Smart Grid Solutions for Loss Minimization and Voltage Profile Enhancement using Genetic Algorithm-Optimized Capacitor and Solar PV Integration in Radial Feeder

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ABSTRACT
This research addresses the critical challenge of power loss in distribution systems caused by increasing electricity demand. It focuses on reducing power losses and enhancing voltage profiles in a radial distribution system through the optimal placement of capacitors and solar PV. The project employs comprehensive analysis and optimization techniques, including forward and backward sweep algorithms for load flow analysis and Genetic Algorithm (GA) in MATLAB. The performance of the distribution system is evaluated by considering parameters such as power loss and voltage characteristics.

Simulation results on an IEEE 33-bus radial distribution network validate significant improvements after various configurations, including the base case, capacitor case, DG case, and combined DG and capacitor case. In each scenario, active power losses are reduced, reactive power loss diminishes, and voltage profile enhancements are observed. The study further validates these results using ETAP software, ensuring consistency and reliability. Notable improvements are also observed in the Thimi Sallaghari 11kV feeder, showcasing potential practical implementations in real feeders in the future. Different case scenarios are explored for the number of capacitors and DGs, providing insights into the optimal combination for enhanced distribution system performance.

Keywords: Power Loss, Voltage Profiles, Optimal Placement, Genetic Algorithm, Radial Distribution Systems.

I. INTRODUCTION
The escalating demand for electricity presents an intricate challenge in the distribution system network, requiring a meticulous analysis to enhance efficiency. The complexity of power system operation and control is amplified by factors such as aging electrical infrastructure, the integration of renewable sources, and the expansion of the distribution network [1]. The Nepal Electricity Authority (NEA) reports an overall electricity loss of 13.46%, encompassing both transmission and distribution systems [2]. This results in an unfavorable voltage profile, increased power dissipation, strain on the electrical infrastructure due to overload, network failure, and issues related to power quality [3]. Reducing distribution losses is a critical objective and can be achieved through various measures, including careful transformer selection, feeder optimization, network reorganization, strategic placement of shunt capacitors, and the integration of distribution generation at different network locations [4]. Shunt capacitors play a vital role in compensating for reactive power, thereby reducing losses, improving voltage levels, enhancing power factor, and increasing system efficiency [5]. Distribution generation (DG), derived from sources such as fuel cells, solar photovoltaic (PV) systems, wind turbines, and micro hydro turbines, offers a diverse set of solutions [6]. Considering Nagarkot's potential for seasonal wind energy production near the Thimi Sallaghari feeder [7], solar PV is chosen as the DG source due to its feasibility in a real distribution system. Research in power system optimization has witnessed extensive investigations into methodologies for minimizing power losses and enhancing energy efficiency. The literature highlights diverse strategies, with a particular focus on optimal capacitor placement [8, 9, 10, 11], DG ( Distributed Generation) siting [12, 13, 14], and integrated approaches combining both capacitor and DG placement [15, 16, 17]. Capacitor placement and DG placement studies have employed methods such as genetic algorithms [14], Tabu search [18], and harmonic search algorithms [19], with a strong emphasis on renewable energy solutions. DG placement literature includes hybrid optimization approaches [20], particle swarm optimization [21], selective particle swarm 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 [11], and hybrid solutions combining particle swarm optimization and genetic algorithms [9].

Poudel and Niraula (2023) explored hybrid energy storage systems integrating PV for isolated DC micro grids, highlighting the importance of energy storage in stabilizing voltage and reducing power losses in isolated grid systems [31]. Their findings underscore the potential of combining PV with energy storage to enhance grid reliability, aligning with the goals of integrating solar PV in radial feeders for voltage profile improvement. Similarly, Mahato et al. (2024) investigated the effects of installing capacitors...
and distributed generation (DG) units on power loss minimization and voltage profile enhancement in radial distribution networks [32]. Their study demonstrated that strategically placing capacitors and DG units could significantly reduce power losses and improve voltage stability, providing a foundational understanding of the benefits of using capacitors optimized by genetic algorithms in smart grid applications. Further reinforcing these concepts, Poudel et al. (2024) examined battery and super capacitor-based energy storage systems combined with PV for islanded DC micro grids, showing that hybrid storage systems could effectively manage power fluctuations and maintain voltage stability [33]. In another relevant study, Poudel and Bhandari (2023) applied the Ant Colony Optimization (ACO) algorithm for tuning PID parameters in the control of BLDC motors, illustrating the potential of advanced optimization algorithms in power systems for optimizing capacitor placement and sizing in radial feeders [34]. Bhandari et al. (2023) also employed the Particle Swarm Optimization (PSO) algorithm for PID parameter tuning in BLDC motor speed control, further supporting the use of heuristic algorithms for capacitor optimization in smart grids [35]. Additionally, Poudel et al. (2023) discussed the design and control of distributed generations (DGs) for Microgrid applications, emphasizing the integration of DGs to enhance the resilience and flexibility of smart grids, crucial for optimizing voltage profiles and minimizing losses in radial feeders [36]. The novel design methodology for high-frequency transformers in solid-state transformers for power distribution systems presented by Poudel et al. (2023) offers insights into advanced power electronics components that can complement smart grid solutions, enhancing overall system efficiency and stability [37].


Furthermore, Jamil [17] investigated grid strategies, including real power distribution, reactive power addition, and transformer tap changing, emphasizing the superiority of the Genetic Algorithm over Newton-Raphson for optimizing power flow. Lastly, Abraham & Oluwafemi [9] developed a Hybrid Solution (HS) combining particle swarm optimization and genetic algorithms 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. Genetic algorithm 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 [24]. By combining these considerations, the research aims to contribute practical insights into minimizing distribution losses and enhancing overall distribution system performance.

II. PROBLEM FORMULATION

The problem formulation involves addressing the challenges in the smart grid context, specifically focusing on minimizing losses and enhancing voltage profiles. This study aims to utilize Genetic Algorithm-Optimized Capacitor and Solar PV Integration within radial feeders as an effective solution to optimize the smart grid system's performance while adhering to certain operational constraints. A key assumption made is that the system is in balanced state. The aim is to comprehensively study various case scenarios to evaluate the efficacy of this approach in enhancing smart grid performance.

Power Loss of Radial Distribution System

The two types of losses occur in the distribution system are

(i) Active power loss (ii) Reactive power loss

\[ P_{loss} = \sum_{i=0}^{n} I_i^2 R_{i} \]  
\[ Q_{loss} = \sum_{i=0}^{n} I_i^2 x_{i} \]  

Where, \( R_{i} \) and \( x_{i} \) are current, resistance and reactance of \( i_{th} \) line. The fitness function for the optimal capacitor & DG placement problem is formulated to minimize the total power loss across the system, as defined by following expression.

\[ P_{n+1} = P_{n} - P_{loss,n} - P_{Ln+1} \]  
\[ Q_{n+1} = Q_{n} - Q_{loss,n} - Q_{Ln+1} \]

Here, \( P_{n} \) = Real power flow out of bus \( P_{Ln+1} \), is the Real power loss at n+1 bus.
\[ Q_{\text{loss}}(n, n + 1) = R_n \frac{P_n^2 + Q_n^2}{V_n^2} \]
\[ Q_{\text{loss}}(n, n + 1) = X_n \frac{P_n^2 + Q_n^2}{V_n^2} \]

Here
\[ P_{\text{loss}}(n, n + 1) \] is the real power loss between \( n \) and \( n+1 \).
\[ Q_{\text{loss}}(n, n + 1) \] 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
\[ P_{\text{loss}}(n, n + 1) = \sum_{n=1}^{t} P_{\text{loss}}(n, n + 1) \]
\[ Q_{\text{loss}}(n, n + 1) = \sum_{n=1}^{t} Q_{\text{loss}}(n, n + 1) \]

This comprehensive evaluation accounts for both real and reactive power losses in the distribution network, providing a holistic perspective on the system’s efficiency.

Objective function
The goal of the objective function centered on minimizing power losses within the network. The objective function is represented as:
\[ F = \text{min} \left( \sum_{i=1}^{n} I_i^2 r_i \right) \]
\[ F = \text{min} \left( \sum_{i=1}^{n} I_i^2 x_i \right) \]

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.

Constraints
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 within the range of 90% to 105% of the nominal voltage.
\[ V_{\text{min}} \leq V_i \leq V_{\text{max}} \]
Where \( V_{\text{max}} \) and \( V_{\text{min}} \) are maximum and minimum acceptable voltage limit at bus \( n \), respectively. And \( V_i \) is the magnitude of voltage at \( i \)th bus.

b) DG output constraint (continuous variable):
\[ P_{\text{dg}, \text{min}} \leq P_{\text{dg}} \leq P_{\text{dg}, \text{max}} \]
Where \( P_{\text{dg}, \text{min}} \) and \( P_{\text{dg}, \text{max}} \) represent the lower and upper bounds of acceptable DG output, respectively.
\[ 0 \leq P_{\text{dg}} \leq 50\% \text{ of } P_{\text{total}}. \]

c) Capacitor size constraint:
\[ C_{\text{min}} \leq C \leq C_{\text{max}} \]
Where \( C_{\text{max}} \) and \( C_{\text{min}} \) denotes the upper and lower limit for acceptable capacitor sizes, respectively.

d) Power balance constraint for the system:
The equilibrium between the generated power and the demanded power must be maintained,

\[ P_G + \sum_{n=1}^{ncd} P_i = \sum_{i=1}^{n} P_l + P_L \]
\[ Q_G + \sum_{n=1}^{ncd} Q_i = \sum_{i=1}^{n} Q_l + Q_L \]

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 \( Q_i \) stands for the active and reactive power demand at bus \( i \). \( P_L \) and \( Q_L \) correspond to the total active and reactive power losses. ‘\( n \)’ is the number of buses & ‘\( ncd \)’ is the number of DGs or capacitors.

**Load flow Analysis**

Power flow analysis is employed to determine power losses in each branch and the overall system. Traditional methods face convergence challenges in distribution networks, particularly due to high R/X ratios. Achieving computational efficiency and rapid convergence is crucial for an effective power flow analysis in such networks. 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 method a more suitable alternative in these scenarios. The proposed method performs a load flow analysis, accurately establishing power losses for each branch and voltage magnitudes at individual nodes within a radial distribution system. Testing on an IEEE 33-bus radial distribution system using MATLAB yielded promising results [25].

![Fig 1. Block diagram of IEEE 33 bus test system(ETAP)](image-url)
Fig 2. Block diagram of Sallaghari Thimi feeder (ETAP)

The block diagrams for the IEEE 33-bus test system and the Sallaghari-Thimi feeder are presented below, derived from ETAP simulations. These diagrams illustrate the practical realization for load flow analysis and optimal placement of components, showcasing different locations for enhanced system performance.

The introduced Backward-Forward sweep algorithm is applied to IEEE 33–bus network. The line and load data of this test system are from [26]. The test system has been simulated using matlab code. The proposed test system has 4 feeders, 33 Bus and bus 0 is taken as slack bus shown in figure above. This also applied on real feeder i.e. Sallaghari-Thimi 11 kV feeder which comprises line data (resistance and reactance) and load data (active load and reactive load) [27].

III. ALGORITHMS

The analysis involves a load flow calculation assessment using the forward-backward sweep (FBS) algorithm, with MATLAB scripts initially verified against the IEEE-33bus standard system. The proposed approach seeks to optimize the size and placement of capacitor and Distributed Generation (DG) through the utilization of Genetic Algorithms.

Backward-Forward Sweep Algorithm

In radial distribution networks, conventional power flow methods designed for transmission systems aren’t suitable due to convergence and computational efficiency issues. To address this, the backward-forward sweep (BFS) approach, tailored for radial systems, is used. 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.

\[
\text{Max } (V^{(k+1)} - V^K) < \epsilon \text{ (tolerance value)}
\]

Fig 3. Flow chart showing B/F sweep algorithm
Genetic algorithm (GA)
It is an optimization method that is inspired by the natural process and first introduced by John Holland [26]. Then elaborated in detail using the tutorials by David Goldberg [27].

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 towards 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 genetic algorithm 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 [28].

A Genetic Algorithm (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 [29,30]. 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. Finally, the GA algorithm returns the best individual, which corresponds to the optimal solution discovered by the algorithm the step by step procedure of capacitor and DG allocation is describe by flow chart shown in figure below.

![Flow chart illustrating the genetic algorithm process](image)

**IV. SIMULATION RESULT AND DISCUSSION**

For this experiment, the result obtained from IEEE 33 Bus test system which is divided into four cases i.e. Base case Capacitor Placement case, DG placement Case and DG with Capacitor Placement which is tabulated as: Table 1 shows the parameters value obtained in this experiment. Table 2 shows the result obtained from analysis of Thimi- Sallaghari 11 KV radial real feeder.

**IEEE 33 Bus Test System**
The chosen location and dimensions for various scenarios are determined through MATLAB simulations. The accuracy of these results is further confirmed by cross-referencing with the ETAP software, yielding comparable outcomes. Initially, in IEEE 33
distribution system without any reinforcement, the total active power loss is 202.66 KW and the reactive power loss is 135.13 KVAR. The is lowest voltage magnitude is observed at 18th, measuring 0.91309 pu.

<table>
<thead>
<tr>
<th>Table 1 Finding from IEEE-33 Bus Test System</th>
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<tbody>
<tr>
<td>IEEE 33 Bus Test system</td>
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<tr>
<td>Location (bus)</td>
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<tr>
<td>------------------</td>
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<tr>
<td>Base Case</td>
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<tr>
<td>Cap cap=1</td>
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<td>Cap cap=2</td>
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<td>Cap cap=3</td>
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Fig 5. Comparison of minimized Active Power Loss in IEEE-33 Bus Test System
Following the installation of capacitors (cap=3), the maximum reductions observed in real power loss, reactive power loss, and enhancement in voltage magnitude were 34.78%, 34.63%, and 2.71%, respectively. On the other hand, the introduction of solar as distributed generators (DG=3) led to a more substantial decrease, with real power loss reduced by 64.74%, reactive power loss by 63.45%, and voltage magnitude improved by 6.54%.

Notably, the combined implementation of both DG and capacitors yielded impressive outcomes, showcasing a 72.91% reduction in real power loss, a 63.4% reduction in reactive power loss, and a noteworthy 4.81% improvement in voltage magnitude at 18th bus (bus having lowest voltage magnitude).

**Sallaghari Thimi 11 KV feeder**

In Thimi-Sallaghari 11 KV feeder systems 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.
In the 11 kV feeder at Thimi Sallaghari, the installation of capacitors yielded a substantial 42.46% decrease in power loss and an impressive 2.59% advancement in voltage magnitude. Similarly, the incorporation of distributed generation (DG) resulted in a noteworthy 43.26% reduction in power loss and a 2.8% improvement in voltage magnitude. The combined deployment of up to three capacitors and DG in this feeder further enhanced overall performance, demonstrating a significant 82.72% reduction in power loss and a notable 5.32% increase in voltage magnitude. These findings underscore the effectiveness of these interventions in optimizing the operational efficiency of the real feeder.

The graph below shows the reduction in active power loss in different case scenario in Thimi-Sallaghari 11 KV feeder systems as stated above.

![Graph showing reduction in active power loss](image)

**Fig 8. Block diagram of Sallaghari Thimi feeder**

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V. CONCLUSION

This paper presents a comprehensive methodology leveraging genetic algorithms to optimize the placement and sizing of capacitors and distributed generators (DG) for minimizing power loss and enhancing voltage profiles in radial distribution systems. Utilizing MATLAB for load flow analysis, the study applies the Backward Sweep and Forward Sweep methods on the IEEE 33-bus radial distribution test system and the Thimi-Sallaghari 11 kV feeder. Various scenarios were simulated to determine optimal solutions based on total power loss reduction and voltage profile enhancement. The MATLAB simulation results were rigorously validated with ETAP, confirming their reliability within identical constraints. Despite general consistency between the two tools, discrepancies were noted, particularly in accurately sizing DG (solar PV) within the ETAP environment.

The power flow analysis revealed consistent results across both tools, with variations in active and reactive power flows and losses. Areas prone to voltage drops and high losses were identified, underscoring the importance of strategically placing capacitors and DG units. Comparative evaluations demonstrated that combining DG with capacitor placement outperformed alternative scenarios in both the IEEE 33-bus system and the Thimi-Sallaghari 11 kV feeder. Significant improvements, including reduced power losses and enhanced voltage profiles, were observed, indicating promising potential for practical implementation in other real feeders in the future.

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