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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 issue of power losses in electrical distribution systems, a challenge that has intensified with the rising electricity demand. The study focuses on minimizing these losses and improving voltage profiles within a radial distribution network through the optimal placement of capacitors and solar photovoltaic (PV) systems. A comprehensive methodological framework is employed, integrating load flow analysis via the forward and backward sweep algorithms and optimization using the Genetic Algorithm (GA) implemented in MATLAB.

Key performance indicators such as active and reactive power losses, along with voltage profile characteristics, are used to assess the effectiveness of various configurations. Simulation studies conducted on the standard IEEE 33-bus radial distribution network demonstrate significant improvements across multiple scenarios—namely, the base case, capacitor-only case, distributed generation (DG)-only case, and a combined DG-capacitor case. In each configuration, notable reductions in power losses and enhancements in voltage stability are observed.

The findings are further substantiated through validation in ETAP software, reinforcing the accuracy and reliability of the results. Moreover, the practical feasibility of the proposed approach is demonstrated through a case analysis of the Thimi-Sallaghari 11 kV feeder, revealing promising implications for real-world implementation. The study also explores various deployment scenarios involving up to three units of capacitors and DGs, offering valuable insights into the optimal integration strategy for enhanced distribution system performance

***Keywords*—** Power Loss, Radial Distribution Systems, Voltage Profiles, Optimal Placement, DG (solar PV), Genetic Algorithm, Load Flow Analysis, ETAP, Real Feeder.

1. 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 (Shivanand Hirekodi, 2022). The Nepal Electricity Authority (NEA) reports an overall electricity loss of 13.46%, encompassing both transmission and distribution systems (Authority, 2023). 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 (Magadum, 2023). 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 (Divya, 2015).

Shunt capacitors play a vital role in compensating for reactive power, thereby reducing losses, improving voltage levels, enhancing power factor, and increasing system efficiency (Eltamaly, 2023). 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 (Talha Bin Nadeem, 2023). Considering Nagarkot's potential for seasonal wind energy production near the Thimi Sallaghari feeder (Laudari, Banskota, & Sapkota, 2018), 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 (K.R & K, 2014; Abraham & Oluwafemi, 2022; Adel Ali Abou El-Ela, 2016; Mohd Nabil Bin Muhtazaruddin, Duc Tuyen , Jamian, & Jamani, 2014) , DG (Distributed Generation) siting (A.Alam, Gupta, Bindal, Siddiqui, & M. Zaid, 2018; Amraj, Boonrach, & K. Bhumkittipich, 2021; Siregar, Yuwaldi, Tarmizi, & Akhyar, 2023), and integrated approaches combining both capacitor and DG placement (A & M, 2014; Chege, K. Murage, & K. Kihato, 2018; Jamil, 2023). Capacitor placement and DG placement studies have employed methods such as genetic algorithms (Siregar, Yuwaldi, Tarmizi, & Akhyar, 2023), Tabu search (Rugthaichareoncheepa, Lantharthong, Ratreepruk, & Ratchatha, 2012), and harmonic search algorithms (Kona & Kollu, 2017), with a strong emphasis on renewable energy solutions. DG placement literature includes hybrid optimization approaches (Muhtazaruddin, NGUYEN DUC, Fujita, & Jamian, 2014), particle swarm optimization (Lee, Ayala, & coelho, 2015), selective particle swarm optimization (Sarfaraz, Bansal, & Singh, 2016), and improved multi-objective harmony search algorithms (Kona & Kollu, 2017). Integrated studies addressing both capacitor and DG placement have utilized loss sensitivity factor methods (Dixit, Kundu , & Jariwala, 2016), ant colony optimization (Mohd Nabil Bin Muhtazaruddin, Duc Tuyen , Jamian, & Jamani, 2014), and hybrid solutions combining particle swarm optimization and genetic algorithms (Abraham & Oluwafemi, 2022).

Research by Dixit et al. (Dixit, Kundu , & Jariwala, 2016)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. (Adel Ali Abou El-Ela, 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. N. Amraj et al. (Amraj, Boonrach, & K. Bhumkittipich, 2021) optimized photovoltaic energy storage systems in a radial system using a genetic algorithm with the Newton-Raphson method, contributing to advancements in renewable energy integration. (Rugthaichareoncheepa, Lantharthong, Ratreepruk, & Ratchatha, 2012) employed a genetic algorithm for feeder reconfiguration, effectively minimizing power loss while adhering to constraints.

Furthermore, Jamil (Jamil, 2023)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 (Abraham & Oluwafemi, 2022) 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 (Pavlos S & Nikos D, 2013). By combining these considerations, the research aims to contribute practical insights into minimizing distribution losses and enhancing overall distribution system performance.

2. 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 a balanced state. The aim is to comprehensively study various case scenarios to evaluate the efficacy of this approach in enhancing smart grid performance.

A. Conceptual model for this research

The conceptual model of this study begins with the collection of essential data inputs, including load demand, solar PV generation data, and network parameters. These inputs feed into the radial distribution network modeling, where a forward and backward sweep load flow method is applied to analyze the power distribution. The model then employs a genetic algorithm optimization process, which iteratively performs initialization, selection, crossover, mutation, evaluation, and replacement to identify the fittest solution for minimizing power losses and improving voltage profiles. Following optimization, power flow analysis is conducted using the optimized settings to calculate losses and voltage profiles accurately. The performance evaluation stage compares different scenarios, such as base case, capacitor-only, DG-only, and combined configurations, to assess their effectiveness. Validation and simulation are carried out using MATLAB and ETAP software, supported by a real feeder case study to ensure practical applicability. Finally, the results guide control actions including capacitor switching and solar PV dispatch, providing actionable recommendations for implementation.

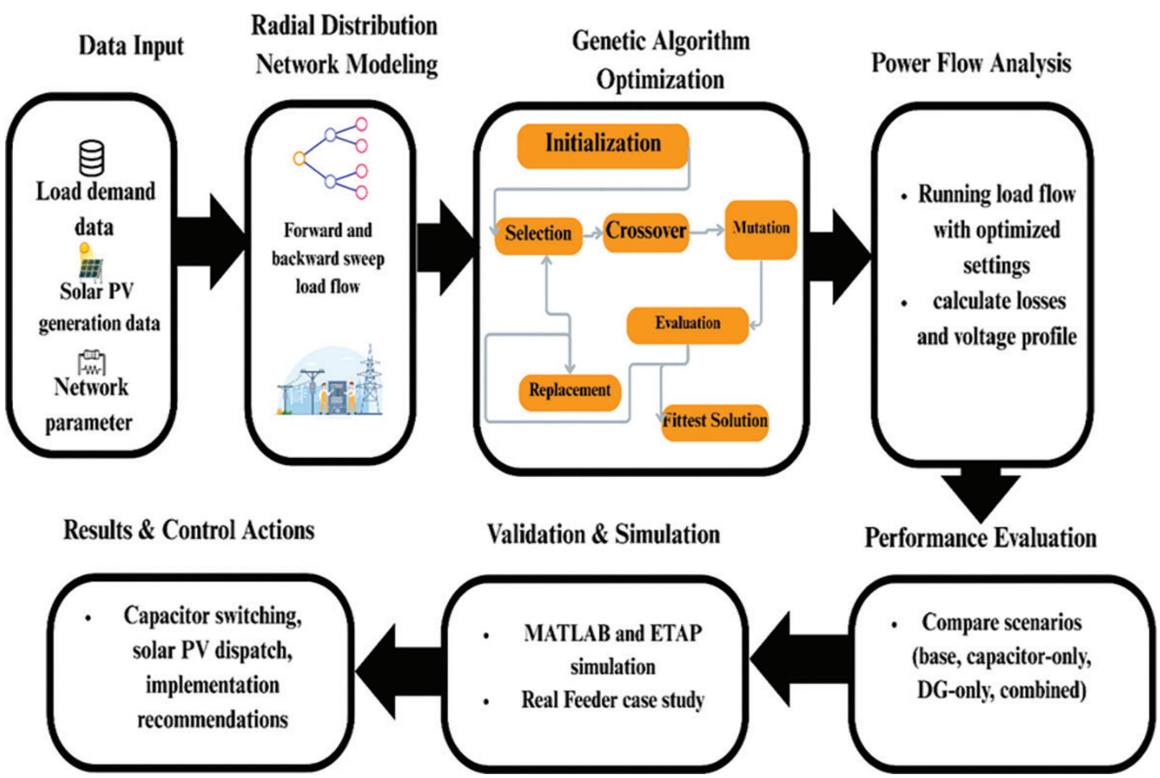

Figure 1: Complete block diagram of the purposed model

B. 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}=$(\sum_{i=0}^{n} I_i^2 R_i)$ (1)

Q_{loss}=$(\sum_{i=0}^{n} I_i^2 x_i)$ (2)

Where, R_i, 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 the following expression.

P_{n+1}=$P_n - P_{loss,n} - P_{Ln+1}$ (3)

Q_{n+1}=$Q_n - Q_{loss,n} - Q_{Ln+1}$ (4)

Here, P_n=Real power flow out of the bus

P_{Ln+1} , is the real power loss at n+1 bus.

Q_{Ln+1}, is the reactive power loss at n+1 bus.

Q_n, is Real power flows out of the bus.

The total power, i.e., real and reactive power loss in the section between n and n+1 buses

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

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

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

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

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

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

C. Objective function

The goal of the objective function is to minimize power losses within the network. The objective function is represented as:

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

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

Where I_i, r_i, x_i are the current, resistance, and reactance of i^{th} line. The sum of active power losses of lines between buses is considered the total losses of the distribution network.

D. 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.

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

Where V_{Max} and V_{Mmin} are maximum and minimum acceptable voltage limit at bus n, respectively. And V_1 is the magnitude of voltage at i^{th} bus.

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, respectively.

$0 \leq P_{dg} \leq 50\%$ of P total.

c) Capacitor size constraint:

$C_{min} \leq C \leq {}_{Cmax}$

Where C_{max} and C_{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,

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

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

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 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.

E. 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 (Michline & Rupa, 2014).

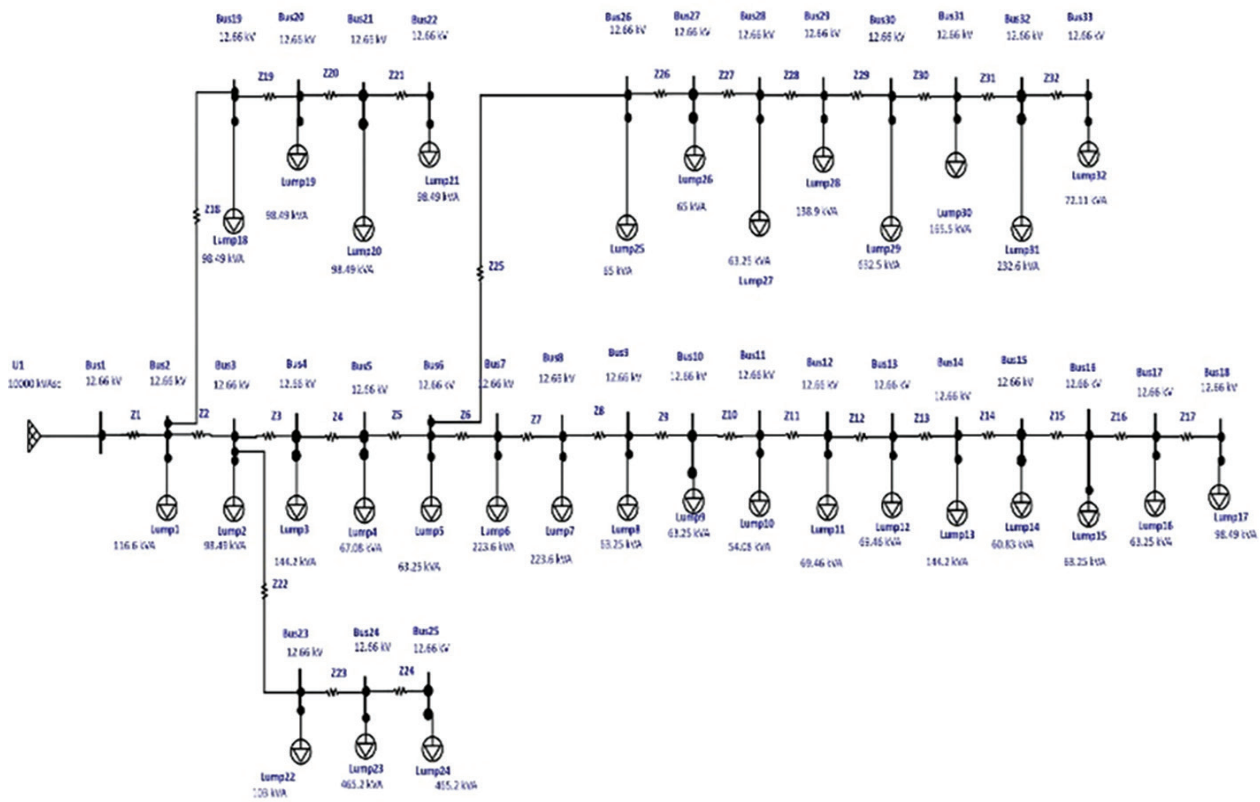

Figure 2: Block diagram of IEEE 33 bus es system(ETAP)

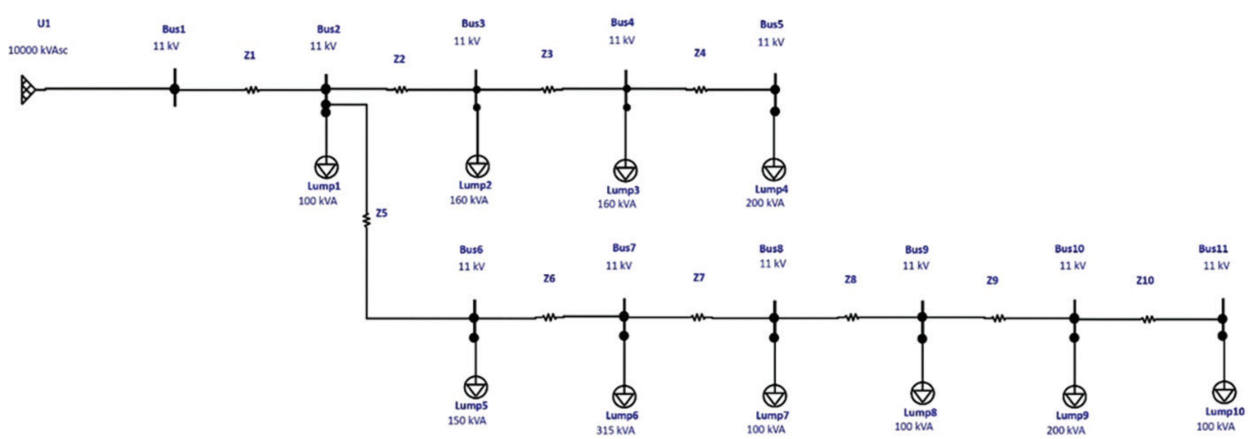

Figure 3: Block diagram of Sallaghari thimi feeder (ETAP)

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].

3. 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 the capacitor and Distributed Generation (DG) through the utilization of Genetic Algorithms.

A. 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.

Max $(V^{(k+1)} - V^{K})<$ e (tolerance value)

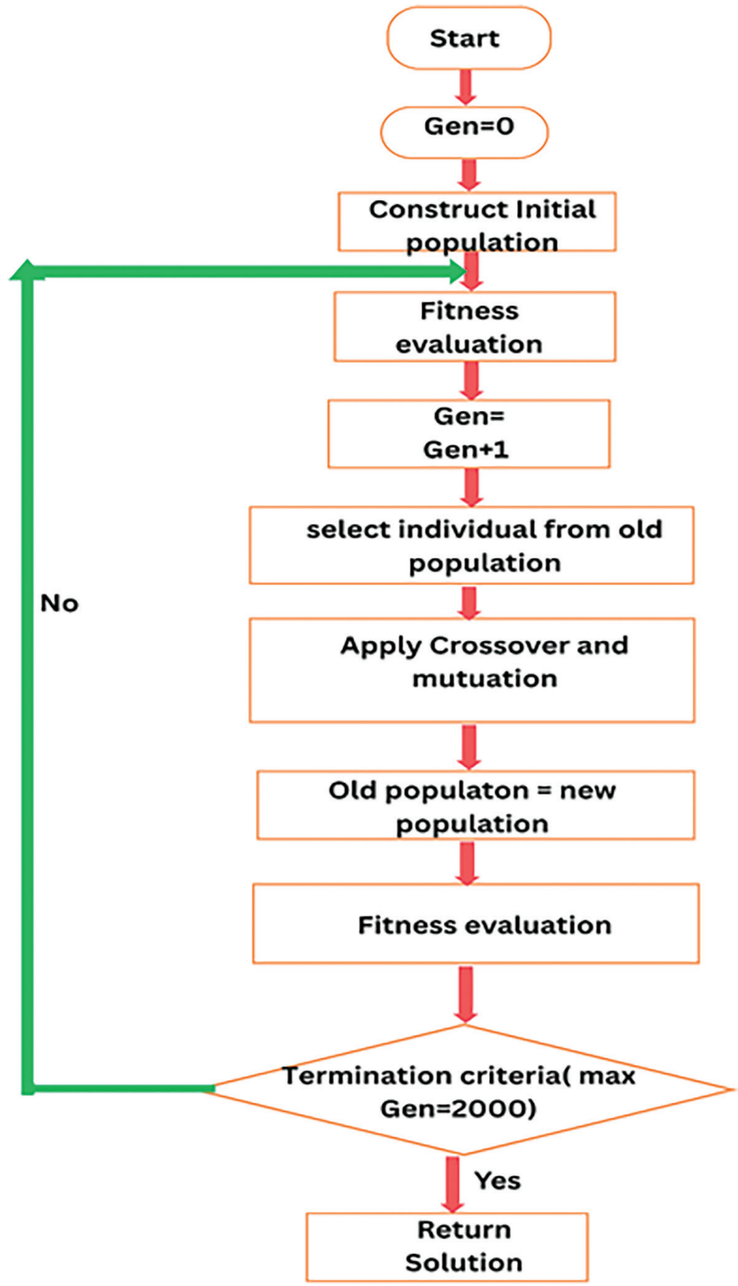

Figure 4: Flow chart showing B/F sweep algoithm

B. Genetic algorithm (GA)

It is an optimization method that is inspired by the natural process and first introduced by John Holland (DE. Goldberg, 1989). Then elaborated in detail using the tutorials by David Goldberg (Gonen, 1986).

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 optimization problems. It draws inspiration from the principle of natural selection and the biological evolution process. GA consists of a population of binary strings, which searches for many peaks in parallel (Michalewic, 1996).

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. 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 the 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 described by the flow chart shown in the figure below

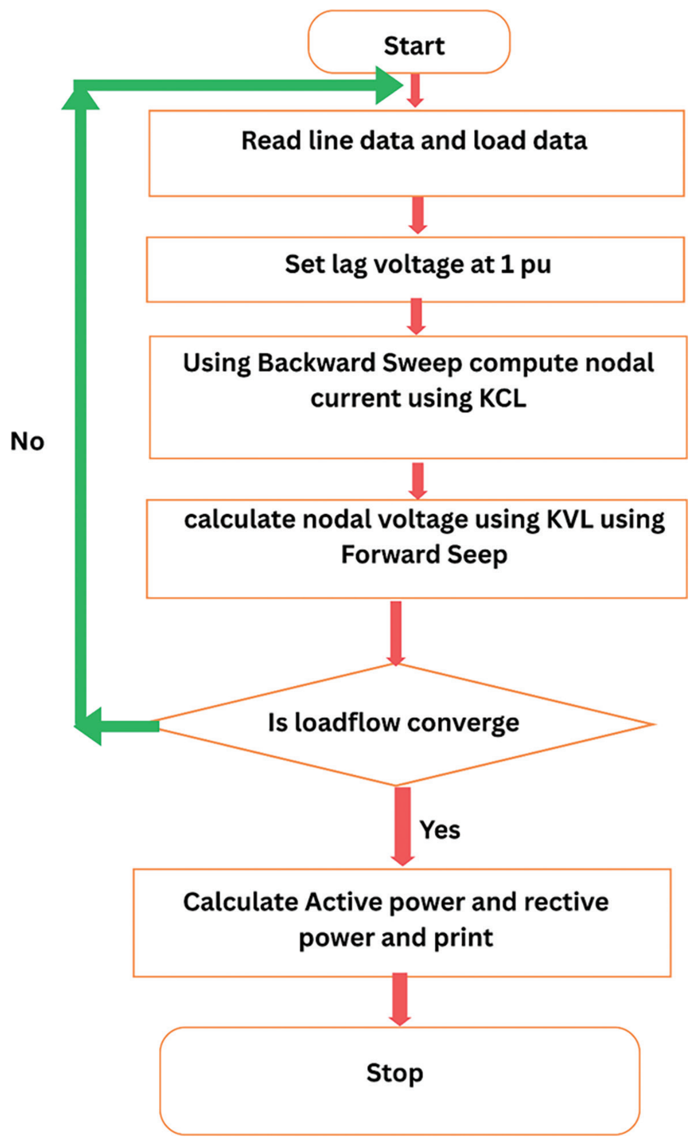

Figure 5: Flow chart illustrating the genetic algorithm process

4 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.

A. 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 the IEEE 33 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.

Table 1: Finding Froms Ieee-33 Bus Test System

		MATLAB					ETAP				
IEEE 33 Bus Test system		**Location (bus)**	**Size (kVAR or kW)**	**P_{Loss} (kW)**	**Q_{loss} (KVA)**	**V_{min} (pu)**	**Location (bus)**	**Size (kVAR or kW)**	**P_{Loss} (kW)**	**Q_{loss} (KVA)**	**V_{min} (pu)**
Base Case		--	--	202.66	135.13	0.913	---	--	201.5	134.3	0.913
Cap	cap=1	30	1252.7	143.60	96.33	0.925	30	1252.7	143.6	96.1	0.924
	cap=2	30	105.78	135.75	90.54	0.936	30	105.78	135.8	90.54	0.934
		12	468.9				12	468.9			
	cap=3	24	544.2	132.17	88.3	0.935	24	544.2	132.2	88.3	0.934
		13	378.7				13	378.7			
		30	1036.7				30	1036.7			
DG	DG=1	7	2000	107.96	75.45	0.949	7	2001	111.4	76.1	0.949
	DG=2	13	846.4	85.90	58.55	0.971	13	846.8	87.5	59.2	0.964
		30	1158.7				30	1159.2			
	DG=3	24	1099.5	71.456	49.390	0.972	24	1098.5	73.3	50.2	0.965
		14	754.0				14	756.5			
		30	1071.4				30	1069.5			
Cap & DG	Cap=1	30	1246.5	54.9	40.61	0.957	30	1246.5	59.0	41.5	0.953
	DG=1	7	2000				7	2001.4			

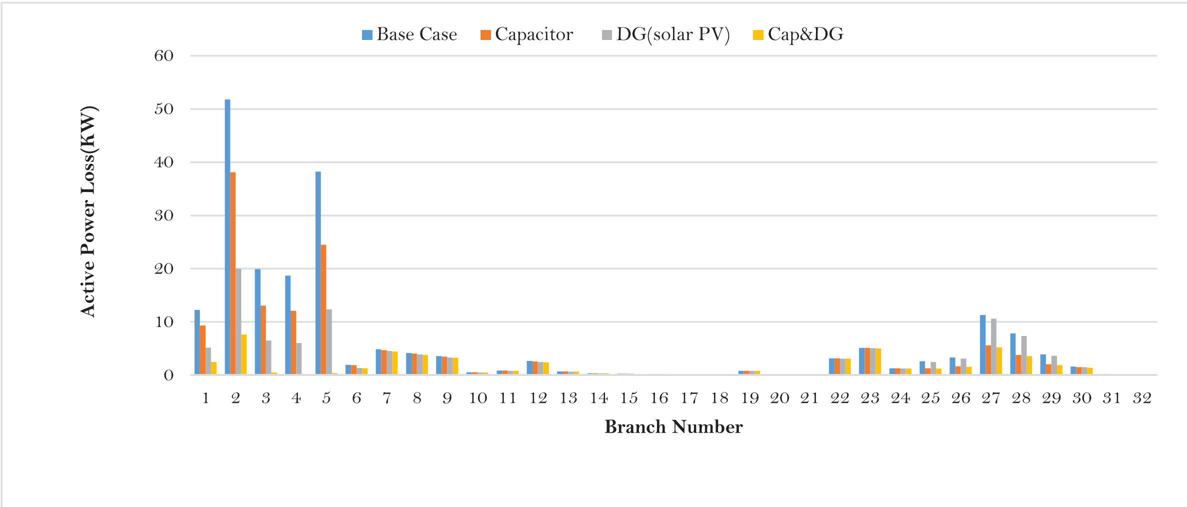

Figure 6: Comparison of minimized Active Power Loss in IEEE-33 Bus Test System

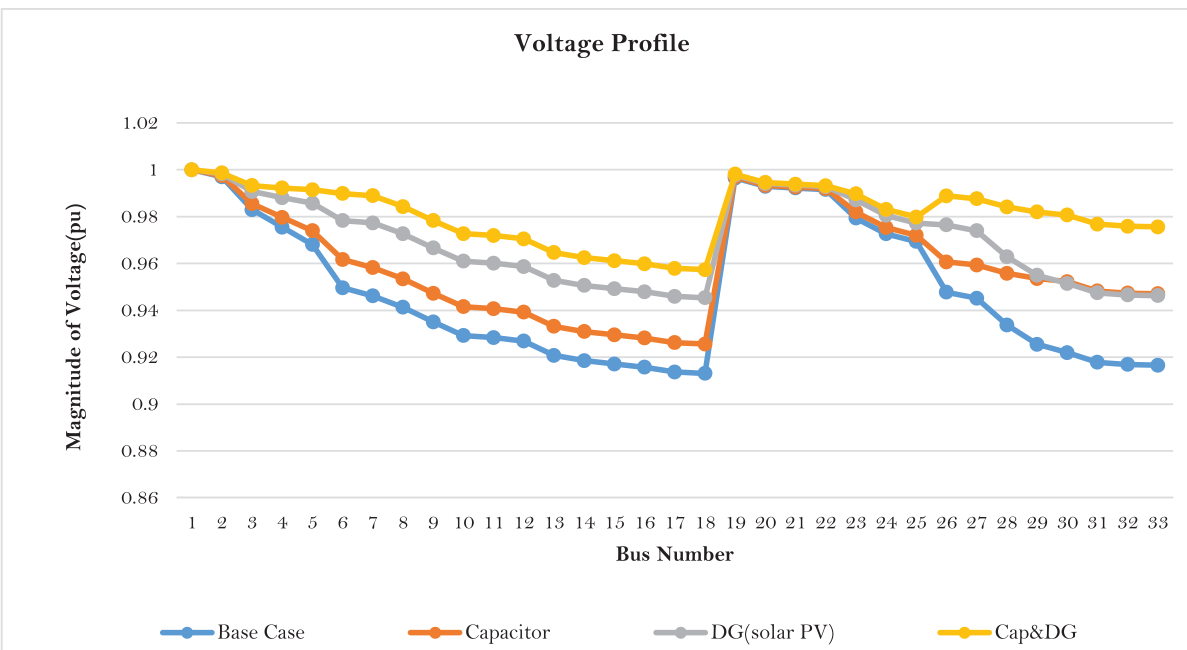

Figure 7: Illustrates the Voltage Profile Comparison in the IEEE 33 Bus Test System

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).

B. 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 the reactive power loss is 52.29 KVAR. The voltage magnitude is lowest at the 11^{th} bus, which is 0.942 pu.

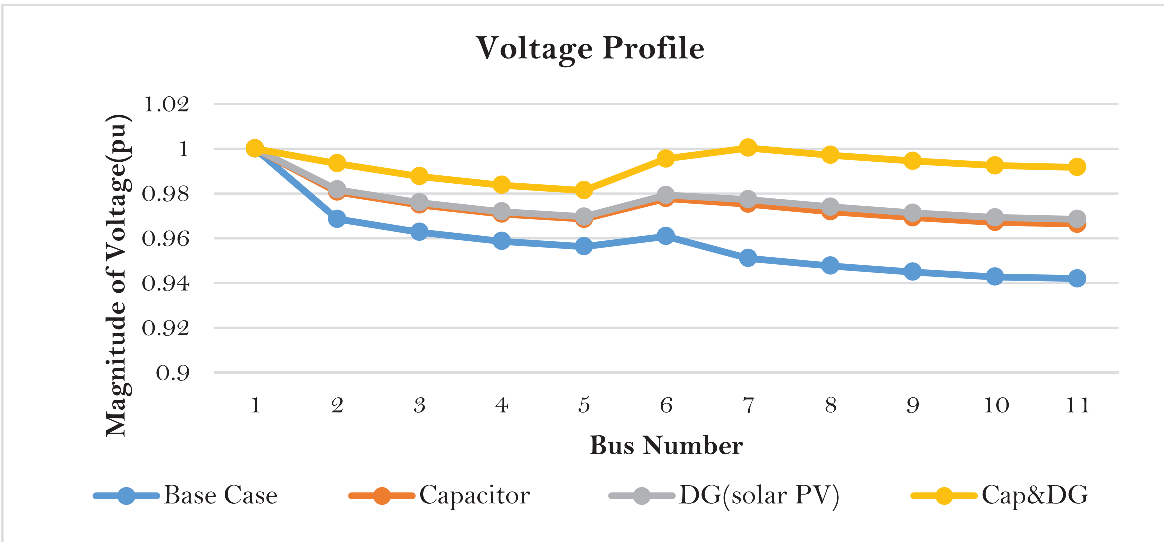

Figure 8: Block diagram of Sallaghari thimi feeder

Table 2 : finding from sallaghari-thimi feeder

Sallaghari Thimi feeder		MATLAB Location (bus)	Size (kVAR or kW)	P_{Loss} (kW)	Q_{loss} (KVA)	V_{min} (pu)	ETAP Location (bus)	Size (kVAR or kW)	P_{Loss} (kW)	Q_{loss} (KVA)	V_{min} (pu)
Base Case		--	--	56.27	52.29	0.942	--	--	56.3	52.3	0.942
Cap	cap=1	7	877.93	32.382	30.09	0.966	7	877.93	32.4	30.1	0.965
	cap=2	7	685.21	28.604	26.579	0.967	7	685.21	28.7	26.6	0.965
		4	388.28				4	388.28			
	cap=3	7	457.13				7	457.13			
		4	389.16	27.670	25.711	0.969	4	389.16	27.7	25.71	0.968
		10	223.54				10	223.54			
DG	DG=1	7	886.07	31.933	29.672	0.968	7	887	32.3	30.0	0.965
	DG=2	7	410.13	28.146	26.153	0.972	7	410.9	30.8	28.6	0.971
		9	597.84				9	596.6			
	DG=3	10	322.33				10	321.8			
		7	379.56	27.034	25.120	0.973	7	379.5	27.5	25.6	0.972
		4	361.51				4	360.7			
Cap & DG	Cap=1	7	388.27	9.72	9.06	0.991	4	388.2	10.1	9.4	0.988
	DG=1	7	685.21				7	869.3			

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 scenarios in Thimi-Sallaghari 11 kV feeder systems as stated above.

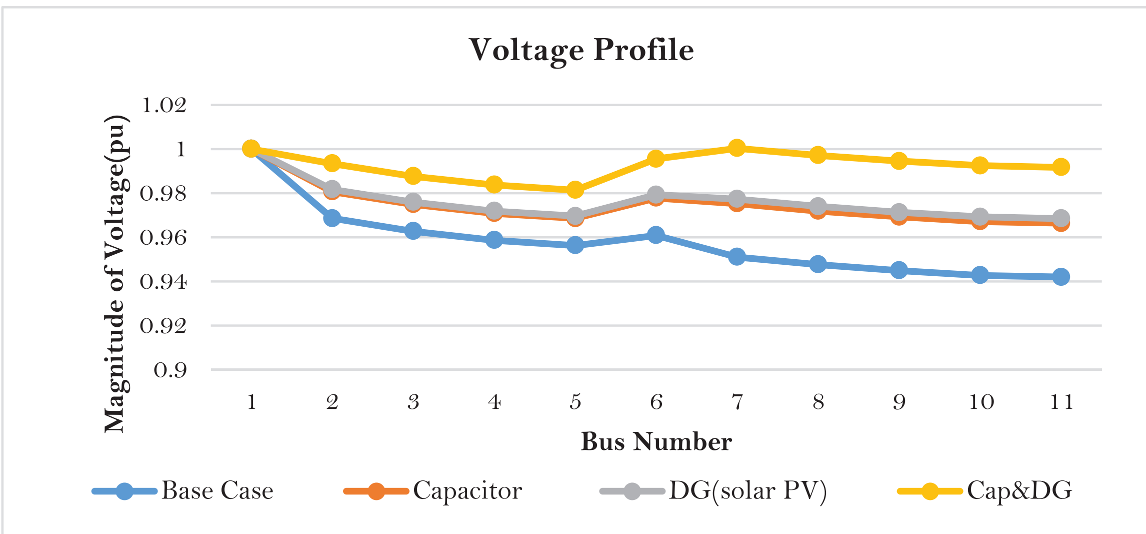

Figure 9: Block diagram of Sallaghari thimi feeder

5 conclusion

V Conclusions

This paper presents a comprehensive methodology utilizing genetic algorithms to optimize both the positioning and magnitudes of capacitors and distributed generators (DG) for minimizing overall power loss and enhancing voltage profiles in radial distribution systems. MATLAB is employed for load flow analysis, utilizing Backward Sweep and Forward Sweep methods on the IEEE 33-bus radial distribution test system and the Thimi-Sallaghari 11 kV feeder. The simulation encompasses diverse scenarios to identify optimal outcomes based on total power loss reduction and voltage profile improvement. The outcomes obtained through MATLAB simulations are meticulously validated using ETAP, affirming their reliability within identical limitations and constraints. Although a general congruence is evident between the two tools, divergences emerge particularly in instances where achieving precise sizing of DG (solar PV) proves challenging in the ETAP environment.

The power flow analysis yields consistent results from both tools, highlighting variations in active and reactive power flows and losses. The analysis effectively pinpoints areas susceptible to voltage drops and high losses, emphasizing the strategic placement of capacitors and DG units for mitigation. Comparative evaluations reveal that the approach of combining DG with capacitor placement surpasses alternative scenarios in both the IEEE-standard radial test system with 33 buses and the Thimi-Sallaghari 11 kV feeder. The notable improvements encompass diminished power losses and heightened voltage profiles, showcasing promising applications for practical implementation in other real feeders in the future.

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