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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

As electricity demand increases in rural Nepal, high line losses and voltage instability have become major challenges. This thesis introduces a framework using the whale optimization algorithm (WOA) to determine the optimal locations and sizes for distributed solar generation (DG) on the 11 kV bypass feeder at the Biratnagar distribution center, which is part of the Nepal Electricity Authority. The study uses real feeder data, including line parameters, load profiles, and solar irradiance, from 300 sunny days each year. The optimization model aims to reduce power losses and improve the lowest bus voltage as the load grows annually. WOA, which is based on how humpback whales hunt, helps to find better solutions than traditional methods. Simulations show that optimally placed solar DG units can reduce real power losses by more than 57.77% and raise the voltage to at least 0.951 PU, all without changing the network or adding energy storage. The method was tested using forward–backward sweep load flow and real operational limits to ensure that it works in practice. By applying this approach to real-world systems rather than standard test cases, the study provides a practical and efficient tool for distribution utilities in developing countries. This work supports Nepal's goals for more renewable energy, a stronger grid, and better rural electrification.

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

1. Introduction

Access to electricity in rural areas of developing countries, such as Nepal, remains challenging. Rapid growth in electricity demand, high transmission and distribution losses, voltage instability, and limited grid expansion in remote areas make it difficult to achieve a reliable power supply.Uniyal and Kumar (2016) According to the Nepal Electricity Authority (NEA), distribution losses exceed 20%. In many rural 11 kV feeders, the voltage often drops below 0.9 power-up (PU) during peak demand periods. Long radial feeders and overloaded lines also lead to frequent

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outages. These problems reduce power quality and limit economic development in rural communities.Nepal Electricity Authority (2025)

Distributed generation (DG) can improve the performance of distribution systems. Solar photovoltaic (PV) systems are a good choice because they produce electricity close to where it is required. This reduces line losses, improves voltage, and enhances system reliability.Kotb et al. (2022) Nepal has strong solar potential, with approximately 300 sunny days annually and an average solar radiation of 4.5 to 5.5 kWh/m^2/day. This makes solar PV a practical option for rural electrification.Adhikari et al. (2014) However, if DG units are not placed or sized correctly, issues such as reverse power flow, overvoltage, and increased system losses can occur. Careful planning is required for the placement of DG devices. Earlier studies used analytical and sensitivity-based methods to identify the best locations for DG units.Gauli et al. (2023); Prakash et al. (2018) These methods often assume a constant load and ideal conditions. In reality, distribution systems are more complex. Radial feeders can exhibit high resistance-to-reactance ratios, unbalanced loads, and variable solar generation. Therefore, traditional methods may not provide accurate results.Uniyal and Kumar (2016); Biswal et al. (2021); Morshidi et al. (2018); Gaonkar et al. (2014); Li et al. (2016)

To address these challenges, many researchers have used metaheuristic optimization methods, such as the genetic algorithm (GA), particle swarm optimization (PSO), and whale optimization algorithm (WOA).Mirjalili and Lewis (2016) These algorithms work well for complex multi-objective problems. The WOA is based on how humpback whales hunt using bubble nets. It can efficiently search for the best solutions. Studies have shown that the WOA can significantly reduce power losses and improve voltage profiles in standard IEEE test systems.Li et al. (2016); Murty and Kumar (2015) However, most existing studies have been tested only on standard benchmark networks. Very few studies have applied the WOA to real distribution feeders using actual operating data. In particular, studies that include real feeder topologies, hourly load variations, solar irradiance data, and future load growth are limited.

To address this gap, this study uses a whale optimization algorithm to determine the optimal placement and size of distributed solar generation in a real distribution feeder. The method was tested on an 11-kV bypass feeder at the Biratnagar Distribution Center under the Nepal Electricity Authority. The analysis uses real feeder layouts, hourly load data, solar irradiance, and expected load growth. The goal is to lower active power losses and improve the lowest bus voltage while meeting practical system limits. Earlier research on DG optimization primarily employed analytical methods to improve voltage stability and reduce system losses. For instance, some studies utilized voltage stability indices to identify suitable locations for DG units. These methods demonstrated significant reductions in losses when applied to standard radial systems, including the IEEE 12-, 69-, and 85-bus networks.Abderahim et al. (2022) However, these approaches typically assume constant loads and focus on a single objective, thereby limiting their applicability in more complex systems. Later studies have examined changing loads and renewable energy generation. Some researchers have developed analytical models to study PV use in standard distribution systems and have identified performance improvements. However, these studies have not used advanced optimization methods or real feeder data. In recent years, attention has shifted toward practical applications and microgrid systems.Gauli et al. (2023) Experimental studies have demonstrated the stable operation of small hybrid renewable energy systems that combine wind and solar power. However, many of these studies have focused on isolated microgrids and have not considered the integration of DGs into existing grid-connected radial feeders.Hung et al. (2014)

Recently, metaheuristic algorithms have become common for DG planning. Methods, such as Cuckoo search, gravitational search algorithm, particle swarm optimization, and genetic algorithm, have been compared for DG placement. These methods demonstrated faster convergence and better results. Later studies used the whale optimization algorithm and reported significant reductions in power losses and improved voltage stability in test systems. However, most research has used simple test networks and has not considered real distribution feeders operating under real conditions.

2. Methodology

This paper presents a method for determining the optimal location and size of distributed generation (DG) units in a radial distribution system. A whale optimization algorithm (WOA) was used to minimize real power losses and improve the voltage profile of the network. Solar photovoltaic (PV) generation is considered a distributed energy source. The simulation and optimization processes were implemented in MATLAB for a 35-bus radial distribution network.

A. Optimization of distributed generation using the whale optimization algorithm

Optimization is the process of selecting the best solution from several possible alternatives. In power distribution systems, optimization techniques help determine the optimal locations and capacities of distributed generation units. Traditional optimization techniques, such as the genetic algorithm (GA) and particle swarm optimization (PSO), are widely used (Figure 1). However, these methods may converge to local optimum solutions or require complex parameter tuning. To overcome these limitations, in this study, the whale optimization algorithm (WOA) is applied. The WOA is a nature-inspired metaheuristic algorithm based on the bubble-net hunting behavior of humpback whales. In this method, each whale represents a possible solution containing DG locations and sizes. The whales iteratively update their positions to search for the best solution.Marimuthu et al. (2017)

B. Problem Formulation

The main objective of the optimization is to reduce the real-power loss of the distribution system and improve the voltage profile.

The objective function is expressed as

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

Where,

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

C. System constraints

The optimization process is performed while satisfying the following operational constraints.

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

These constraints ensure that the obtained solution is feasible for the practical operation of the distribution system.

D. Whale optimization algorithm framework

The whale optimization algorithm models the hunting behavior of humpback whales. The algorithm mainly consists of three mechanisms: encircling prey, bubble-net attack, and prey search.

Whales identify the prey's position and move toward the best solution found thus far. The mathematical model is expressed as

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

- $X^*(t)$: represents the best solution obtained so far (prey)

- $X(t)$: represents the current whale position
- D: distance between the whale and the prey
- A, C: coefficient vectors
- Coefficients are calculated as:

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

- a: decreases linearly from $2 \rightarrow 0$ during the iterations
- r: random number between 0 and 1

Bubble-net attacking method

This stage represents the exploitation phase of the algorithm. Two strategies are used to update whale positions.

The first strategy is shrinking encircling, which occurs when $(|A| < 1)$ and the whale moves toward the best solution.

$X(t+1) = D' \cdot e^{bl} \cdot \cos(2\pi l) + X^*(t)$

The second strategy involves a spiral movement around the prey.

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

where b is a constant that defines the spiral shape, and l is a random number between -1 and 1.

The probability value, p, determines the updating mechanism. If p < 0.5, the encircling method is used; otherwise, spiral movement is applied.

Search for Prey

When $|A| > 1$, the algorithm performs global exploration. In this case, the whales move toward a randomly selected whale rather than the best solution.

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

E. Solar photovoltaic modeling

Solar photovoltaic (PV) generation was considered to be a distributed energy source in this study. The solar irradiance in the Biratnagar region exhibited daily and seasonal variations. Hourly solar PV generation was modeled using average irradiance data for the Morang district obtained from the Alternative Energy Promotion Centre (AEPC) and the Nepal Electricity Authority. The average solar radiation in the region is approximately 4.7–5.2 kWh/m^2/day with nearly 300 sunny days per year.

A PV module efficiency of 18% and an inverter efficiency of 95% were assumed. The output power of a PV unit is 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 data were incorporated into the optimization process to represent the variation in solar generation throughout the day.

F. Simulation procedure

The optimization process was implemented in MATLAB for a 35-bus radial distribution network. First, the system data, including the bus, line, and load parameters, were read into the program. Subsequently, a power flow analysis was performed using the backward-forward sweep method. Subsequently, the whale population, DG size limits, and maximum number of iterations were defined. The initial DG sizes were randomly generated within specified limits. The fitness value of each whale was calculated using an objective function that included the total power loss and voltage deviation. Whale positions were subsequently updated using WOA equations based on encircling, spiral movement, or random exploration. System constraints were applied in each iteration to ensure valid solutions. The process continued until the maximum number of iterations was reached or until the solution converged. Finally, the optimal DG locations and sizes were determined, resulting in minimum power loss and an improved voltage profile in the distribution network.

2.0.1 G. Voltage stability index for optimal DG placement

A voltage stability index (VSI) was used to identify weak buses in the radial distribution system. The branch current between Bus 1 and Bus 2 is expressed as

$$I_{12} = \frac{P_2 + jQ_2}{V_2 \angle \delta} \tag{1}$$

The receiving-end bus voltage is given by:

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

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

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

Simplifying and separating the real and imaginary parts gives:

$$V_2^2 + P_2 R + Q_2 X = V_1 V_2 \cos \delta \tag{4}$$

$$P_2 X - Q_2 R = -V_1 V_2 \sin \delta \tag{5}$$

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

$$V_2^2 + P_2 R + Q_2 X = V_1 V_2 \tag{6}$$

From Eq. (5):

$$R = \frac{P_2 X}{Q_2} \tag{7}$$

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

$$V_2^2 - V_1 V_2 + \left(\frac{P_2^2}{Q_2} + Q_2 \right) X = 0 \tag{8}$$

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:

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

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

2.1 Result and Discussion

The whale optimization algorithm (WOA) was implemented in MATLAB to determine the optimal location and size of distributed generation (DG) units on a 35-bus 11 kV bypass feeder of the Biratnagar distribution center, operated by the Nepal Electricity Authority. The optimization was performed with a population of 50 whales and 200 maximum iterations. In each iteration, a load-flow analysis was performed using the forward–backward sweep method to calculate bus voltages and feeder power losses. The main goal of this study was to reduce power loss and improve system voltage performance by selecting a suitable DG placement and size.

A. Effect of DG Size on Power Loss

The effect of the DG capacity on the total active power loss. The results revealed three operating regions based on DG size. In the first region, as the DG size increases from small to large, the system power loss decreases. This is because the DG supplies power to nearby loads; therefore, less current must travel from the main substation through long lines. Because the power loss is proportional to the square of the current, reducing the current reduces the total loss. This effect was observed as the DG size increases from zero to approximately 2 MVA.

In the second region, an ideal DG size that minimizes power loss exists. At this point, the DG supplies most of the local load; therefore, less power is supplied by the upstream feeder. This improves the system efficiency. Simulations revealed that minimum loss occurs when the DG size is approximately 1.617 MVA. In the third region, if the DG size exceeds the local load demand, the excess power flows back toward the substation. This reverse flow increases the current in some parts of the feeder, resulting in greater losses. Therefore, a very large DG is not always beneficial for the distribution system.

B. Optimal DG Placement and Sizing

After 200 iterations, the WOA algorithm identified the best setup as having two DG units at buses 16 and 30. The DG at bus 16 has a capacity of 0.993 MVA, and the one at bus 30 has a capacity of 0.624 MVA. Together, the total DG capacity was 1.617 MVA (Table 1), with a power factor of 0.88. Before installing the DG units, the voltage at bus 16 was 0.920 PU with a phase angle of 0.200° and at bus 30, it was 0.921 PU with a phase angle of 0.197. After DG installation, the voltage at both buses increased to approximately 0.951 PU, demonstrating that DG placement improves voltage stability in the feeder (Figure 2).

C. Overall System Performance Improvement

System performance was verified by comparing the base case with the system after DG installation. In the base case, the lowest voltage in the network was 0.9191 PU at bus 19, and the highest was 0.9619 PU at bus 2. After DG placement, the minimum and maximum voltages increased to 0.9510 PU and 0.9741 PU, respectively. This indicates that the voltage levels became more stable. The total active power loss decreased from 354.638 kW in the base case to 149.779 kW after DG installation. This represented a reduction of 204.858 kW, or approximately 57.77%. The reactive power loss also decreased from 207.600 kVAR to 87.679 kVAR, a decrease of 119.920 kVAR, or approximately 57.77% (Figure 3).

The branch connecting buses 1 and 2 recorded the highest active power flow. Initially, it was 4927.766 kW, but after DG installation, it decreased to 3402.674 kW. This represented a reduction of 1525.092 kW, or approximately 30.95%. The reactive power flow in this branch also fell from 2615.859 kVAR to 1788.038 kVAR. The objective function value used in the optimization also improved. It decreased from 1.000 in the base case to 0.422 after DG placement. The total feeder load was 4764 kW of active power and 2520 kVAR of reactive power. The optimized DG placement improved the overall system operation (Figure 4).

2.1.1 D. Comparison of Single and Multiple-DG Configuration

Several DG installation scenarios were tested. Using multiple DG units slightly improved the voltage profile and reduced power losses compared with using a single DG unit. However, the difference in loss reduction between two, three, and four DG units was negligible (less than 0.15 kW). The objective function values for cases with multiple DG units were nearly identical, at approximately 0.422. The single-DG case had a slightly higher value of 0.424; however, the difference was insignificant. From an economic perspective, the installation cost is important. Each DG unit requires additional investment and increases operating and maintenance costs. Although three or four DG units can reduce losses slightly more, the improvement is very small compared to the extra system cost. In conclusion, having two DG units with a total capacity of 1.617 MVA (Table 2) at buses 16 and 30 is the best practical solution. This setup delivers a significant voltage improvement and reduces losses while maintaining lower installation and operating costs (Figure 5).

3. Table and Figures

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**

Table 2: 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)

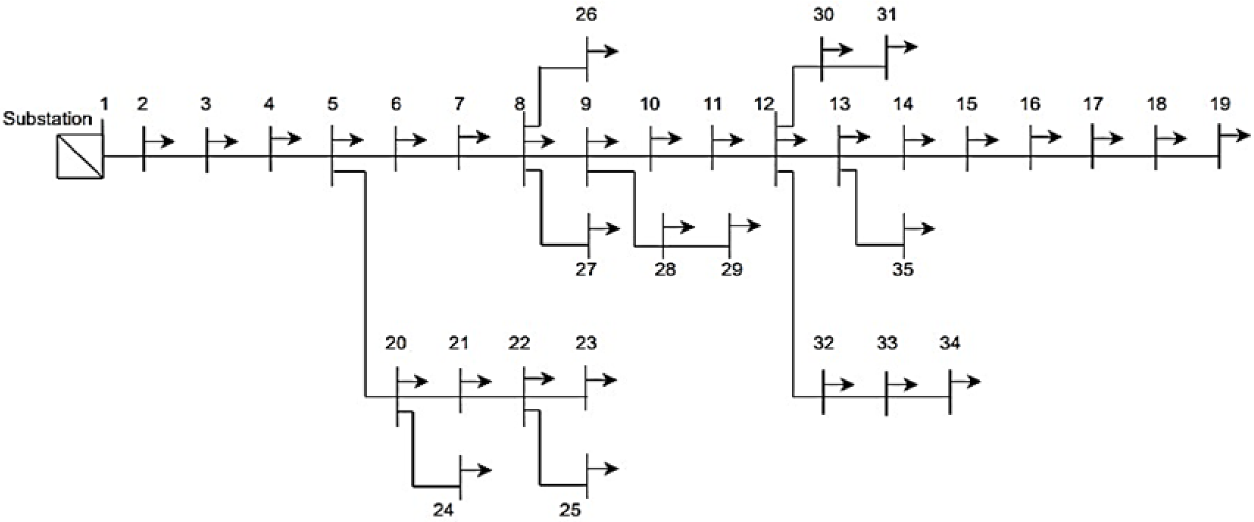

Figure 1: SLD of 11KV Bypass feeder

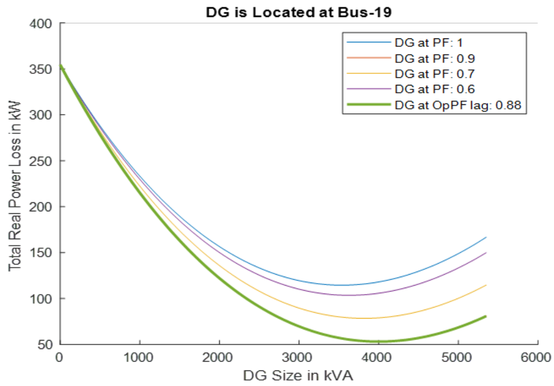

Figure 2: Impact of DG Size on Active Power Losses in Bypass Feeder

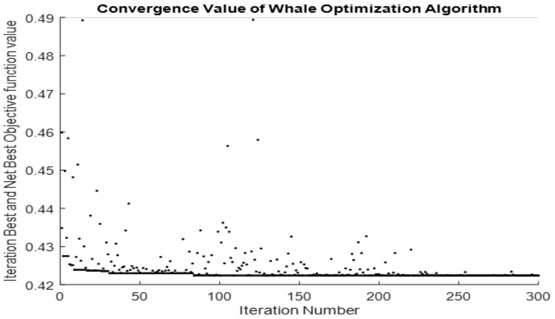

Figure 3: Convergence of Whale Optimization Algorithm

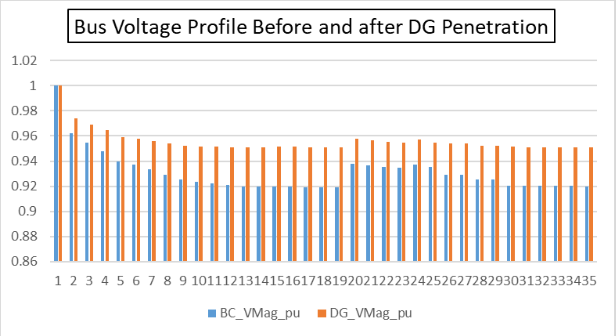

Figure 4: Bus voltage profile before and after DG Penetration

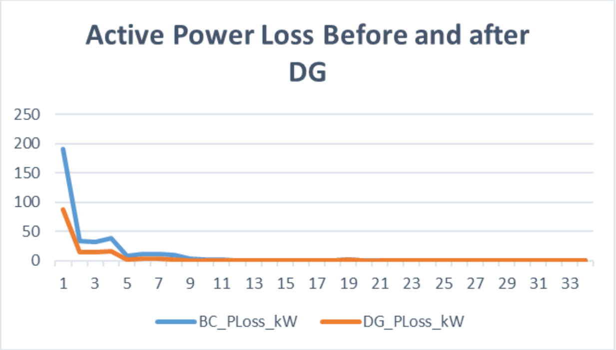

Figure 5: Voltage and loss profile across scenarios

4. Conclusion and Future Scope

In this study, the whale optimization algorithm was successfully applied to determine the optimal location and size of solar DG units in a real 35-bus, 11 kV bypass feeder of the Biratnagar distribution center of the Nepal Electricity Authority. With two solar DG units totaling 1.617 MVA placed at buses 16 and 30, active power losses were reduced by 57.77 % (from 354.6 to 149.8 kW), and the minimum bus voltage improved from 0.919 to 0.951 PU without any network reconfiguration or energy storage. These results prove that appropriately sized solar DGs units can significantly enhance the performance of rural long-radial feeders in Nepal.

5. Future Scope

1. Integration of short-duration battery energy storage to handle evening peak loads and cloudy periods.
2. Extension of the model to include seasonal load growth forecasts (5%–8 % annual growth in the Morang District) and multiple years of operation.
3. Investigation of hybrid solar + small hydro DG for feeders with access to both resources.
4. Development of a simple Excel- or MATLAB-based tool for NEA field engineers to quickly evaluate the DG potential on other 11 kV feeders.
5. Real-time field pilot installation on the bypass feeder to validate the simulation results.

6. Author's declaration

The authors declare no conflicts of interest regarding the publication of this research paper. All contributors agreed to the final draft of the manuscript.

7. Declaration of the conflict of interest

The authors declare that there are no irreconcilable circumstances. All authors contributed to the preparation of the final manuscript.

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