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Optimal Placement of Photovoltaic Distributed Generation for Voltage Regulation Enhancement in an 11 kV Radial Distribution Feeder

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Abstract

The strategic placement and sizing of distributed generation (DG) units play a crucial role in enhancing distribution systems by minimizing real power losses and fulfilling both active and reactive power demands. When DG units are effectively integrated, a greater portion of the generated energy can be utilized by consumers, thereby enhancing reliability, voltage stability, and network efficiency. In this study, a genetic algorithm (GA) was employed to identify the optimal locations and sizes of DG units within a distribution system. Tests were conducted on the IEEE-33 bus radial distribution system and the 11 kV NTC feeder of the Nepal Electricity Authority in Itahari. Prior to the installation of the PV units, the 11 kV NTC feeder experienced active and reactive power losses of 477.965 kW and 396.643 kVAR, respectively, with a minimum voltage at bus 31 of 0.8293 PU. Following the installation of the three PV units, the real and reactive power losses were reduced by approximately 73%, and the minimum voltage at bus 31 increased to 0.9466 PU. These findings demonstrate that the optimized setup significantly reduces the real power losses while maintaining a stable and improved voltage profile across the network.

Keywords :
Distributed Generation (DG), Radial Distribution System, GA, Photovoltaic, Voltage Regulation, Power Loss

1 Introduction

Distributed generation (DG) refers to small-scale electricity generation systems located close to where electricity is consumed.[1] Distributed generation (DG) systems typically use modular and renewable energy technologies, such as solar photovoltaic (PV), wind, and other clean energy sources. Unlike centralized power plants, which generate electricity far from consumers, DG supports decentralized power supply and improves local energy access.[2] With the rapid growth of global electricity demand and increasing attention to environmental protection, renewable energy sources have become important in modern power systems.[3] Solar photovoltaic (PV) technology is widely used in distribution networks. The integration of PV systems into distribution networks can improve voltage regulation, reduce energy losses, and enhance system reliability. However, these benefits can only be achieved when PV systems are properly sized and placed at suitable locations in the network.[4]

Distribution networks are generally designed as radial systems with unidirectional power flow from the source to consumers. These networks usually have high resistance-to-reactance ratios, which make

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them more vulnerable to voltage drop and power loss. If PV systems are installed without proper planning, problems such as reverse power flow, voltage rise, and network imbalance may occur.[5] Therefore, selecting the optimal locations and capacities of PV units is crucial for maintaining stable and efficient network operations.[6, 7] The optimal placement and sizing of distributed generation (DG) units are complex optimization problems because distribution systems have many buses and operating constraints. Installing DG units at unsuitable locations may increase losses and worsen voltage conditions instead of improving the system performance. Therefore, voltage stability is often considered a key objective in DG planning.

Various mathematical and heuristic optimization techniques have been developed to solve this type of problem. Metaheuristic algorithms, such as particle swarm optimization, differential evolution, and genetic algorithms, are widely used for nonlinear power system optimization problems.[8] Among these methods, the genetic algorithm is particularly suitable for distribution network optimization because of its simplicity, flexibility, and fast convergence characteristics. Genetic algorithms are based on the concepts of natural selection and evolutionary processes.[5] In recent years, many studies have focused on optimizing the DG and PV placements in radial distribution networks to improve their technical performance.[9] Some studies have used hybrid or advanced optimization techniques, such as the gray wolf-seagull (SLA) and marine predator algorithms, which have demonstrated better performance than traditional methods, such as gray wolf optimization and the gray wolf–seagull algorithm. Most optimization approaches follow a two-stage process. First, sensitive buses are identified using loss sensitivity analysis, and then optimization algorithms are used to determine the best DG location and size.[1]

Experimental studies conducted on standard test systems, such as IEEE 33-, 69-, and 118-bus networks, as well as practical distribution feeders, have reported significant loss reductions and voltage-profile improvements. Some results have shown a power-loss reduction of up to 80% when DG units and capacitors are installed in a coordinated manner.[2, 10] These findings confirm that the hybrid integration of DGs and reactive power compensation devices can improve system stability and efficiency.[8] Recent research also suggests considering multi-objective optimization frameworks that include technical and economic factors.[6, 7] Early studies mainly focused on minimizing power loss in small networks. However, modern distribution systems require consideration of renewable energy intermittency and load uncertainty. Probabilistic approaches have been introduced to model the variable nature of solar and wind power generation. Studies have also shown that distributed generation (DG) units operating at a lagging power factor can improve voltage regulation and reduce losses.[2]

Energy storage systems, especially lithium-ion battery storage, are also being considered in modern distribution networks.[4] The proper placement and management of energy storage can further reduce energy loss and improve power system performance.[11] This study focuses on optimal PV placement in radial distribution networks. The IEEE 33-bus test system and the 11 kV NTC feeder of NEA Itahari were used as case studies. The main objective of this research is to improve voltage regulation and reduce real power loss using a genetic algorithm-based optimization approach. In this study, a genetic algorithm was applied to determine the best location and capacity of solar PV distributed generation units in the IEEE 33-bus system and the 11 kV NTC feeder.[11] The performance of the system was evaluated by comparing the power loss and voltage profile before and after optimization. The proposed method provides an effective approach to improve distribution network reliability and operational performance.[12]

2 Methodology

This study aims to improve the performance of radial distribution networks by optimally placing and sizing photovoltaic (PV) units. Two systems were considered: the IEEE 33-bus test system and the 11 kV NTC feeder of NEA Itahari. Both real operational data and simulation modelling were used to analyses system performance.

A. Data Collection and System Description

IEEE 33-bus system data, including line parameters, loads, resistances, and reactance, were obtained from IEEE Resources and the literature. For the 11 kV NTC feeder, operational data were collected from the NEA, including

- Line lengths, resistances, and reactance
- Active and reactive power demands at each bus

The network configuration of the studied distribution system is illustrated in Figure 1, which shows a single-line diagram of the 11 kV NTC feeder.

B. Distribution Load Flow Analysis

Load-flow analysis, or power-flow study, is a method used to calculate the voltages, currents, and real and reactive power flows in a network under specific load conditions. This analysis is essential for planning and operational decision-making, such as verifying line capacities during maintenance or load growth.

In this study:

- Load-flow simulations were performed using MATLAB.
- IEEE 33-bus and 11 kV NTC feeder systems were analyzed.
- Two- and three-PV units were considered for the NTC feeder to supply some loads.
- The base voltage and base power were 11 kV and 1000 kVA, respectively.

The load on each bus is expressed as follows:

$$S_i = (P_i + jQ_i), \qquad i = 1, 2, \ldots, N \tag{1}$$

The bus voltages and branch currents were calculated using the bus injection-to-branch current (BIBC) and branch current-to-bus voltage (BCBV) matrices:

$$[B] = [BIBC][I] \tag{2}$$

$$[\Delta V] = [BCBV][B] \tag{3}$$

By combining the above equations, the bus voltage can be expressed in terms of these matrices and the bus current as follows:

$$[\Delta V] = [BCBV][BIBC][I] = [DLF][I] \tag{4}$$

The current injection at the k^{th} iteration is

$$I_i^k = I_i^r + jI_i^i = \left(\frac{P_i + jQ_i}{V_i^{(k-1)}}\right)^* \tag{5}$$

where V_i, I_i, P_i, and Q_i denote the bus voltage, current injection, real power, and reactive power at the i^{th} bus in the k^{th} iteration, respectively.

The bus voltages are updated iteratively as follows:

$$\left[\Delta V^{(k+1)}\right] = [\text{DLF}]\left[I^k\right] \tag{6}$$

$$V^{(k+1)} = V^0 + \Delta V^{(k+1)} \tag{7}$$

The real power loss for each branch is calculated as follows:

$$P_{\text{loss}(i,j)} = R_{(i,j)}\frac{P_i^2 + Q_i^2}{V_i^2} \tag{8}$$

The iterations were continued until convergence, thereby providing steady-state voltages, currents, and power losses for the system.

D. Genetic Algorithm

A genetic algorithm (GA) was applied to determine the optimal locations and capacities of the PV units. The GA is inspired by natural evolution and improves a set of solutions over successive generations using selection, crossover, and mutation.

The GA parameters used in this study are as follows:

- Population size = 50
- Number of generations = 500
- Stall generation limit = 100
- Time limit = 500 seconds
- Stall time limit = 50 seconds
- Plot function = @gaplot

In the PV placement problem, the GA evaluates multiple candidate solutions for PV locations and sizes. Each solution is assessed for:

1. Minimizing real power loss in the network
2. Improving voltage profile across buses

Better solutions are selected to form new populations, which gradually evolve toward the optimal configuration. The GA is suitable for nonlinear and constrained optimization problems, such as PV placement. Although parameter tuning is important, GA provides practical and efficient results for complex distribution networks.

Objective of the Study

The main objectives of this methodology are as follows.

1. Minimizing active power loss in distribution systems using PV placement.
2. To improve the voltage stability and profile of all buses.
3. To identify optimal PV locations and capacities that can achieve maximum efficiency and reliability in both IEEE 33-bus and 11 kV NTC feeder systems.

In this study, a practical approach for enhancing the performance of radial distribution networks with distributed solar generation is proposed by combining load-flow analysis and GA optimization.

3 Results and Discussion

The performance of the proposed PV placement method was evaluated using two distribution systems: the IEEE 33-bus radial distribution system and the 11 kV NTC feeder of NEA Itahari. Load-flow analysis and genetic algorithm (GA) optimization were used to study the impact of PV integration on voltage profile improvement and power loss reduction.

A. IEEE 33- Bus Radial Distribution System

The IEEE 33-bus system was first analyzed under base-case operating conditions without PV integration. The load-flow results revealed that the system experienced high technical losses and poor voltage regulation. The total active power loss in the base case was 269.033 kW, and the reactive power loss was 184.123 kVAR. The lowest bus voltage was 0.8727 PU at Bus 18, which is below the acceptable voltage limit. The slack bus voltage was maintained at 1.0 PU. These results indicate that the system exhibited large voltage drops at remote buses and a limited margin for load expansion. Therefore, optimization was required to improve system performance. After applying the genetic algorithm, three PV units with a total capacity of 2461.2 kW were optimally placed at buses 6, 14, and 31. The GA minimized an objective function that considered both loss reduction and voltage improvement. The optimization results demonstrated a significant performance improvement. The minimum bus voltage increased from 0.8727 PU to 0.9607 PU. The active power loss decreased from 269.033 kW to 90.59 kW. This corresponds to a substantial reduction in the feeder current and thermal stress in the network. A comparison between the results obtained in this study and previously reported IEEE-33 bus studies at different voltage levels is summarized in Table 2, and the improvement in the voltage profile is shown in Figure 2.

B. 11kV NTC Feeder Analysis

An analysis of an 11 kV NTC feeder was conducted as a practical distribution network case. First, a base-case load-flow analysis was conducted without PV integration. The base system exhibited an active power loss of 477.965 kW and a reactive power loss of 396.643 kVAR. The minimum bus voltage was 0.8293 PU at Bus 31, indicating poor voltage regulation. These results confirm the need for system improvement. Figure 3 should be cited in the subsection where you discuss the voltage profile results of the 11 kV NTC feeder after PV integration. The optimization results for different PV installation scenarios, including the number of PV units and their optimal bus locations, are summarized in Table 3.

Single PV Unit Integration

A genetic algorithm was used to place a single 1000 kW PV unit at Bus 28. After optimization:

- Minimum bus voltage increased to 0.9239 PU
- Active power loss reduced to 155.35 kW

This improvement occurred because the local PV generation reduced the current flow from the main source.

Three PV Unit Integration

In the final optimization case, three PV units with a total capacity of 1518.43 kW were placed at buses 10, 29, and 21. The GA algorithm solves a multi-objective problem that simultaneously minimizes power loss and improves voltage stability. After optimization:

- Minimum bus voltage increased to 0.9466 PU
- Active power loss reduced to 127.72 kW

C. Economic Performance Evaluation

The economic performances of the two- and three-PV configurations, including the NPV, BCR, and payback period, are summarized in Table 4. The economic feasibility of PV integration was evaluated from a utility perspective. The study assumed:

- PV capital cost: NPR 80,000 per kW
- Annual OM cost: 1% of capital cost
- Discount rate: 8%
- Project lifetime: 25 years
- Electricity tariff: NPR 10 per kWh

Three PV Unit Case (1.519 MW)

- Loss reduction: 73.27% (477.96 kW - 127.72 kW)
- Annual energy saving: approximately 1.84 GWh
- Total project cost (PV): NPR 134.49 million
- Present value of benefits: NPR 196.51 million
- Net Present Value (NPV): NPR 62.02 million
- Benefit-Cost Ratio (BCR): 1.46
- Payback period: about 6.6 years

Two PV Unit Case (1.345 MW)

- Loss reduction: 72.22%
- Annual energy saving: approximately 1.81 GWh
- Net Present Value: NPR 74.59 million
- Benefit-Cost Ratio: 1.63
- Payback period: about 5.93 years

The economic results confirm that PV integration in the 11 kV NTC feeder is financially viable. In addition to economic benefits, the system achieves better voltage stability and higher operational reliability.

4 Table and Figures

Table 1: Pre- and Post-Optimization Performance Comparison in IEEE 33-Bus Radial Distribution Network with Three PV Units

Metrics	Pre-optimization	Post-optimization
Voltage Profile	1.0000 pu (Bus 1) to 0.8727 pu (Bus 18)	1.0000 pu (Bus 1) to 0.9607 pu (Bus 18)
Active Power Loss	269.033 kW	90.59 kW
Reactive Power Loss	184.123 kVAR	63.46 kVAR

Table 2: Comparison of the 11 kV research on the IEEE 33 bus system with the 12.66 kV results from the case study.

S.N.	Description	Referenced 11 kV Research		This Study (12.66 kV)		Remarks
		Base Case	With 3 DG	Base Case	With 3 DG	
1	Location (bus)	–	8, 13 and 31	–	6, 14 and 31	–
2	Size (kW)	–	450, 580.64 and 750	–	1127.8, 614.7 and 718.7	–
3	Active power losses (kW)	210.98	85.74	269.03	90.59	Converting the system voltage from 12.66 kV to 11 kV raises the base-case active power loss to 269 kW, consistent with the referenced 11 kV study, as power loss varies inversely with the square of the voltage under constant power load conditions.
4	Magnitude of voltage at Bus 18 (PU)	0.9038	0.9606	0.8727	0.9607	–

Table 3: Optimal position with different number of PV placements in the 11 kV NTC feeder

S.N.	Pre-optimization Minimum Voltage (PU)-Bus Number	Post-optimization Number of PV, Size Limit Per PV	PV Placement Bus Number	Post-optimization Minimum Voltage (PU)-Bus Number
1	0.8293-31	1, 1000 kW	28	0.9239-31
2	0.8293-31	2, 500 kW	24, 29	0.9218-31
3	0.8293-31	2, 1000 kW	21, 29	0.9463-31
4	0.8293-31	2, 1500 kW	21, 29	0.9463-31
5	0.8293-31	3, 500 kW	16, 24, 29	0.9460-31
S.N.	**Pre-optimization Minimum Voltage (PU)-Bus Number**	**Post-optimization Number of PV, Size Limit Per PV**	**PV Placement Bus Number**	**Post-optimization Minimum Voltage (PU)-Bus Number**
6	0.8293-31	3, 1000 kW	10, 21, 29	0.9466-31
7	0.8293-31	3, 1500 kW	10, 21, 29	0.9466-31
8	0.8293-31	4, 500 kW	10, 18, 24, 29	0.9463-31
9	0.8293-31	4, 1000 kW	7, 12, 21, 29	0.9468-31
10	0.8293-31	4, 1500 kW	7, 13, 21, 29	0.9467-31
11	0.8293-31	5, 500 kW	7, 13, 18, 24, 29	0.9459-31
12	0.8293-31	5, 1000 kW	7, 13, 18, 24, 29	0.9468-31
13	0.8293-31	5, 1500 kW	5, 13, 18, 24, 29	0.9468-31

Table 4: Comparative cost analysis of the size and location of DG in an 11 kV NTC feeder

S.N.	Parameter	Case 3 (3 DGs: Buses 10, 29 and 21)	Case 2 (2 DGs: Buses 29 and 21)
1	Total DG Size (kW)	1519	1345
2	Minimum Voltage (PU)–Bus Number	0.9466–31	0.9463–31
3	Total Power Loss (kW)	127.72	132.76
4	Total Reactive Power Loss (kVAR)	104.24	107.76
5	Active Power Loss Reduction (kW)	350.25 (73.27%)	345.20 (72.22%)
6	Reactive Power Loss Reduction (kVAR)	292.40 (73.71%)	288.88 (72.83%)
7	Net Present Value (NPV)	NPR 62 million (Positive)	NPR 74 million (Positive)
8	Benefit–Cost Ratio (BCR)	1.461 (Greater than one)	1.626 (Greater than one)
9	Simple Payback Period	6.60 years	5.93 years

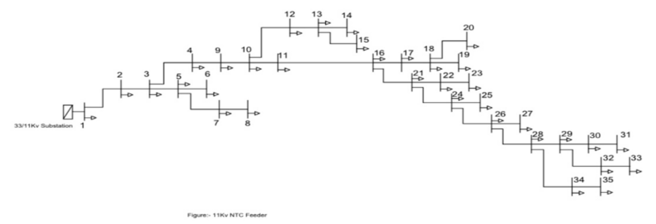

Figure 1: 11kv NTC

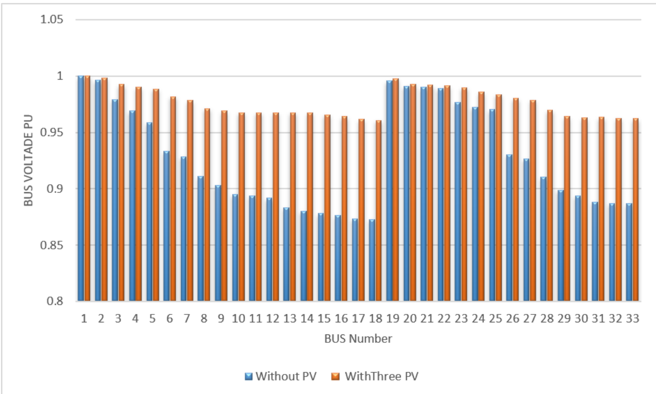

Figure 2: Voltage profile comparison of IEEE 33 bus system with and without PV integration

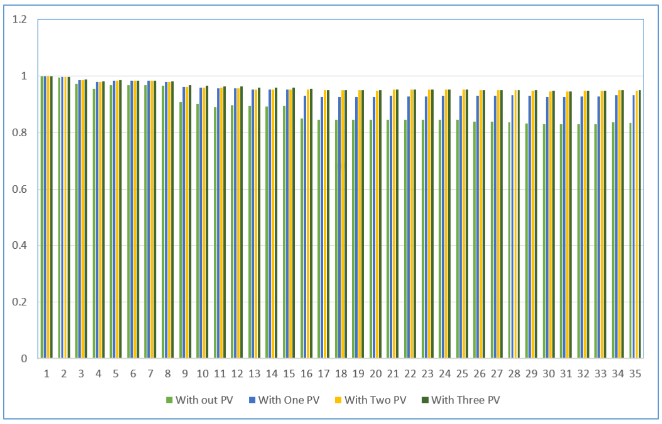

Figure 3: Voltage profile comparison of 11kV NTC feeder with and without PV integration

5 Conclusion

In this study, the IEEE 33-bus system and 11 kV NTC feeder were analyzed using distribution load-flow analysis to evaluate system performance. The load-flow equations were solved to obtain key parameters, including bus voltages, branch power flows, and network losses. The results show that the voltage profile of low-voltage distribution networks is significantly influenced by solar photovoltaic (PV) distributed generation units. PV integration led to improved voltage profiles across the network and reduced active power losses, indicating enhanced power delivery efficiency. These outcomes confirm that appropriate PV placement can improve voltage regulation and minimize losses in radial distribution systems. The analysis showed that PV integration significantly enhanced network performance. In the base case, the minimum bus voltage was 0.8293pu, indicating poor voltage regulation. After optimization, the minimum bus voltage improved to 0.9463pu for the two-PV and 0.9466pu for the three-PV cases, showing substantial voltage profile enhancement. Real power losses were reduced from 477.965 to 132.76 and 127.72 kW for the two-PV and three-PV configurations, representing reductions of 72–73 %. Reactive power losses decreased by over 72% in both cases.

An economic assessment over 25 years showed that both configurations were financially viable, with positive net present values (NPV) and benefit cost ratios (BCR) above one. The two-PV configuration demonstrated better economic performance, with a higher NPV of NPR 74.59 million, BCR of 1.626, and a shorter payback period of 5.93 years, compared with the three-PV configuration. This indicates that the marginal technical improvement from a third PV unit does not yield proportional economic benefits.

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.

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