MOGA-Based Optimal Placement of SOPs in DG-Integrated Distribution Network

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Abstract

This research paper proposes a multi-objective genetic algorithm (MOGA) optimization framework based on Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) for the optimal placement and sizing of Soft Open Points (SOPs) in distribution networks with high penetration of distributed generation (DG). The methodology addresses key operational challenges introduced by DG, including voltage deviation and increased real power losses, issues that cannot be effectively mitigated using conventional tie-switches. By replacing these switches with SOP devices, implemented through back-to-back voltage source converters (B2B-VSCs), continuous bidirectional control of active and reactive power between feeders is achieved. The IEEE 33-bus test system is used as the study platform, and eight operating cases are examined to evaluate the performance of standalone DG placement, standalone SOP deployment, and coordinated planning of both technologies. The optimization framework efficiently manages discrete location variables and continuous sizing variables, demonstrating stable convergence and avoiding entrapment in local optima. Multiple objectives, including minimization of real power losses, improvement of voltage profiles and minimization of cost are optimized simultaneously. The outcomes confirm that the proposed MOGA-based strategy is highly effective for enhancing power flow control, voltage stability, and overall operational flexibility in active distribution networks, making it a practical solution for future DG-dominated grid environments.

Keywords: Distributed Generation, Distribution Network, Multi Objective Genetic Algorithm, Non-Dominated Sorting Genetic Algorithm-II, Soft Open Points

1. Introduction

An SOP is a power electronic (PE) device capable of accurately controlling active and reactive power flows (Azizi et al., 2023). In traditional radially operated electricity DNs, backup connection points between Medium Voltage (MV) feeders with remotely operated switch disconnects are typically called as normally open points (NOPs). These NOPs could be replaced by SOPs equipped with rapidly controllable PE converters. SOPs, typically implemented using B2B-VSCs, have emerged as a key technology for enhancing flexibility, economy, and controllability in active distribution networks (ADNs). Various optimization and control approaches have been proposed, including MOPSO with taxi-cab refinement, mixed-integer nonlinear formulations for restoration and siting, adaptive droop and sliding-mode control for dynamic stability (B. Li et al., 2020), and autonomous voltage management for smart grids with EV and DG growth. The NSGA-II based optimization methods have demonstrated that SOP deployment can significantly reduce power losses, improve voltage profiles, mitigate unbalance, increase hosting capacity, and outperform conventional network reconfiguration strategies in IEEE 33-bus and similar benchmarks (Hafezi & Laaksonen, 2019). Overall, literature confirms SOPs as a practical enabler of flexibility, resilience, and techno-economic efficiency in modern distribution systems (Long et al., 2016).

1.1 Back-to-back VSCs based Soft Open Point

Fig.1 illustrates a two-feeder distribution network connected by a B2B-VSC based SOP. The SOP consists of two IGBT-based VSCs linked through a common DC capacitor that stabilizes the DC voltage. Each VSC is connected to the feeder through a series filter inductance, which reduces harmonics, limits fault current, and enables power flow control. The short line between the filter and feeder is assumed to have negligible resistance and reactance.

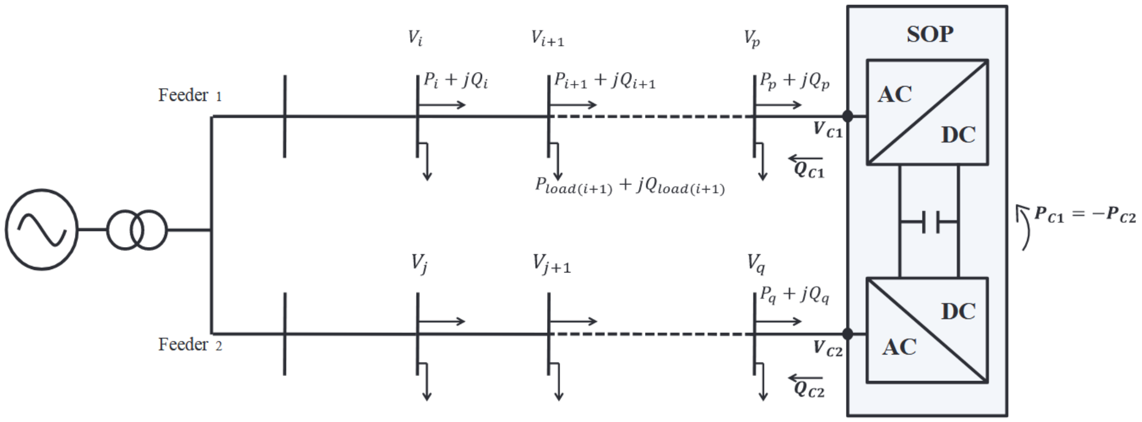


Fig.1: SOP installation in DN

The operational constraints of such device are:

$$P_{C1} + P_{C2} + P_{SOP,loss} = 0 \tag{1}$$

If $P_{SOP,loss}$ is the power losses at the SOP. These power losses are relatively low compared to the power losses of the entire network and thus can be neglected. So, it can be simplified as,

$$P_{C1} = -P_{C2} \tag{2}$$

$$\sqrt{P_{C1}^2 + Q_{C1}^2} \leq S_{C1} \tag{3}$$

$$\sqrt{P_{C2}^2 + Q_{C2}^2} \leq S_{C2} \tag{4}$$

Where, P_{C1}andQ_{C1}, P_{C2} and Q_{C2} are real and reactive power injections/absorptions of each VSC to/from the network at their interfaces. $S_{C1} and S_{C2}$ are the rated capacity of each VSC (Qi & Wu, 2017).

SOP can:

- control active power flow P_{flow} in both-direction between feeders.
- not generate active power P internally unless coupled with ESS.
- supply or absorb reactive power Q to the network as needed in one or both-direction simultaneously.

SOPs replace conventional tie switches and use power electronic control to manage active and reactive power, enhancing voltage stability and network flexibility. Previous studies and simulations confirm that optimized SOP operation reduces losses, increases DG hosting capacity, and improves system resilience under normal and disturbed conditions (Cai et al., 2018), (Aithal et al., 2016).

Multi-objective optimization captures the trade-offs between loss reduction, voltage improvement, and load balancing in SOP planning. Coordinated SOP operation with network reconfiguration provides better performance than single-objective or uncoordinated approaches (Qi et al., 2017).

SOP installation can achieve loss reduction and voltage improvement comparable to extensive network reconfiguration. Even a single SOP significantly enhances feeder load balancing and overall operational efficiency (Cao et al., 2016a)

1.2 Multi-Terminal SOP

A multi-terminal SOP (MT-SOP) as shown in Fig.2 uses three or more VSCs on a shared DC link to control power flow across several feeders, helping relieve voltage and thermal limits in MV networks with high DG penetration. Tested on an 11 kV system, the optimization-based control approach lowered energy losses and increased DG hosting capacity by about 20% compared to a conventional two-terminal SOP (Abdelrahman et al., 2018)

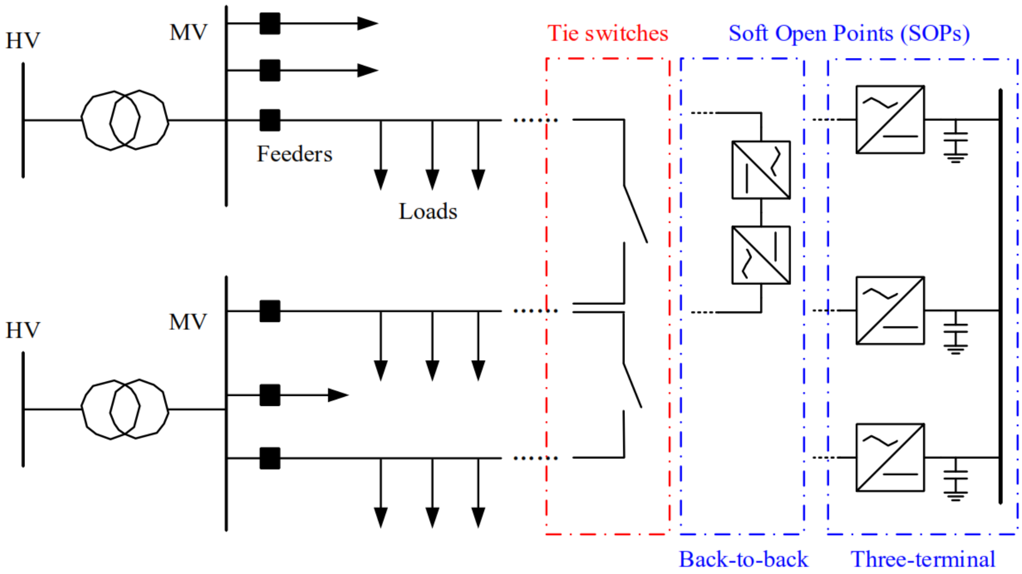


Fig.2: Schematic of SOP Installation

1.3 Characteristics of SOP

The B2B-VSC is suitable for SOP operation due to the following characteristics:

1.3.1 Flexible active and reactive power control

Each VSC independently generates voltage with controlled magnitude and phase, enabling precise active power transfer through the DC link and independent reactive power control at both terminals. This capability supports feeder load balancing, loss reduction, and voltage profile improvement under normal operating conditions.

1.3.2 Instantaneous and independent voltage control

The VSCs can rapidly adjust their voltage waveforms, enabling fast transient control such as dynamic Volt/VAR regulation and power oscillation damping. They can also generate the required voltage without an active source at the receiving end.

1.3.3 Isolation of disturbances and faults

Transient overvoltage and overcurrent of VSCs are able to be limited by control strategies, thus network disturbances or faults on one connected feeder can be isolated from the other side by VSCs.(Cao et al., 2016b)

2. Methodology

The methodology as in Fig.3 starts with load flow analysis of the IEEE 33-bus system to obtain base-case power losses and minimum voltage. DG units are then optimally placed and sized using NSGA-II, followed by performance evaluation through load flow analysis. Selected standard tie lines are replaced with SOPs, and NSGA-II is again applied to determine their optimal locations and ratings. The results are compared with the base and DG-only cases to evaluate improvements in power loss and voltage profile.

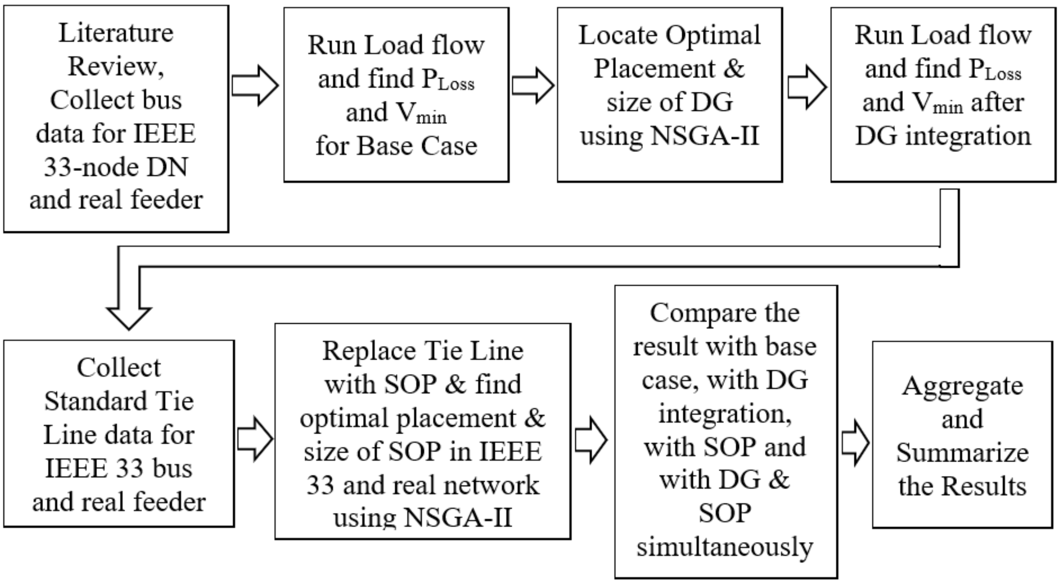


Fig.3: Block Diagram of the Research Methodology

2.1 IEEE 33-Bus System Description

The IEEE 33-bus test system is widely used because it offers:(Dolatabadi et al., 2021)

- moderate complexity, making it suitable for optimization studies.
- weak voltage buses (e.g.17,18,32and33) useful for voltage analysis.
- sensitive network to DG integration, SOP control, and reconfiguration.
- useful for load flow, loss minimization, voltage stability and hosting capacity studies.
- the base system supplying 3715kW and 2300kVAR with about 203kW of real power loss.

2.2 Forward–Backward Sweep Method

The Forward–Backward Sweep method is applied for load flow analysis in the IEEE 33-bus radial distribution system. It is well suited for such networks due to their high resistance-to-reactance ratio. The method alternates between forward sweeps to compute branch currents from load demands and backward sweeps to update bus voltages from the slack bus. This process continues until voltage changes between iterations meet the convergence criterion, yielding the final voltages, branch currents, and power losses.

2.3 Tie Line in IEEE-33 Bus

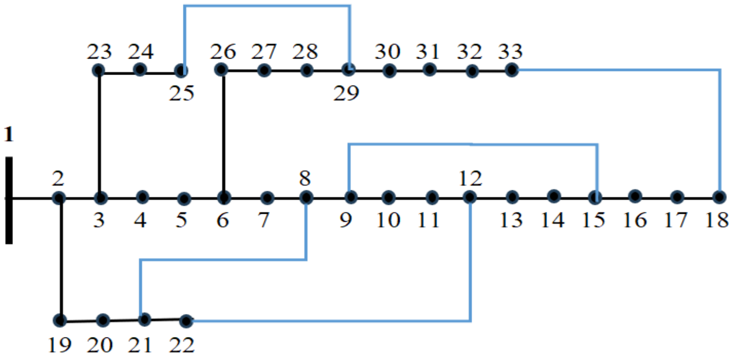


Fig.4: Standard Tie line in IEEE 33-node DN

The IEEE 33-bus system contains normally open tie lines (such as: 8–21,9–15,12–22,18–33 and 25–29) used for network reconfiguration. These tie lines support loss reduction, voltage improvement, and service restoration during switching or contingencies. Although they do not carry power under normal operation, they enhance system flexibility and reliability. The Fig.5 illustrates possible SOP placements, for example at buses 12–22 and 18–33.

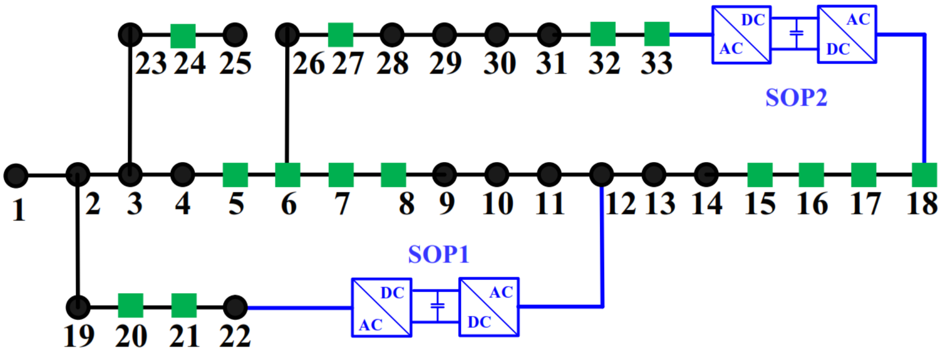


Fig.5: Possible Placement of SOP in DG-integrated DN

2.4 Multi-objective Optimization

Multi-objective optimization addresses problems involving two or more conflicting objectives by identifying a set of trade-off solutions rather than a single optimum. These solutions form the Pareto front, where improvement in one objective leads to degradation in at least one other.

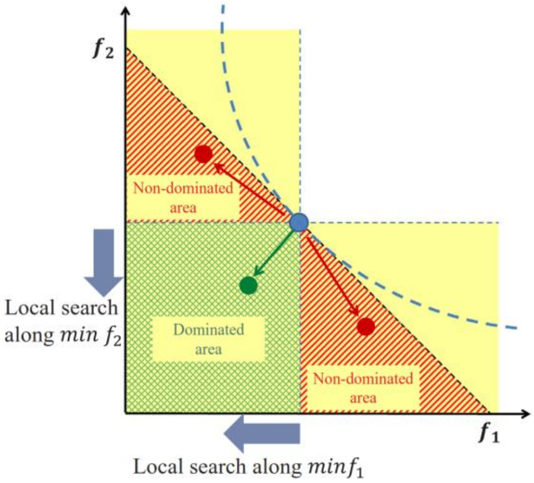


Fig.6: Pareto front Solution to find two-objective minimization problem(Qi et al., 2017)

Compared to the weighted-sum method, which yields a single solution and depends on predefined weights, NSGA-II provides a diverse set of unbiased pareto-optimal solutions, making it more suitable for research applications. Genetic algorithms achieve this by using non-dominated sorting and crowding distance to maintain solution diversity along the pareto-front as in Fig.6.

2.5 Non-dominated Sorting Genetic Algorithm II (NSGA-II)

The NSGA-II is an efficient evolutionary method for solving multi-objective optimization problems. It employs fast non-dominated sorting, elitism, and crowding distance to preserve solution diversity. NSGA-II is well suited for the nonlinear and mixed-integer nature of SOP placement problems, providing stable convergence and a well-distributed set of pareto-optimal solutions while improving upon the computational limitations of the original NSGA.

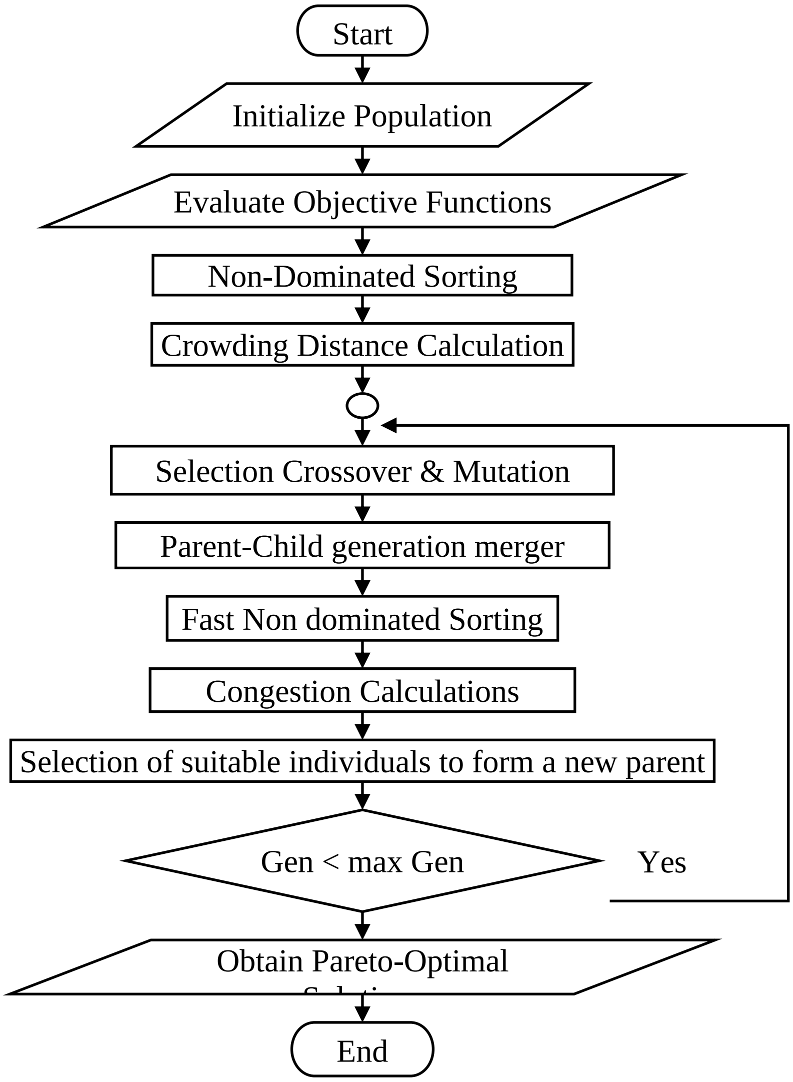


Fig.7: Flowchart of NSGA-II algorithm

3. Mathematical Modelling of System

3.1 Objective Function

The multi-objective optimization problem is as follows:

Minimize: $F = [f_1(x),\ f_2(x),\ f_3(x)]$ (5)

Minimize: $f=w_1.f_1(x)+w_2.f_2(x)+w_3.f_3(x)$ (6)

With constraint: $w_1+w_2+w_3=1$ (7)

Typically, $w_1=0.70, w_2=0.20, w_3=0.10$

Where:

Objective 1: Minimize Active Power Loss:

$$f_1(x) = \sum_{i=1}^{N_b} P_{loss,i} = \sum_{i=1}^{N_b} I_i^2 R_i \tag{8}$$

Objective 2: Minimize Voltage Deviation:

$$f_2(x) = \sum_{j=1}^{N_b} \left|V_j - V_{ref}\right| \tag{9}$$

Where $V_{ref} = 1.0 p.u.$

Objective 3: Minimize SOP Investment & Operational Cost:

$$f_3(x) = \sum_{k=1}^{N_{SOP}} \left(C_{inv,k} + C_{opr,k}\right) \tag{10}$$

Where, cost components are: Investment Cost,

$$C_{inv,k} = a.S_k^{SOP}+\mathrm{b} \tag{11}$$

S_k^{SOP} is SOP rating (in kVA)

Operation Cost,

$$C_{opr,k} = c.E_{loss,k} \tag{12}$$

Annual energy losses in SOP(kWh/year)

$$E_{loss,k}=P_{loss,total} \times 8760 \times LLF \tag{13}$$

Table 1: Cost Parameters (Qi et al., 2017) (P. Li et al., 2019)

Description	**Symbol**	**Value**	**Unit**
Cost of SOP	a	150	USD/kVA
Fixed base cost (infrastructure, installation, controls)	b	30000	USD/N_{SOP}
Energy Cost	c	0.08	USD/kWh
Loss of Load Factor	LLF	0.3	

3.2 Constraint Formulation

The optimization must satisfy the following constraints:

Power balance: $P_{gen} - P_{load} - P_{loss} = 0$ (14)

Voltage Limits: $V^{min} \le V_i \le V^{max}$;$[V^{min} = 0.95; V^{max} = 1.05]$ (15)

Branch Current Limits: $I_i \le I_i^{max}$(=300A) (16)

SOP Rating Constraints: $|P^{SOP}| \le P_{max}^{SOP},\ |Q^{SOP}| \le Q_{max}^{SOP}$ (17)

$$\sqrt{(P_k^{SOP})^2 + (Q_k^{SOP})^2} \le S_k^{SOP} \tag{18}$$

$$R_D = \overbrace{\underbrace{P_1, \dots, P_{N_{SOP}}}_{\text{SOP}_{\text{1or2}}\text{ active power injection}}}^{\text{Real control variables}} \quad \overbrace{\underbrace{Q_1^1, \dots, Q_{N_{SOP}}^1}_{\text{SOP}_1\text{ Reactive power injection}}}^{\text{Real control variables}} \quad \overbrace{\underbrace{Q_1^2 \dots, Q_{N_{SOP}}^2}_{\text{SOP}_2\text{ Reactive power injection}}}^{\text{Real control variables}} \quad \overbrace{\underbrace{L_1, \dots, L_{N_{SOP}}}_{\text{SOP Location}}}^{\text{Integer control variables}}$$

Fig.8: The Structure of the Initial individual variables of SOP for NSGA-II

3.3 Tools and Software

The proposed optimization toolbox, algorithms and load flow analysis were developed and run in MATLAB software R2024b on a Laptop with Processor of 13th Gen Intel® Core™ i7-13620H (2.40 GHz) with installed RAM of 16.0 GB, 64-bit operating system.

4. Results and Discussion

This study evaluates eight operating cases on the IEEE 33-bus DN with DG-integration and SOP installation at standard tie lines. Three DG units are optimally placed, while the locations and sizes of SOPs are determined using the NSGA-II algorithm with a population size of 100 and 500 generations. The base case and seven additional scenarios are simulated for performance comparison(Alwash et al., 2023):

- Base case: A power-flow solution without considering DG and SOP in IEEE 33-node DN
- Case 1: One optimal SOP placement without DG penetration
- Case 2: Two optimal SOP placement without DG penetration
- Case 3: Three optimal SOP placement without DG penetration

- Case 4: Optimal placement of 3-DG without SOP placement
- Case 5: One optimal SOP placement in 3-DG integrated DN
- Case 6: Two optimal SOP placement in 3-DG integrated DN
- Case 7: Three optimal SOP placement in 3-DG integrated DN

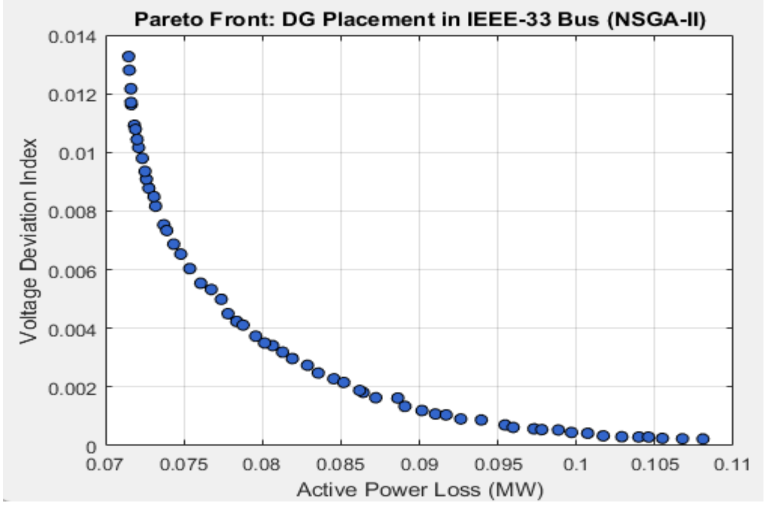


Fig.9: Pareto-optimal Solution for optimal DG placement

Fig.9 shows the Pareto-optimal DG placement solutions obtained using NSGA-II, highlighting the trade-off between power loss reduction and voltage deviation. Higher DG sizes reduce losses but increase voltage deviation, while moderate DG sizes offer a balanced performance.

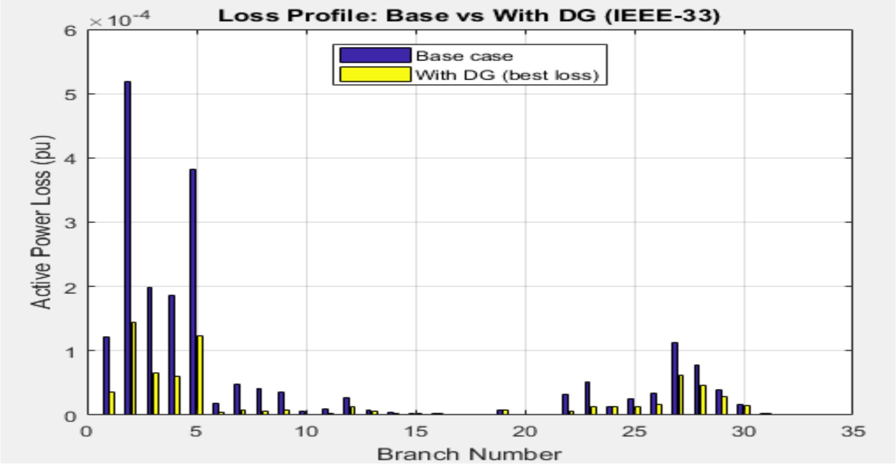


Fig.10: Power Loss Profile in branches 1-32: Base Vs With_DG

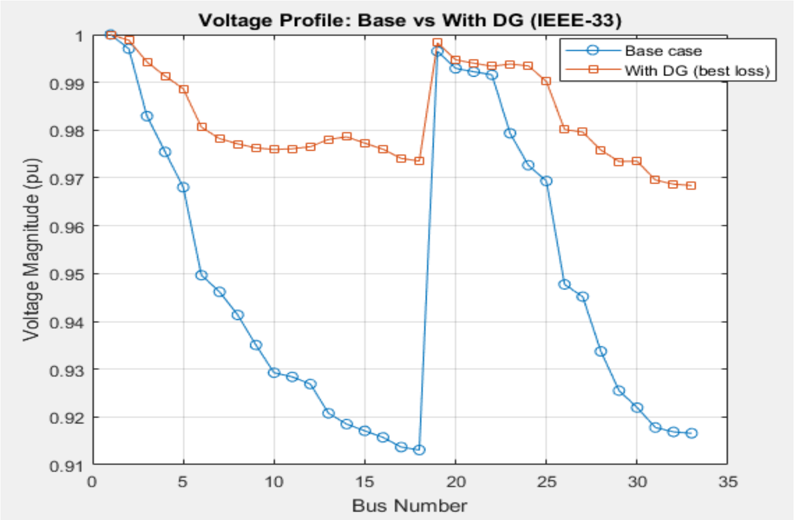


Fig.11: Voltage Profile Comparison with base_case vs DG_Placement(w_1=1.0,w_2=0.0)

The above Fig.10 compares the branch-wise active power losses (branches 1–32) of the IEEE 33-bus system under base conditions and after optimal DG placement. DG integration significantly reduces losses across most branches. The corresponding voltage profile comparison in Fig.11 shows an improvement in the minimum voltage from 0.9131 p.u. in the base case to 0.9687 p.u. with DG placement.

Table 2: Optimal Placement of 3-DG in IEEE 33-node

Optimal DG placement at node no.	14	24	30
DG Size(kW)	754	1099	1071

From the best solution obtained as in Table 2 and Table 3, total power loss in all 32 branches of IEEE 33-node DN was reduced by 64.73% with the optimal placement of DG compared to base case.

Table 3: Loss reduction comparison with and without DG placement

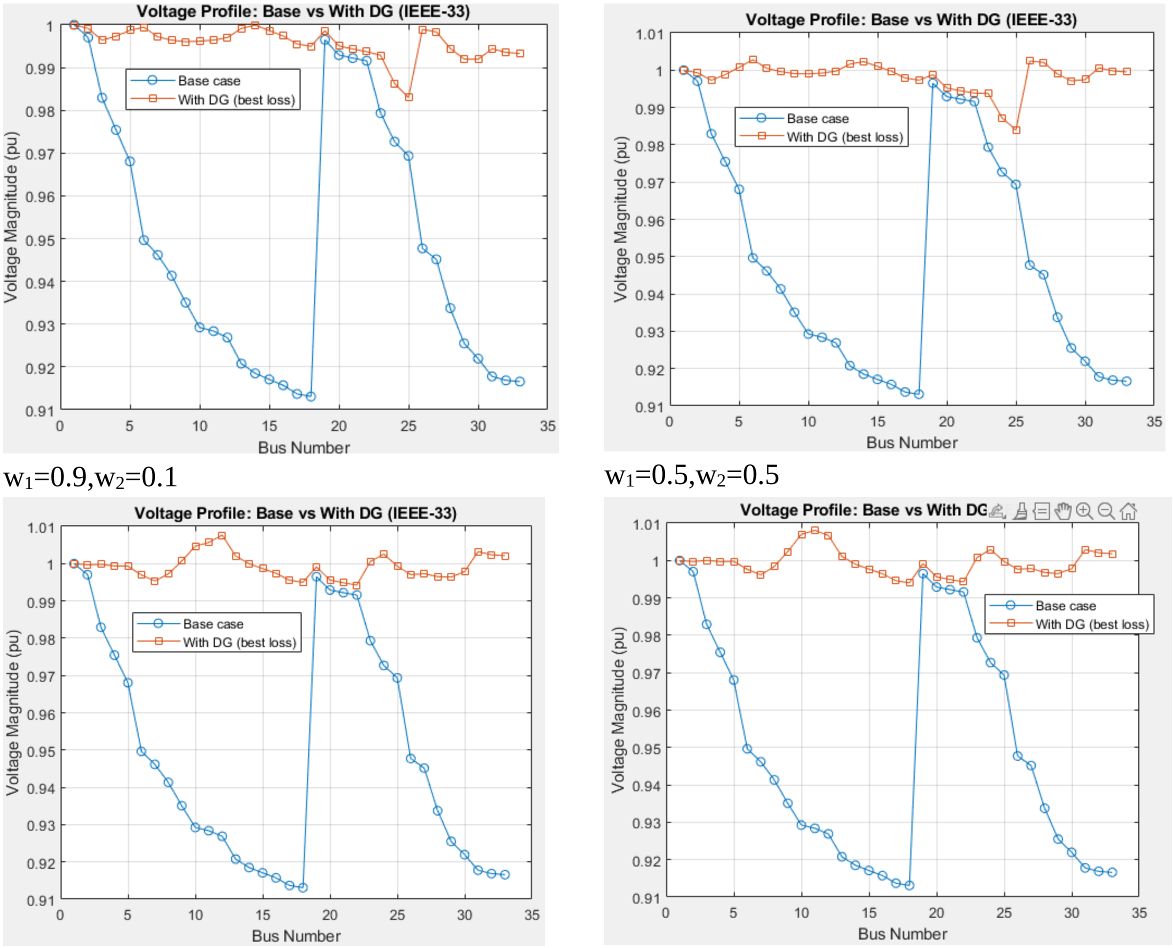
Case	**Power loss (kW)**	**Loss Reduction (%)**	**V_{min} (p.u.)**	**V_{max} (p.u.)**
Base	202.7	-	0.9131	1.0
With DG	71.5	64.73%	0.9687	1.0

While taking weighted objective function, Minimize **$f=w_1.f_1(x)+w_2.f_2(x)$**
Where $f_1(x)$ is a function of minimize power loss and $f_2(x)$ is a function of minimize voltage deviation with $w_1+w_2=1$. The different size of DG is obtained with the different boundary conditions.

Table 4: Comparison of Loss reduction and Voltage deviation in different scenarios with DG

Case	**w_1+w_2**	**DG buses**	**DG sizes kW**	**Loss kW**	**Loss Reduction%**	**V_{min}/V_{max} p.u.**
Base	-	No DG	No DG	202.7	-	0.9131/1.0000
1	0.0+1.0	11,24,31	1542,1536,1471	111.1	45.18%	0.9940/1.0081
2	0.2+0.8	12,24,31	1453,1517,1514	110.1	45.69%	0.9942/1.0077
3	0.5+0.5	06,14,31	1827,819,1151	105.4	48.01%	0.9839/1.0028
4	0.9+0.1	06,14,31	1660,848,1029	95.7	52.79%	0.9830/1.0000
5	1.0+0.0	14,24,30	754,1099,1071	71.5	64.73%	0.9687/1.0000

The Table 4 shows that increasing the weight (w_1) on loss minimization reduces total power loss but increases voltage deviation. The minimum loss of 71.5kW (64.73% reduction) is achieved at the expense of a decrease in minimum voltage from 0.994p.u. to 0.9687p.u., highlighting the trade-off between loss reduction and voltage performance.



w_1=0.9,w_2=0.1

w_1=0.5,w_2=0.5

w_1=0.2,w_2=0.8

w_1=0,w_2=1

Fig.12: Voltage Profile Comparison with DG only for various w_1 & w_2

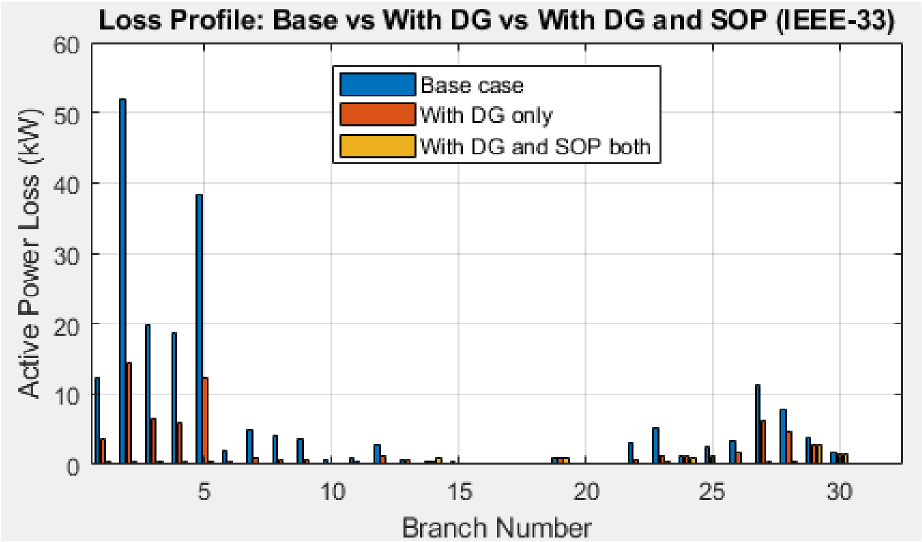


Fig.13: Loss Profile of IEEE 33-node: Base Vs with_DG Vs with_DG_SOP

The Fig.13 indicates the active power loss in branches of IEEE 33-node DN under three conditions: the base network, the system with three optimally placed DG units, and the system with both three DG units and two SOPs installed at the optimal tie-line locations.

The Fig.14 compares the voltage profiles of the IEEE 33-bus system for the base case, with optimal DG placement, and with combined DG and SOP installation. DG integration improves node voltages to about 0.98 p.u., while the addition of SOPs further enhances the profile, with voltages approaching 1.0 p.u., demonstrating the advantage of coordinated DG and SOP deployment.

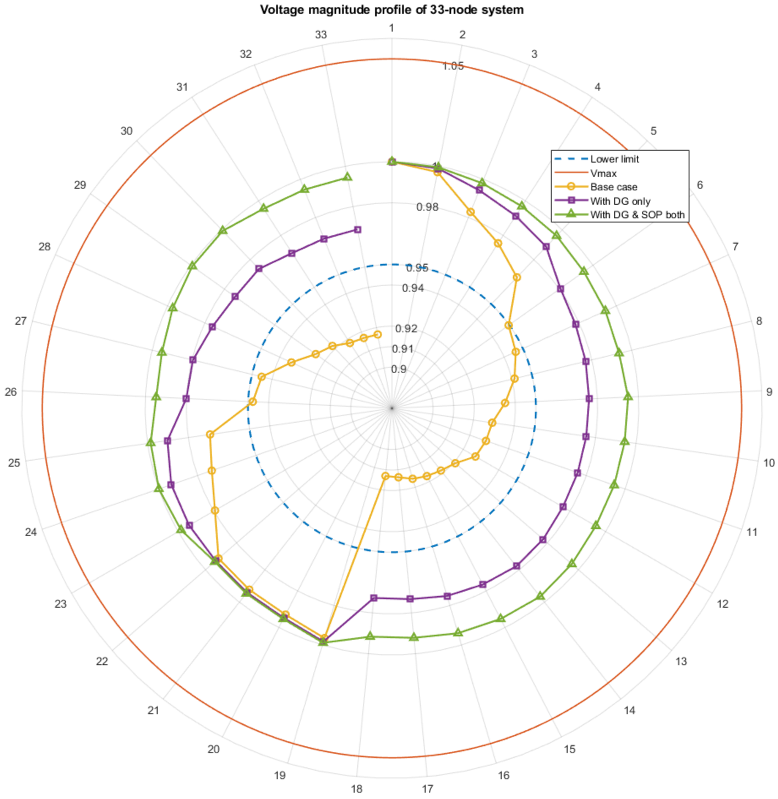


Fig.14: Voltage Profile Comparison (Base_Case Vs with_DG Vs with_DG_SOP)

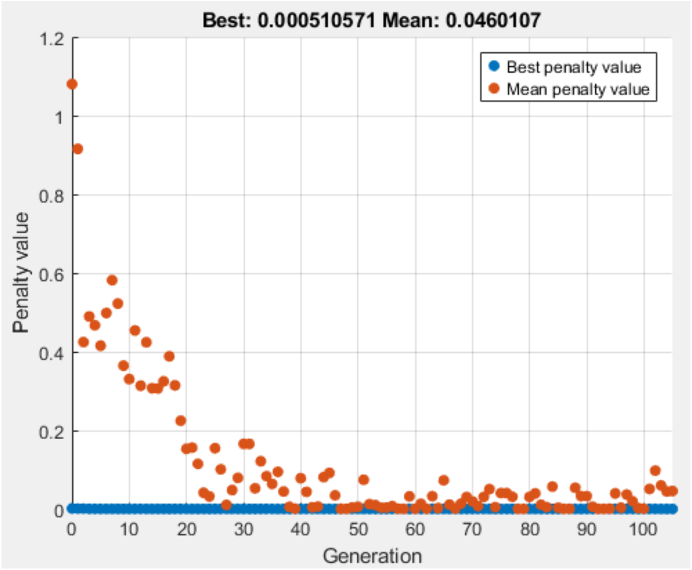


Fig.15: Convergence of Generation vs Penalty value in NSGA-II

The results in Table 5 shows that the base system has a power loss of 202.7 kW with a minimum voltage of 0.9131p.u. Installing one SOP at tie line 8–21 reduces the loss to 133.63kW and improves the minimum voltage to 0.95p.u. With two SOPs placed at 12–22 and 25–29 decrease losses further to

86.96kW and the minimum voltage rises to 0.9658p.u. The best performance is achieved with three SOPs placed at 8–21, 25–29, and 9–15, reducing losses to 81.79kW (59.64%) and maintaining a minimum voltage of 0.9676p.u., demonstrating that increased SOP deployment enhances both loss reduction and voltage profile.

Table 5: Power Loss and Voltage Profile with optimal placement of SOP only

Case	**SOP at Tie line**	**P_1 SOP kW**	**P_2 SOP kW**	**Q_1 SOP kVAR**	**Q_2 SOP kVAR**	**Loss kW**	**Loss redn%**	**V_{min}/ V_{max} p.u.**
Base						202.7		0.9131/ 1.0000
1SOP	8-21	1665	-1665	1000	231.1	133.63	34.07%	0.95/1.00
2SOP	12-22	742.6	-742.6	428.6	125.1	86.96	57.09%	0.9658/ 1.0000
	25-29	-409	409	418.5	1000			
3SOP	8-21	927.6	-927.6	318.4	153.5	81.79	59.64%	0.9676/ 1.0000
	25-29	-361.5	361.5	387.8	954			
	9-15	-466.5	466.5	62.8	209.5			

Table 6 shows that DG installation alone reduces system losses to 71.5kW, corresponding to a 64.73% reduction. The addition of SOPs further improves performance, reducing losses to 20.28 kW with one SOP, 12.45 kW with two SOPs, and 10.46 kW with three SOPs, achieving a maximum reduction of 94.84%. Compared to cases without DG, coordinated DG and SOP deployment provides greater loss reduction and maintains minimum voltages above 0.98 p.u.

Table 6: Power Loss and Voltage Profile with DG and SOP

Case	**SOP at Tie line**	**P_1 SOP kW**	**P_2 SOP kW**	**Q_1 SOP kVAR**	**Q_2 SOP kVAR**	**Loss kW**	**Loss redn%**	**V_{min}/ V_{max} p.u.**
Base						202.7		0.9131/ 1.0000
DG only						71.5	64.73%	0.9687/ 1.0000
1SOP	25-29	33.7	-33.7	499.1	1000	20.28	89.99%	0.9827/1
2SOP	25-29	35.3	-35.3	392	969.2	12.45	93.86%	0.9909/ 1.0001
	9-15	174.5	-174.5	394.5	144.2			
3SOP	9-15	258.8	-258.8	277.5	146.6	10.46	94.84%	0.9940/ 1.0000
	18-33	85.8	-85.8	68.0	354.6			
	25-29	3.5	-3.5	400.3	620.1			

5. Conclusion

This work developed an NSGA-II–based multi-objective framework for optimal siting and sizing of SOPs in a DG-integrated distribution network using the IEEE 33-bus system. Results show that optimal placement of three DG units alone reduces real power loss by 64.73% and improves the minimum voltage to 0.9687 p.u. The coordinated integration of SOPs further enhances performance, achieving up to 94.84% loss reduction and raising the minimum voltage to 0.9940 p.u., clearly outperforming standalone DG or SOP deployment.

The proposed NSGA-II approaches efficiently handled mixed decision variables and converged reliably to well-distributed Pareto-optimal solutions. Optimal SOP placement along standard tie lines improved voltage regulation, reduced feeder loading, and increased DG hosting capability while maintaining all operational constraints. Overall, the results confirm that coordinated planning of DGs and SOPs provides a practical and effective solution for enhancing the efficiency, flexibility, and reliability of modern distribution networks.

Future Recommendations

- Extend the proposed approach to larger and unbalanced distribution systems (e.g., IEEE 69-bus and real utility networks).
- Consider dynamic and real-time operation of SOPs under load and generation uncertainty.

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