEE test systems without applying WOA to real feeders.
2. **Dynamic modeling**:Static load and irradiance assumptions dominate, ignoring time-varying solar and demand growth typical of Nepal.
3. **Contextual relevance**:Nepal's 11 kV rural radial feeders with high R/X ratios and hydropower dependence remain unaddressed.

This thesis bridges these gaps by developing a WOA-based framework for optimal solar DG placement on the real 35-bus Bypass Feeder, Biratnagar, incorporating actual NEA load data, time-varying irradiance, and multi-objective optimization. The proposed model achieves over 57.77 % active power loss reduction with a minimum voltage of ≥ 0.951 p.u., providing a field-validated and policy-aligned solution for rural electrification in Nepal.

3. Methodology

3.1 Optimization of Distributed Generation Performance Using Whale Optimization Algorithm (WOA):

The proposed optimization model uses a whale optimization algorithm (WOA) to identify the best configuration of the DG parameters that yield the highest possible energy output. This process involves iterative selection, reproduction, and evaluation of candidate solutions based on their performance efficiency.

3.1.1 Whale Optimization Algorithm for DG Placement

- Optimization is the process of finding the best possible solution among many alternatives.
- Traditional algorithms (GA, PSO) face challenges such as local minima and complex tuning.

- WOA (2016, Mirjalili) is a nature-inspired metaheuristic based on the hunting behavior of humpback whale hunting behavior.

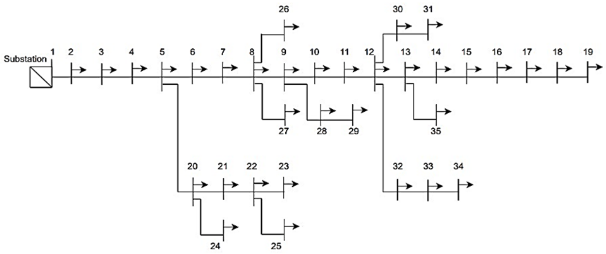

Figure 1: SLD of 11KV Bypass feeder

Problem Formulation Objective (Fitness Function):

Minimize power loss and improve voltage profile.

$$\text{Minimize } F = w_1 f_1 + w_2 f_2$$

Where,

- f_1 = total real power loss of the system
- f_2 = voltage deviation index
- w_1 and w_2 = weighting factors such that $w_1 + w_2 = 1$

Operational Constraint:

1. Voltage limits: $0.95 \leq V_i \leq 1.05$
2. Power balance: $P_G = P_D + P_{loss}$
3. DG capacity limits: $P_{DG(min)} \leq P_{DG} \leq P_{DG(max)}$

Initialization:

Generate initial whale positions = possible DG placements and sizes. Each solution is evaluated using a fitness function.

3.1.2 Whale Optimization Algorithm Framework:

1.Encircling Prey (Mathematical Model):

$$D = |C \cdot X^*(t) - X(t)|; \quad X(t+1) = X^*(t) - A \cdot D$$

$$A = 2ar - a, \quad C = 2ra$$

Where,

- a: decreases from $2 \to 0$ over iterations,
- $X^*(t)$: best solution (prey); $X(t)$: current solution (whale)
- C: A coefficient used to adjust influence of the best position
- D: Distance between the current whale and the prey

2. Bubble-Net Attacking (Exploitation Phase)

Two hunting strategies:

- Shrinking Encircling ($|A| < 1$): Moves closer to the best solution.
- Spiral Motion; $X(t+1) = D' \cdot e^{bl} \cdot \cos(2\pi l) + X^*(t)$

The combined model assumes a 50% probability for either mechanism.

$$X(t+1) = \begin{cases} X^*(t) - A \cdot D, & \text{if } p < 0.5 \\ D' \cdot e^{bl} \cdot \cos(2\pi l) + X^*(t), & \text{if } p \geq 0.5 \end{cases}$$

3. Search for Prey (Exploration Phase) When $|A| > 1$, whales search globally by referencing a random whale instead of the best one:

$$D = |C \cdot X_{rand} - X|; \quad X(t+1) = X_{rand} - A \cdot D$$

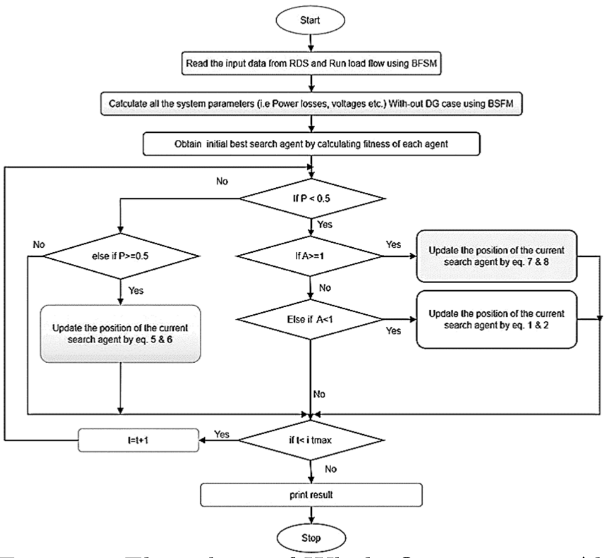

Figure 2: Flow chart of Whale Optimization Algorithm (WOA)

3.2 Solar PV Modeling:

The Solar irradiance in the Biratnagar region exhibits significant daily and seasonal variations. For this study, hourly solar PV generation was modelled using average irradiance data for the Morang district published by the Alternative Energy Promotion Centre (AEPC) and Nepal Electricity Authority. The average daily solar insolation is 4.7-5.2 kWh/m^2/day with approximately 300 sunny days per year [AEPC, 2022].

A standard photovoltaic conversion efficiency of 18 % and an inverter efficiency of 95 % were assumed. Therefore, the active power output of each solar DG unit at any hour was calculated as:

$$P_{PV} = G \times A \times \eta_{PV} \times \eta_{inv}$$

Where

- G = instantaneous solar irradiance (kW/m^2)
- A = total panel area corresponding to the rated DG capacity
- η_{PV} = panel efficiency (0.18)
- η_{inv} = inverter efficiency (0.95)

Hourly irradiance profiles for a typical year in Biratnagar were directly incorporated into the load flow and optimization processes to reflect the time-varying nature of solar generation.

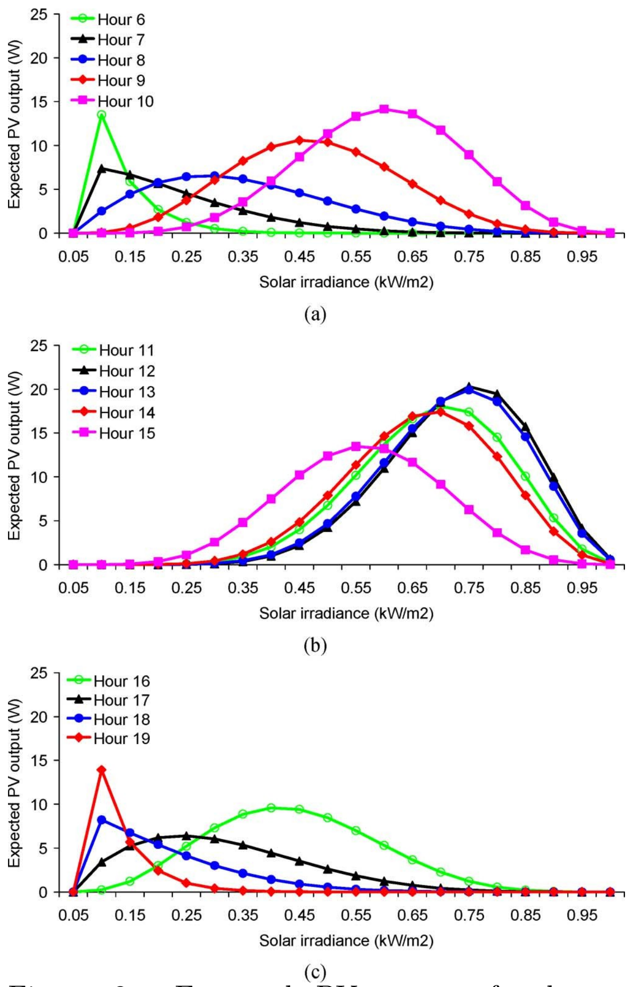

Figure 3: Expected PV output for hours: (a)6–10, (b)11–15, and (c)16–19

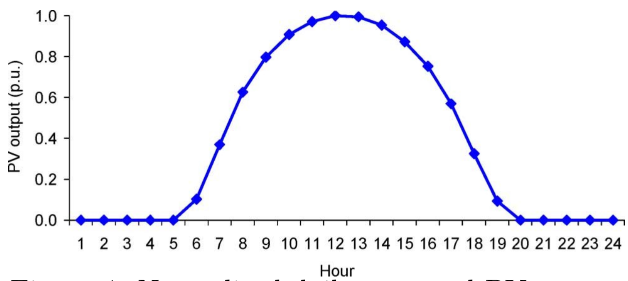

Figure 4: Normalized daily expected PV output

3.3 Methodology for Calculation

I used a MATLAB-based whale optimization simulation to model 35 bus radial networks:

Step 1: Read the system data, including bus, line, and load parameters.

Step 2: Perform a power flow analysis using the backward–forward sweep method.

Step 3: Initialize the population (number of whales), DG size limits (DG$_{min}$ and DG$_{max}$), and iterations.

Step 4: Generate the initial DG sizes randomly within limits.

Step 5: Evaluate the fitness of each whale using the objective function (total loss and voltage deviation).

Step 6: Update the whale positions using the WOA equations (encircling, spiral, or random search).

Step 7: Apply the system constraints to ensure valid solutions.

Step 8: Repeat until convergence or the maximum number of iterations is reached.

Step 9: Display the optimal DG sizes and locations with minimized losses and improved voltage profiles.

3.3.1 Proposed voltage stability index for optimal DG placement in radial distribution system

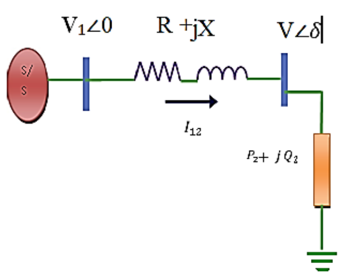

Figure 5: Equivalent circuit model of RDS

A simple radial distribution system (RDS) can be represented by a source at one end and a load at the other, as shown in Fig.

The mathematical formulation of the Voltage Stability Index (VSI) is derived as follows.

Let the branch current between Bus 1 and Bus 2 be expressed as:

$$I_{12} = \frac{P_2 + jQ_2}{V_2\angle\delta} \quad (1)$$

The receiving-end bus voltage is given by:

$$V_2\angle\delta = V_1\angle 0 - (R + jX)I_{12} \quad (2)$$

Substituting Eq. (1) into Eq. (2):

$$V_2\angle\delta = V_1\angle 0 - (R + jX)\frac{P_2 + jQ_2}{V_2\angle\delta} \quad (3)$$

Simplifying and separating the real and imaginary parts gives:

$$V_2^2 + P_2R + Q_2X = V_1V_2\cos\delta \quad (4)$$

$$P_2X - Q_2R = -V_1V_2\sin\delta \quad (5)$$

Assuming small phase angle difference ($\delta \approx 0$), Eq. (4) simplifies to:

$$V_2^2 + P_2R + Q_2X = V_1V_2 \quad (6)$$

From Eq. (5):

$$R = \frac{P_2X}{Q_2} \quad (7)$$

Substituting Eq. (7) into Eq. (6):

$$V_2^2 - V_1V_2 + \left(\frac{P_2^2}{Q_2} + Q_2\right)X = 0 \quad (8)$$

For the system to remain voltage-stable, the discriminant of the quadratic equation must be positive:

$$b^2 - 4ac \geq 0$$

From this condition, the Voltage Stability Index (VSI) is defined as:

$$VSI = \frac{4X}{V_1^2}\left(\frac{P_2^2}{Q_2} + Q_2\right) \leq 1 \quad (9)$$

The value of voltage stability index at any point represents the condition of the node. The lesser the value of VSI the more the node is sensitive to voltage collapse. For stable operation of radial distribution network VSI values must be higher i.e., near to 1.

1. Data Used

Table 1: 11 kV Bypass Feeder Data

S.N	**Bus No**	**R (Ω)**	**X (Ω)**	**Ampere**	**KVA**	**Bus No**	**KW**	**Kvarh**
0		0	0			1	0	0
1	1	0.8165	0.4780	400	200	2	170	90
2	2	0.1577	0.0923	400	100	3	85	45
3	3	0.1528	0.0894	400	100	4	85	45
4	4	0.1940	0.1136	400	300	5	255	134
5	5	0.0818	0.0479	400	200	6	170	90
6	6	0.1187	0.0695	400	200	7	170	90
7	7	0.1364	0.0798	400	200	8	170	90
8	8	0.1485	0.0869	400	100	9	85	45
9	9	0.1045	0.0612	400	200	10	170	90
10	10	0.0703	0.0412	400	100	11	85	45
11	11	0.0850	0.0497	400	200	12	170	90
12	12	0.0772	0.0452	400	160	13	136	72
13	13	0.0118	0.0069	400	160	14	136	72
14	14	0.0674	0.0395	400	100	15	85	45
15	15	0.0051	0.0030	400	100	16	85	45
16	16	0.0547	0.0320	400	100	17	85	45
17	17	0.0251	0.0147	400	160	18	136	72
18	18	0.0738	0.0432	400	200	19	170	90
19	5	0.2026	0.1186	400	200	20	170	90
20	20	0.2465	0.1443	400	200	21	170	90
21	21	0.3960	0.2319	400	25	22	21	11
22	22	0.3158	0.1849	400	200	23	170	90
23	20	0.2449	0.1434	400	200	24	170	90
24	22	0.0833	0.0488	400	200	25	170	90
25	8	0.0721	0.0422	400	200	26	170	90
26	8	0.0721	0.0422	400	100	27	85	45
27	9	0.0491	0.0287	400	300	28	255	134
28	28	0.0221	0.0129	400	200	29	170	90
29	12	0.0812	0.0475	400	100	30	85	45
30	30	0.0715	0.0419	400	200	31	170	90
31	31	0.1399	0.0819	400	100	32	85	45
32	12	0.0791	0.0463	400	100	33	85	45
33	33	0.0229	0.0134	400	200	34	170	90
34	13	0.0406	0.0237	400	200	35	170	90
Total		**4.52**	**2.65**		**5605.00**		**4764.25**	**2508.85**

4. Results and Discussions:

The Whale Optimization Algorithm was implemented in MATLAB and applied to the actual 35- bus, 11 kV Bypass Feeder of the Biratnagar Distribution Center. The population size was set to 50 whales, and the maximum number of iterations was 200. The forward-backward sweep load flow method was used to calculate the power losses and bus voltages in each iteration.

4.1 Effect of DG Size on Power Losses

Figure 6 illustrates the impact of the DG capacity on the total active power loss. Three zones were observed: loss reduction (0–2 MVA), optimal point (1.617 MVA), and loss inflation (> 2 MVA) due to reverse power flow.

4.2 Optimal DG Placement and Sizing

After 200 iterations, the WOA converged to the solution presented in Table II.

Table 2: Optimal Solar DG Placement and Sizing

Bus No.	**DG Size (MVA)**	**Power Factor**	**Voltage before DG (p.u.)**	**Voltage after DG (p.u.)**
16	0.993	0.88 lag	0.92	0.951
30	0.624	0.88 lag	0.921	0.951
Total	**1.617**			

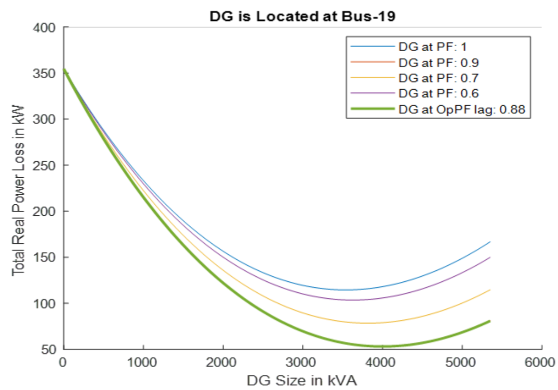

Figure 6: Impact of DG Size on Active Power Losses in Bypass Feeder

Phase 1: Loss Reduction Zone

In this initial phase, increasing the DG size reduced the total system losses. The DG supplies power to nearby loads, decreasing the current drawn from the central substation through long feeder lines. Because power losses are proportional to the square of the current ($P_{loss} = I^2R$), this reduction in current flow results in a sharp decline in losses, as shown in the chart between 0 and 2000 KVA DG size.

Phase 2: Optimal Penetration Point

A specific optimal DG size exists at which the system power losses are minimized. At this point, the local load is almost entirely met by the DG, minimizing the power transfer over the network and maximizing the efficiency. The chart shows that the minimum loss point occurred at approximately 4000 KVA of local load demand. In practice, this optimum is influenced by the network impedance and load concentration.

Phase 3: Loss Inflation Zone

When the DG size exceeds the local load requirements, the system experiences a reverse power flow. Excess generation is fed back toward the substation, increasing the current magnitude in the feeder segments. This creates new loss pathways, causing losses to rise rapidly beyond the optimal point. Hence, over-sizing the DG can produce higher losses than the original system configuration, while also potentially causing voltage regulation problems.

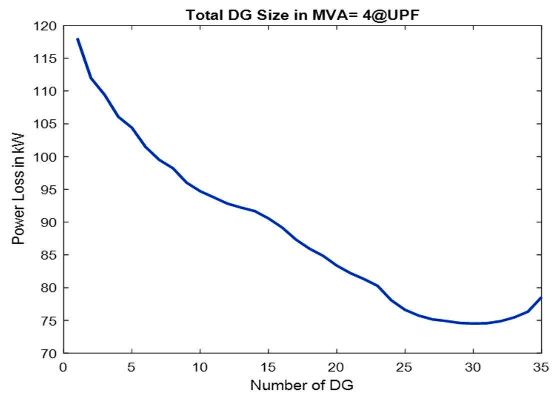

Figure 7: System Power Loss versus DG Penetration Level for 35 bus network

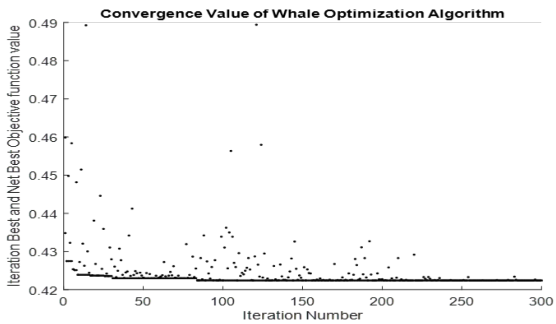

Figure 8: Convergence of Whale Optimization Algorithm

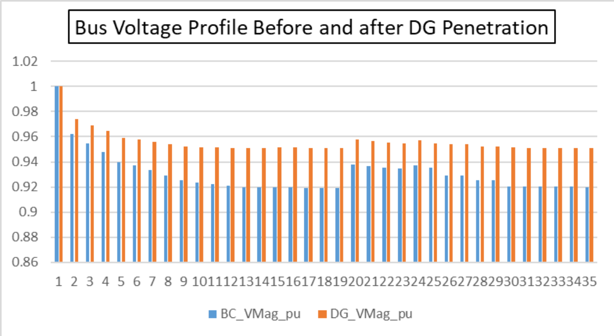

Figure 9: Bus voltage profile before and after DG Penetration

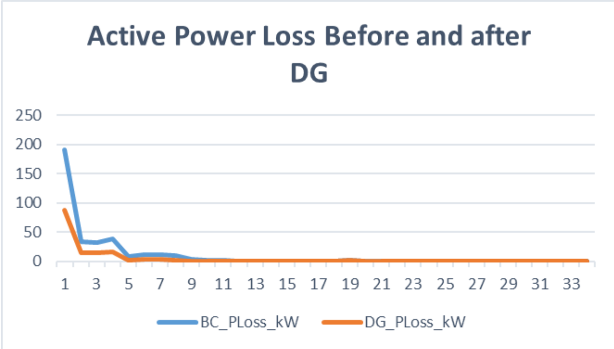

Figure 10: Voltage and loss profile across scenarios

Table 3: DG Placement Comparison in Bypass Feeder

S.N.	Parameter	Case 1 (2 DGs: Bus 16, 30)	Case 2 (3 DGs: Bus 10, 12, 17)	Case 3 (4 DGs: Bus 34, 18, 13, 35)	Case 4 (5 DGs: Bus 13, 12, 18, 31, 5)	Remarks
1	Total DG Size (MVA)	1.617	1.617	1.617	1.617	Equal total DG size in all cases
2	Minimum Voltage (p.u.)	0.951	0.9507	0.9507	0.9507	Almost identical across all cases
3	Maximum Voltage (p.u.)	0.9741	0.9741	0.9741	0.9741	Identical
4	Total Power Loss (kW)	149.779	149.806	149.641	149.733	Case 3 gives the lowest power loss
5	Total Reactive Power Loss (kVAR)	87.679	87.695	87.598	87.652	Case 3 again has the lowest reactive loss
6	Objective Function Value	0.422	0.422	0.422	0.422	All same (optimized equally)
7	Active Power Loss Reduction (kW)	204.858 (57.77%)	204.832 (57.76%)	204.996 (57.80%)	204.904 (57.78%)	Highest reduction in Case 3
8	Reactive Power Loss Reduction (kVAR)	119.920 (57.77%)	119.905 (57.76%)	120.001 (57.80%)	119.947 (57.78%)	Highest reduction in Case 3
9	Active Power Flow Reduction (kW)	1525.092 (30.95%)	1525.067 (30.95%)	1525.219 (30.95%)	1525.117 (30.95%)	Case 3 slightly best
10	Minimum Voltage Bus No.	19	32	32	32	Case 1 improves voltage at bus 19 (critical)

Result Summary of DG Placement

```
-----------------------------------------------------------------
| Bus    |  BC_Vm   |  BC_Va   |  DG_Vm   |  DG_Va   |   DG   |
| No     |  p.u.    |  Degree  |  p.u.    |  Degree  |   MVA  |
-----------------------------------------------------------------
```

```
  16    0.920    -0.200       0.951   -0.135     0.993
  30    0.921    -0.197       0.951   -0.134     0.624
------------------------------------------------
Total Size of DG =  1.617 MVA @pf=0.880
------------------------------------------------
```

Overall Summary of DG Placement

```
----------------------------------------------------------------
**************************Base Case -------> With DG Placed***
Minimum Voltage in p.u.@bus:  0.9191 @ 19  ---->   0.9510 @ 19
Maximum Voltage in p.u.@bus:  0.9619 @ 2 ---->  0.9741 @ 2
Total Power Loss in kW:  354.638 ----> 149.779
Total Power Loss in kVAR:  207.600 ----> 87.679
Maximum Active Power Flow in kW@From-To Bus: 4927.766@1-2  ---->  3402.674@1-2
Maximum Reactive Power Flow in kVAR@From-To Bus: 2615.859@1-2 --> 1788.038@1-2
Objective Function Value: 1.000 ----> 0.422
----------------------------------------------------------------
Amount of Active Power Loss reduction = 204.858 KW and 57.77%
Amount of Reactive Power Loss reduction = 119.920 KVar and 57.77%
Objective Function reduction With DG = 57.77%
Amount of Active Power Flow reduction in Branch having Maximum flow = 1525.092 KW and 30.95%
****************************************************************
Total Active and Reactive Load =  4764.000 kW and  2520.000 kVar respectively
```

Observations

1. Technical Performance:

- Multi-DG configurations slightly improve active/reactive loss reduction and voltage profiles compared to single DG.
- Differences between 2, 3, and 4 DG cases are marginal (active loss reduction difference < 0.15 kW).

2. Objective Function:

- All multi-DG configurations achieve similar objective function values (0.422), indicating near-optimal performance.
- Single DG has slightly higher OF (0.424) — minor difference.

3. Cost Considerations:

- Fixed installation cost per DG unit is a significant factor.
- Single DG has the lowest installation and O&M cost but slightly inferior technical performance.
- Two DGs achieve almost the same performance as 3–4 DGs while keeping installation and operational costs lower.

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