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RESEARCH ARTICLE

Power Loss Minimization and Voltage Profile Improvement of Radial Distribution Network Through the Installation of Capacitor and Distributed Generation (DG)

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Abstract: The growing demand for electricity has raised concerns about power dissipation in distribution systems. To mitigate these losses, capacitors and distributed generation (DGs), particularly solar photovoltaic (PV) systems, are strategically placed within the system. This project is committed to reducing power losses and improving the voltage profile through an in-depth analysis, optimizing the placement of capacitor and distributed generation along the distribution feeder. The application of forward and backward sweep (FBS) algorithms assists load flow analysis in distribution networks with high *R*/*X* ratios, while the incorporation of the genetic algorithm (GA) within MATLAB identifies optimal locations and size for capacitors and DGs inside the large solution space of this complex, nonlinear optimization problem. Test outcomes, conducted on an IEEE 33-bus test system as its convincing representation of medium-sized distribution network providing a versatile platform for evaluating proposed methodologies with practical implementation, showcase load flow examination, improvements in voltage profiles, and minimized energy dissipation. The methodology is further applied to the real distribution network of the Sallaghari–Thimi 11 kV feeder in Bhaktapur, Nepal, sustaining the approach's effectiveness in mitigating power losses and increasing voltage profiles. Distributed generation with capacitor outperforms capacitors, and DG integration in the power system results in significant reductions of 72.91% in real power loss and 63.45% in reactive power loss, with a notable 6.542% increase in voltage magnitude. Application of these strategies in the Thimi–Sallaghari 11 kV feeder demonstrates significant power loss saving (up to 82.72%) and worthy improvements in voltage profiles (up to 5.32%), focusing on their effectiveness in enhancing operational efficiency. This approach provides a practical solution for optimizing capacitor and solar PV DG placement in distribution networks considering various case scenarios.

Keywords: power loss reduction, voltage profile enhancement, capacitor placement, DG (solar PV) placement, genetic algorithm, IEEE 33-bus radial network, Sallaghari–Thimi 11 kV feeder

1. Introduction

The demand for electricity is increasing on daily basis. This brings complexity in the distribution system network. Analyzing the distribution system is crucial as it serves as the essential link connecting the bulk power system with consumers. Nepal Electricity Authority [1] has overall system losses of electricity of 13.46% including the loss in transmission system and distribution system. Sallaghari–Thimi feeder significantly contributes to this overall power loss in Nepal. This feeder is used for realization of different case scenario for power loss reduction and voltage characteristic improvement.

Reducing distribution losses is attainable through careful selection of distribution transformers, feeder optimization, network reorganization, strategic placement of shunt capacitors, and integration of distributed generation at various network points. Capacitors play a vital role in compensating reactive power, reducing losses, improving voltage levels, enhancing power factor, and increasing system efficiency. Distributed generation derived from various sources, including fuel cells, solar photovoltaic (PV) systems, wind turbines, micro-hydro turbines, gas turbines, and micro-turbines, contributes to the overall efficiency. Seasonal production of energy from wind energy appears feasible in Nagarkot (particularly near to Thimi–Sallaghari feeder) given the average wind speed and the wind power density of the sites [2]. Consequently, solar PV is most suitable option.

In this project, solar PV is utilized as a distributed generation source, injecting active power into the system and proving to be feasible for a real distribution system. Various optimization techniques are employed to determine the optimal placement, size, and locations of capacitors and distributed generation units. It is crucial to ensure that their placement is optimal to maximize benefits and minimize their impact on the power system, as inappropriate placement may compromise overall system operation [3].

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Inadequate selection of the size and placement of reactive power support can lead to increased power losses and degradation of the system's voltage profile. The distribution system experiences two types of losses: active power loss and reactive power loss, calculated using Equations (1) and (2), respectively,

$$P_{loss} = \left(\sum\nolimits_{i=0}^{n} I_i^2 R_i\right) \tag{1}$$

$$Q_{loss} = \left(\sum\nolimits_{i=0}^{n} I_i^2 x_i\right) \tag{2}$$

where

R_i, x_i are current resistance and reactance of i_{th} line, respectively.

P_{loss} and Q_{loss} are the active power loss and reactive power loss in system, respectively.

This work utilizes genetic algorithms (GAs) because of its ability to explore a large solution space and find near-optimal solutions. GA uses the process of natural selection, evolving potential solutions over multiple generations. This evolutionary approach is well suited for complex, nonlinear optimization problems, such as determining the optimal locations for capacitors and DGs in a distribution system. Its aims are to decrease power losses and improve the voltage profile across different scenarios in a 33-bus test system defined by IEEE standards. The practical application of these strategies is emphasized for real-world impact, i.e., in Sallaghari–Thimi 11 kV feeder. It is significant as it validates the effectiveness of the proposed strategies in a real-world setting. This application offers insights into the challenges and complications of implementing optimal capacitor and distributed generation placement, clarifying the adaptability and reliability of the approach in addressing practical distribution system complexities.

2. Literature Review

A study was conducted to assess the impact of coordinating DG, capacitors, and combined coordination of DG with capacitor to reduce power loss. This was compared to individual coordination methods, with a focus on evaluating their effectiveness. Research in power system optimization has seen through examination of methodologies for minimizing power losses and enhancing energy efficiency. The literature highlights diverse strategies, with a particular focus on optimal capacitor placement [4–7], DG (distributed generation) siting [8–13], and integrated approaches combining both capacitor and DG placement [14–17]. Capacitor placement and DG placement studies have employed methods, such as GAs [11], Tabu search [18], and harmonic search algorithms [19], with a strong emphasis on renewable energy solutions. DG placement literature includes hybrid optimization approaches [7], particle swarm optimization [20], selective particle swarm optimization [21], local search optimization [22], and improved multi-objective harmony search algorithms [19]. Integrated studies addressing both capacitor and DG placement have utilized loss sensitivity factor methods [23], ant colony optimization [7], and hybrid solutions (HSs) combining particle swarm optimization, coot bird optimization [24], and GAs [4].

Research by Dixit et al. [23] explored optimal shunt capacitor positioning in radial distribution networks using the loss sensitivity factor method and particle swarm optimization, yielding cost savings and improved system performance. Additionally, Adel Ali et al. (2016) proposed a two-stage approach integrating loss sensitivity analysis and ant colony optimization for optimal capacitor positioning and sizing, demonstrating significant cost savings and competitive performance. Chaudhary and Lodhi [25] optimized different type of DG systems in a radial system using a GA with the Newton–Raphson method, contributing to advancements in renewable energy integration. Rugthaicharoencheep et al. [26] employed a GA for feeder reconfiguration, effectively minimizing power loss while adhering to constraints.

Furthermore, Jamil [16] investigated grid strategies, including real power distribution, reactive power addition, and transformer tap changing, emphasizing the superiority of the GA over Newton–Raphson for optimizing power flow. Lastly, Abraham and Oluwafemi [4] developed a HS combining particle swarm optimization and GAs to adjust shunt capacitor placement and size in a radial distribution system (RDS), resulting in a substantial decrease in real power loss and higher voltage stability.

This project focuses on the utilization of solar PV as DG to inject active power into the system, addressing the need for optimal capacitor and DG placement. GA optimization techniques are employed to determine the size and locations of capacitors and DG units. It is crucial to find an optimal balance, as improper placement can diminish benefits and pose operational risks to the entire system [3]. By combining these considerations, the research aims to contribute practical perceptions into minimizing distribution losses and enhancing overall distribution system performance. The literature review underscores various optimization approaches, highlighting that the simultaneous coordination of distributed generation (DG) and capacitors using hybrid algorithms consistently outperforms separate methods, leading to superior power loss reduction and enhanced voltage profiles. These studies provide valuable insights into optimal component placement and sizing, addressing challenges related to increasing electricity demand and integrating renewable energy sources. The findings contribute to guiding research and advancing the development of efficient and sustainable distribution systems through the study of different case scenarios.

3. Problem Formulation

The goal is to compute both real and reactive power losses within the network. This study primarily aims to determine the best placement and size for shunt capacitors and DGs with objective of minimizing overall power loss enhancing system voltage profile, while adhering to certain operational constraints. A key assumptions made is that the system is in balanced state. The fitness function for the optimal capacitor and DG placement problem is formulated to minimize the total power loss across the system, expressed by Equations (3) and (4):

$$P_{n+1} = P_n - P_{loss,n} - P_{Ln+1} \tag{3}$$

$$Q_{n+1} = Q_n - Q_{loss,n} - Q_{Ln+1} \tag{4}$$

where

P_n and Q_n are the real power and reactive power flow out of n bus, respectively, and

P_{Ln+1} and Q_{Ln+1} are the real power losses and reactive power losses at $n+1$ bus of distribution network, respectively.

Real and reactive power losses at each bus are calculated, taking into account the power flow, losses, and voltage parameters.

The total power, i.e., real and reactive power loss in section between n and n+1 bus, is expressed by Equations (5) and (6),

$$P_{loss}(n, n+1) = R_n \frac{P_n^2 + Q_n^2}{V_n^2} \tag{5}$$

$$Q_{loss}(n, n+1) = X_n \frac{P_n^2 + Q_n^2}{V_n^2} \tag{6}$$

Here,

$P_{loss}(n, n+1)$, is the real power loss between n and n+1.

$Q_{loss}(n, n+1)$, is the reactive power loss between n and n+1.

The total power loss of the system is determined by the summation of losses in all line sections, which is given as:

$$P_{loss}(n, n+1) = \sum_{n=1}^{t} P_{loss}(n, n+1) \tag{7}$$

$$Q_{loss}(n, n+1) = \sum_{n=1}^{t} Q_{loss}(n, n+1) \tag{8}$$

This comprehensive evaluation considers for both real and reactive power losses in the distribution network, providing an integrated perspective on the system's efficiency.

Objective Function:

The objective function centers on minimizing power losses within the network, represented as the sum of squared currents multiplied by the resistance and reactance of each line. The goal of the objective function centered on minimizing power losses within the network. The objective function is represented as:

$$F = \min\left(\sum_{i=0}^{n} I_i^2 r_i\right)$$

$$F = \min\left(\sum_{i=0}^{n} I_i^2 x_i\right)$$

where I_i, r_i, and x_i *are* current, resistance, and reactance of i^{th} line. In fact, sum of active power losses of lines, between buses, are considered as total losses of the distribution network. The analysis takes into account various constraints to ensure that all crucial parameters fall within acceptable limits. The constraints are enumerated below:

a) Voltage constraint

The voltage magnitude at every bus should fall bus within the range of 90% to 105% of the nominal voltage:

$$V_{min} \leq V_i \leq V_{max}$$

where V_{max} and V_{min} are maximum and minimum acceptable voltage limits in volt at bus n, respectively. And V_i is the magnitude of voltage at i^{th} bus.

Constraints on DG output and capacitor size further regulate their contributions to the system.

b) DG output constraint (continuous variable):

$$P_{DG,min} \leq P_{DG} \leq P_{DG,max}$$

where $P_{DG,min}$ and $P_{DG,max}$ represent the lower and upper bounds of acceptable DG output in *kW*, respectively.

$0 \leq P_{DG} \leq 50\%$ of total power.

c) Capacitor size constraint:

$$C_{min} \leq C \leq C_{max}$$

where C_{max} and C_{min} denote the upper and lower limits for acceptable capacitor sizes in kVAr, respectively.

d) Power balance constraint for the system:

Power balance constraints enforce equilibrium between generated and demanded power, accounting for the active and reactive power of generators, DGs, capacitors, and losses across the network. The equilibrium between the generated power and the demanded power must be maintained:

$$P_G + \sum_{K=1}^{ncd} P = \sum_{i=1}^{n} P_i + P_L$$

$$Q_G + \sum_{K=1}^{ncd} Q = \sum_{i=1}^{n} Q_i + Q_L$$

where P_G and Q_G represent the active and reactive power of the generator at the slack bus. P and Q denotes the active and reactive power of the DG or capacitor. P_i and Q_i stand for the active and reactive power demand at bus i^{th}. P_L and Q_L correspond to the total active and reactive power losses. "n" is the number of buses and "*ncd*" is the number of DGs or capacitors.

4. Research Methodology

The proposed approach seeks to optimize the size and placement of capacitor and DG through the utilization of GAs. The primary objective is to minimize both active and reactive power losses while ensuring compliance with predefined constraints. The analysis involves a load flow calculation assessment using the forward and backward sweep (FBS) algorithm, with MATLAB code initially verified against the IEEE 33-bus standard system. The approach subsequently implemented on Sallaghari–Thimi 11 kV feeder within the Bhaktapur distribution system, encompassing a total of 11 buses.

4.1. Proposed algorithms

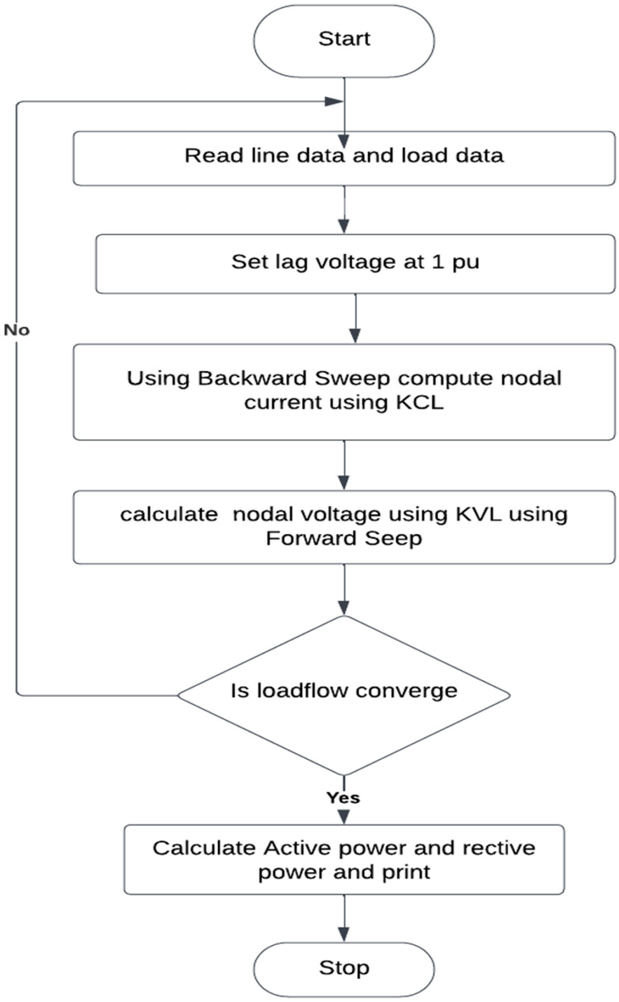
4.1.1. Genetic algorithm (GA)

It is an optimization method that is inspired by the natural process and first introduced by John Holland [27]. Then, it is elaborated in detail using the tutorials by David Goldberg [28]. GA is a population-based algorithm that starts with a randomly generated set of solutions, referred to as individuals or chromosomes it iteratively refines a population of solutions, progressively steering them toward the optimal solution. In MATLAB, the GA implementation begins by defining the fitness function, which assesses the objective function to be minimized or maximized. The GA is a global search technique employed for solving the optimization problems. It draws inspiration from the principal of natural selection and biological evolution process. GA consists of population of binary string, which searches many peaks in parallel [29].

- A GA starts by creating a population of individuals with random binary or real values. Each individual's fitness is evaluated using a fitness function. The algorithm uses roulette wheel selection to pick parents with higher fitness for the next generation.
- These parents undergo crossover (gene swapping) and mutation (gene modification) to produce offspring. The offspring and best parents are evaluated for fitness, and the fittest individuals are selected to create the next generation.
- This process repeats to evolve better solutions. This process is repeated until the algorithm reaches a termination criterion, such as reaching maximum number of iterations or achieving convergence of the fitness value.

The objective is to minimize power losses, and the fitness function quantifies how well a particular set of capacitor and DG placements contributes to achieving this goal. It takes into account the active and reactive power losses in different sections of the network, providing a quantitative measure of the overall system efficiency. By defining and optimizing this fitness function, the GA iteratively refines the population of solutions, steering them toward configurations that result in lower power losses and improved operational efficiency in the distribution system.

Figure 1
Flow chart illustrating the genetic algorithm process



Finally, the GA algorithm returns the best individual, which corresponds to the optimal solution discovered by the algorithm shown by flow chart in Figure 1.

4.1.2. Backward–forward sweep algorithm

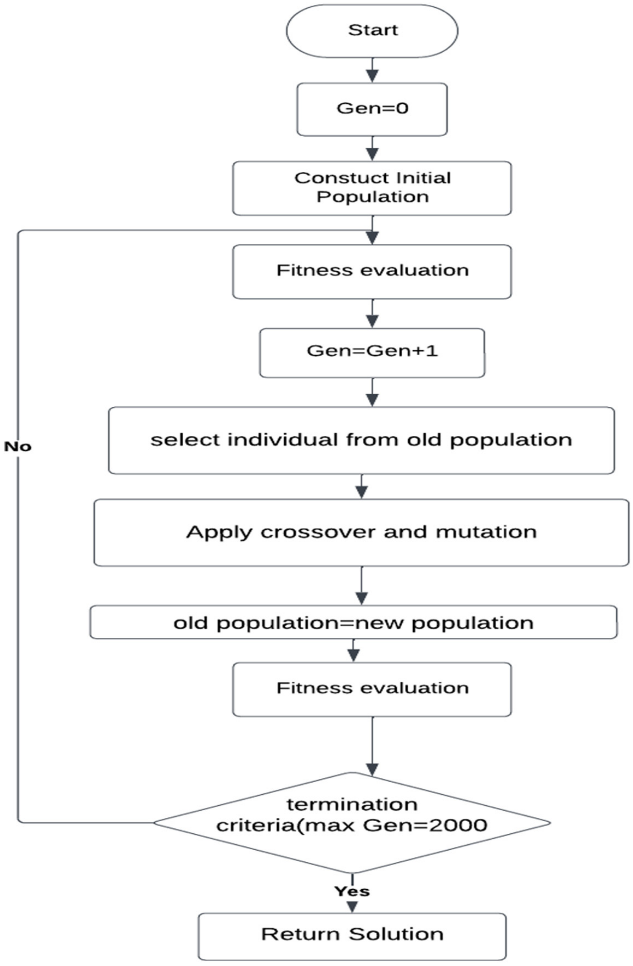
Traditional techniques such as Newton–Raphson and fast decoupled methods are ill suited for handling systems characterized by high *R*/*X* ratios, making the backward–forward sweep (BFS) method a more in handling complex distribution network. In systems with high *R*/*X* ratios, the impedance (*R*/*X*) of the lines is significant compared to the resistance (*R*) alone. This can result in voltage drops that have a more pronounced impact on the system's performance. The proposed method performs a load flow analysis, accurately establishing power losses for each branch and voltage magnitudes at individual nodes within a RDS. Testing on an IEEE 33-bus RDS using MATLAB yielded promising results [30].

In radial distribution networks, conventional power flow methods designed for distribution systems are not suitable due to convergence and computational efficiency issues. To address this, the BFS approach, tailored for radial systems, is applied. By dividing the network into forward and backward sweeps, the algorithm processes the system in a step-by-step manner, iteratively updating voltage values and handling complex interactions between loads, capacitors, and DGs. It involves two processes in each iteration: backward sweep calculates power or current flow from terminal nodes to the reference node, while the forward sweep computes node voltages from the reference node to the end nodes. Voltage convergence is tested after each iteration, with the BFS process starting by calculating node injection currents and then iteratively determining voltage magnitudes until convergence is achieved. i.e.,

$$\mathrm{Max}\left(V^{(k+1)} - V^{K}\right) < \mathrm{e}\,(\text{tolerance value in Volt})$$

The introduced BFS algorithm is implemented to IEEE 33-bus network and practically applied in a real feeder for load flow calculations. Flow chart of BFS process is shown in Figure 2.

Figure 2
Flow chart showing process of sweep algorithm



5. Results and Discussion

For this experiment, the line and load data of this test system are from Baran and Wu [31]. The test system has been simulated using MATLAB code. The proposed test system has 4 feeders and 33 buses, and bus 0 is taken as slack bus as shown in Figure 1. This is also applied in real feeder, i.e., Sallaghari–Thimi 11 kV feeder which comprises line data (resistance and reactance) and load data (active load and reactive load) for the Sallaghari–Thimi feeder [32] whose line diagram is shown in Figure 2. The results obtained from IEEE 33-bus test system are divided into three cases, i.e., base case, capacitor placement case, DG placement case, and tabulated in Table 1. This shows the parameters value obtained in this experiment. The results obtained from the analysis of Sallaghari–Thimi 11 kV radial feeder are shown in Table 2.

5.1. IEEE 33-bus test system

The block diagram of IEEE 33-bus test system is shown in Figure 3. The candidate location and size for the different cases are selected as given from MATLAB. Table 1 represents the results of the proposed method's performance. Initially, in IEEE 33-bus distribution system without any reinforcement, the total active power loss is 202.66 KW and the reactive power loss is 135.131 KVAR. The lowest voltage magnitude is observed at 18th, measuring 0.91309 pu. These results are obtained by the MATLAB simulation.

Figure 4 shows the voltage profile of a 33-bus RDS under three different conditions: the base case, after placing capacitors, after placing DG (solar PV), and placing capacitor with DG. The voltage profile is the magnitude of the voltage at each bus in the system, expressed as a per-unit (pu) value. The base case is the system with no capacitors or DG.

The voltage profile is fairly flat and minimum at 18th bus in base case. After placing capacitors at optimal location with its optimal size improves the voltage profile by raising the voltage at those buses. This is because capacitors can absorb reactive power, which can help to improve voltage regulation as capacitor is placed at 30th bus. Also placing DG at optimal positon with optimal size further improves the voltage profile by both raising the voltage and reducing the load on the system. This is because DG can provide both real and reactive power. In this, solar PV gives active power to the distribution system which can help to improve voltage stability and reduce losses. Overall, the results of this study show that capacitors with DG can be effective tools for improving the voltage profile of distribution systems.

From Figure 5, the strategic placement of capacitors proves instrumental in mitigating power loss by enhancing the voltage profile and diminishing the flow of real power, particularly evident near the 27th, 28th, 29th, and 30th branches, with a capacitor positioned at the 30th bus. Concurrently, DGs, represented by solar PV systems, contribute to power loss reduction by locally generating real power, thereby minimizing the need for external transmission from the main grid. The optimal placement of solar PV at the 7th bus optimally injects active power into the system, resulting in an overall reduction in power loss. The regions with the most substantial power loss, notably at the 2nd, 3rd, 4th, and 5th buses, showcase the significant impact of solar PV placement. Additionally, the noticeable power loss reduction at the 27th, 28th, 29th, and 30th buses highlights the effectiveness of capacitor placement in improving the voltage profile.

Form Table 1, the placement of capacitors in the power system resulted in significant improvements, with a reduction of 29.142% in actual (real) power loss, 28.714% in reactive power loss, and an enhancement of the magnitude of voltage by 1.38%. Additionally, the placement of DG sources led to even more substantial improvements, yielding a reduction of 46.72% in real power loss, 44.16% in reactive power loss, and a voltage magnitude improvement of 3.54%. Combining DG and capacitor placement produced remarkable results, with a 72.91% reduction in real power loss, a 63.45% reduction in reactive power loss, and a significant 6.542% improvement in voltage magnitude. These enhancements contribute to the reliability and overall efficiency of the infrastructure of power system.

5.2. Sallaghari–Thimi 11 KV feeder

The line diagram of Sallaghari–Thimi 11 kV feeder system is sown in Figure 6. In this system, without any reinforcement, the total active power loss is 56.2797 KW and reactive power loss is 52.29 KVAR. The voltage magnitude is lowest at 11th bus which is 0.942 pu.

Table 1
Findings from the IEEE 33-bus test system

	Base case	Capacitor placement case	DG placement case	Capacitor and DG placement case
Location (bus)	–	30	7	7 = (DG) and 30 (Cap)
Size	–	1252.7 kVAr	2000 kW	2000 (kW) and 1246.5(kVAr)
Active power losses (kW)	202.66	143.602	107.969	54.9
Reactive power losses (kVAr)	135.131	96.3378	75.4512	40.61
Magnitude of voltage at 18th bus (pu)	0.9130	0.9256	0.9453	0.9573

Table 2
Results of Sallaghari–Thimi 11 KV feeder

	Base case	Capacitor placement case	DG placement case	Capacitor and DG placement case
Location (bus)	–	7	7	7 = (DG) and 4 (Cap)
Size	–	877.93 kVAr	886.074 kW	685.2079 (kW) and 388.278 (kVAr)
Active power losses (kW)	56.27	32.3825	31.9334	9.72
Reactive power losses (kVAr)	52.29	30.0902	29.6728	9.06
Magnitude of voltage at 11th bus (pu)	0.942	0.9664	0.9684	0.991

Figure 3
Load flow diagram for IEE-33 bus radial distribution system (ETAP)

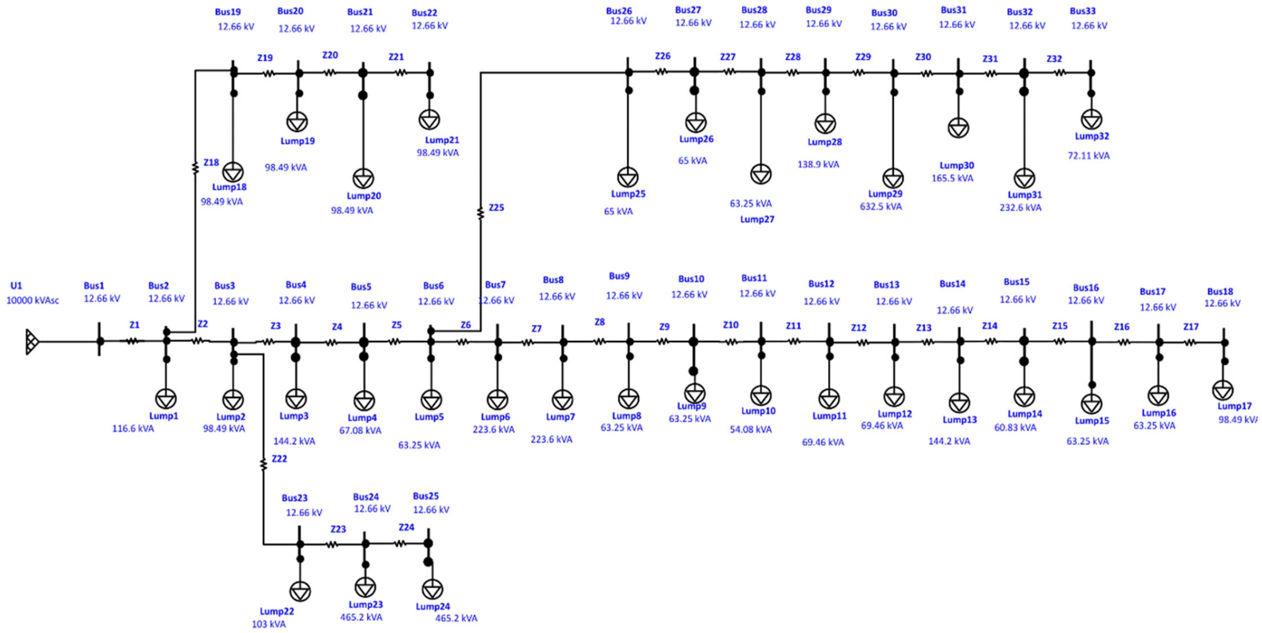
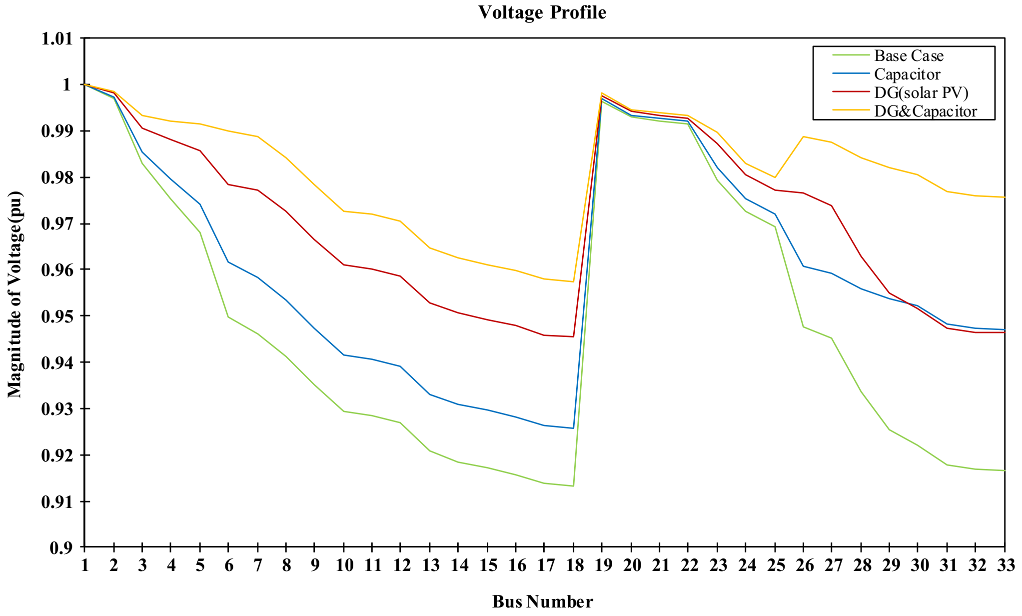


Figure 4
The voltage profile comparison in the IEEE 33-bus test system



Following the load flow analysis in MATLAB across various case scenarios, including the base case, capacitor placement case, DG placement case, and DG with capacitor placement case, the distinct voltage profiles for each scenario are illustrated in Figure 7. Similarly, the graph depicting the characteristic reduction in active power loss is presented in Figure 8, providing a comprehensive visual representation of the system's performance under different configurations. These figures serve as valuable tools for assessing and comparing the impact of capacitor placement, DG integration, and their combined deployment on the voltage profile and active power loss within the power system.

Maintaining the proper voltage magnitude is essential for the efficient and reliable operation of electrical power systems. It ensures the optimal performance of equipment, protects against damage, promotes energy efficiency, and contributes to the overall stability and reliability of the power grid. Figure 7 shows the voltage profile in different case scenario by capacitor and DG placement. As electricity travels through the conductor, there is a

Figure 5

Comparison of minimized active power loss in IEEE-33 bus test system

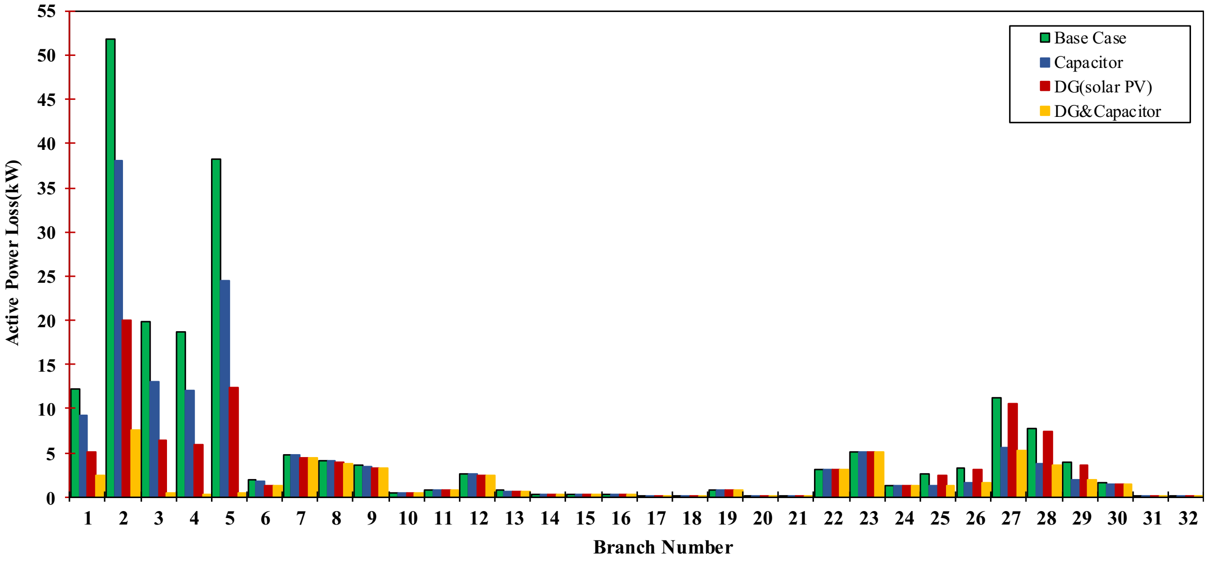


Figure 6

Load flow diagram of Thimi–Sallaghari 11 KV radial feeder

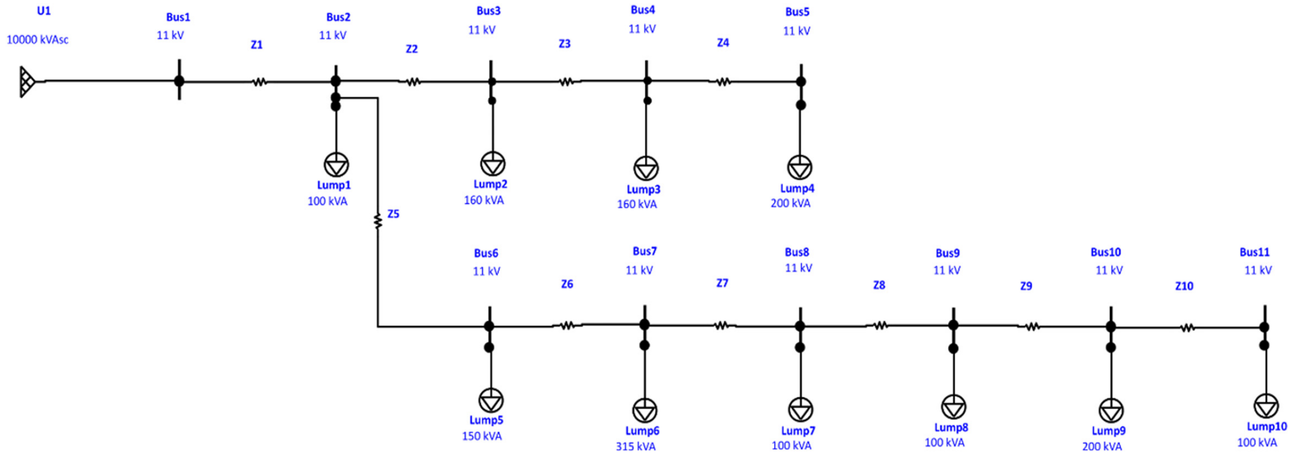


Figure 7

Comparison of voltage profile for Sallaghari–Thimi feeder

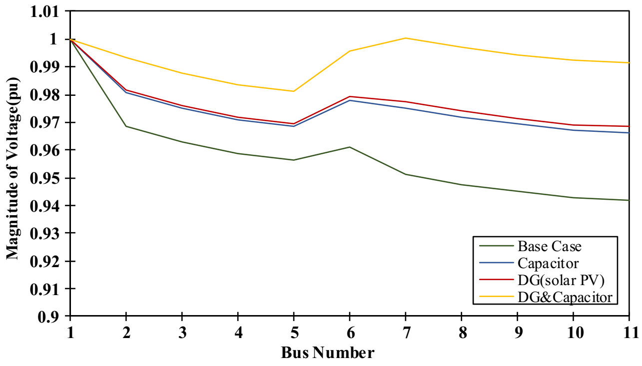
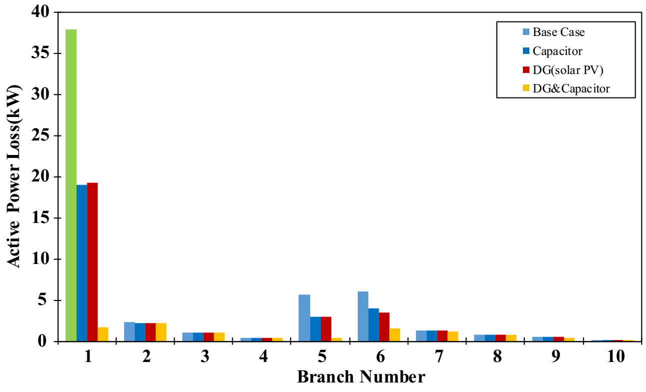


Figure 8

Comparison of reactive power loss minimized in Sallaghari–Thimi feeder



natural resistance that leads to a voltage drop. The longer the feeder line, the higher the voltage drop, so at 11th bus voltage drop is more.

Similarly, the maximum power loss occurs at 1st branch, and this is due to higher load demand which results in higher current flow through the branch, leading to increased resistive losses (I^2R losses) and higher power losses.

Adding capacitors and DG to the system can significantly reduce active power losses and improve the voltage regulation as shown in Figures 7 and 8. This is because capacitors can absorb reactive power, which can help to improve power factor along with voltage characteristic and reduce line losses. DG (solar PV) can also provide real power, which can help to reduce overall load on the system and further reduce losses.

In the Sallaghari–Thimi 11 kV feeder, the placement of capacitors resulted in a substantial 42.46% reduction in power loss and an impressive 2.59% progress in magnitude of voltage. Similarly, the introduction of DG led to a noteworthy 43.26% decrease in power loss and a 2.8% enhancement in voltage magnitude. Combining DG and capacitors in this feeder further improved the performance, with a significant 82.72% reduction in power loss and a 5.32% increase in voltage magnitude, underscoring the efficacy of these measures in enhancing the operational efficiency of the feeder.

6. Conclusion

This paper outlines a methodology for optimizing both the location and size of capacitors and DGs approaching GAs to minimize total power loss and enhance voltage profiles within RDSs. Load flow analysis is conducted in MATLAB, employing BFS methods for the IEEE 33-bus radial distribution test system and the Thimi–Sallaghari 11 kV feeder. This research assumes that system is balanced. Various scenarios are simulated to determine the most favorable outcomes based on total power loss reduction and improvement in the profile of voltage. The power flow results acquired from these tools are consistent, revealing different flows and losses of both active and reactive power. The analysis identifies areas with potential voltage drops and high losses, which can be addressed through the strategic placement of capacitors and DG units. The findings indicate that the DG with capacitor placement approach outperforms other scenarios in both the radial test system with 33 buses according to the IEEE standard and the Sallaghari–Thimi 11 kV feeder. This is best suited practically for Sallaghari–Thimi 11 kV feeder as it has the possibility of injecting solar PV. These enhancements encompass reduced power losses and improved voltage profiles, suggesting promising prospects for practical implementation in other real feeders in the future.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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