A novel analytical hybrid optimization methodology for maximizing renewable energy integration in radial distribution networks

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ABSTRACT

Integrating distributed generation (DG) units into radial distribution systems (RDS) presents significant challenges, including voltage instability, power losses, and compliance with modern grid standards. To address these limitations, this study proposes a novel hybrid optimization methodology that combines advanced mathematical models with iterative power flow analysis. The approach introduces a multi-objective optimization framework that integrates voltage sensitivity factors, power loss indices, and voltage stability measures. A key innovation is the use of voltage stability indices (VSIs) as dynamic weighting factors to guide the optimization process, ensuring a balanced trade-off between minimizing power losses and enhancing network stability. This framework provides a precise and scalable solution for optimizing DG placement and sizing simultaneously. The methodology is validated on the IEEE 33-bus distribution system, demonstrating a 68% reduction in power losses, a 4.88% improvement in voltage stability, and a 70.4% DG integration rate, all achieved without altering the network configuration. These results highlight the proposed framework's potential to enhance the resilience, efficiency, and reliability of RDS, offering a robust and standards-compliant solution for DG integration.

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1. INTRODUCTION

The global energy transition is driving the rapid integration of distributed generation (DG) from renewable sources into electrical grids. While this shift is crucial for reducing reliance on fossil fuels and lowering CO_2 emissions [1]-[3], the intermittent nature of renewables such as solar and wind introduces significant technical challenges for existing radial distribution systems (RDS). Key among these is voltage instability, increased power losses, and network congestion [4], [5], underscoring the critical need for innovative strategies to optimize DG integration while ensuring grid stability and efficiency.

In response, a substantial body of research has focused on optimizing the placement and sizing of DG units using advanced computational algorithms. Techniques such as particle swarm optimization (PSO) [6], [7], genetic algorithms (GA) [8], and neural networks [9] have been employed to reduce losses, improve voltage profiles, and maximize economic benefits [10], [11]. For instance, GA-based approaches have been used to enhance reliability and minimize costs [12], while hybrid models combining GA with neural networks have improved forecasting and scheduling [9]. Similarly, PSO has been applied to optimize biomass-based DG, achieving notable reductions in power losses [6], [13], [14]. Furthermore, adaptive protection schemes have been developed to maintain stability in networks with high DG penetration [15]. Despite these advances, most existing studies treat DG sizing and placement as separate or sequential optimization problems. A major limitation of these metaheuristic approaches is the insufficient precision of the dimensioning procedure, which often overlooks the interdependence between DG capacity, voltage stability, and compliance with modern grid codes, resulting in suboptimal network configurations. In addition, traditional power flow methods, such as the newton–raphson [10] and backward forward sweep [6], [16], [17], although accurate, lack adaptability and multi-objective optimization capability, restricting their applicability for integrated DG planning in dynamic distribution networks.

To address these gaps, this paper proposes a novel hybrid multi-objective optimization framework that concurrently determines the optimal DG sizing and placement. The key innovation lies in integrating voltage stability indices (VSIs) as adaptive weighting factors within the objective function, enabling a dynamic trade-off between power loss reduction and voltage enhancement. The proposed methodology synthesizes voltage sensitivity factors, loss indices, and stability metrics into a unified model, offering a more comprehensive optimization strategy.

Validated on the IEEE 33-bus system, the proposed method achieves 68% loss reduction, 4.88% voltage stability improvement, and supports a 70.4% DG penetration rate, all without network reconfiguration. Comparative analyses confirm the robustness, accuracy, and scalability of the method against established algorithms, positioning it as an effective and adaptive tool for the reliable integration of distributed generation in modern distribution networks.

2. DEVELOPMENT OF THE CALCULATION ALGORITHM

This section outlines the development of the calculation algorithm for optimizing the location and sizing of DG units in a symetric radial distribution system (RDS). The algorithm is based on mathematical modeling of the network. It employs power flow analysis to achieve optimal DG placement and sizing while adhering to bus voltages and voltage drop constraints.

2.1. Mathematical modeling of a radial distribution system and power flow analysis

The proposed methodology uses a mathematical model of an RDS, represented as a graph of buses (nodes) and branches (lines). As shown in Figure 1, the network has a radial topology. Each bus is assigned a unique identifier, and the system's structure is defined by their interconnections.

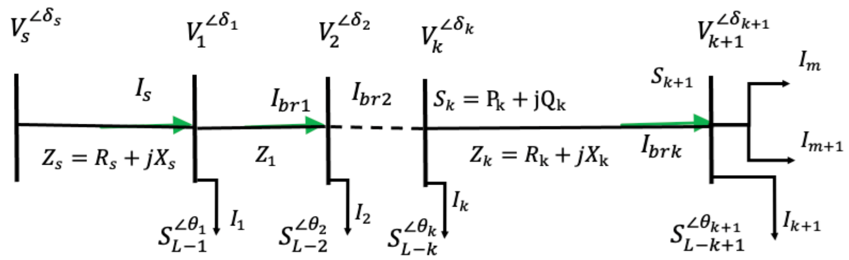

Figure 1. Scheme of a branch of a distribution system

The complex load S_k at bus k is expressed as (1). The load current at bus (k+1) is calculated using (2).

$$S_k = P_k + jQ_k \tag{1}$$

$$I_{(k+1)}^{n} = \left(\frac{S_{L-k+1}^{\angle\theta_{k+1}}}{V_{k+1}^{\angle\delta_{k+1}}}\right)^{*} \tag{2}$$

Active and reactive power losses in branch $(k, k+1)$ are evaluated as (3) and (4).

$$P_{loss(k,k+1)} = \frac{P_k^2 + Q_k^2}{|V_k|^2} R_k \tag{3}$$

$$Q_{loss(k,k+1)} = \frac{P_k^2 + Q_k^2}{|V_k|^2} X_k \quad (4)$$

The total active and reactive power losses of the system are calculated by summing the losses in all branches.

$$P_{Total_{loss}} = \sum_{k=1}^{nb-1} P_{LOSS(k,k+1)} \quad (5)$$

The voltage drop in branch k is given by (6).

$$\Delta V_k = V_k - V_{k+1} = I_{brk} * Z_k \quad (6)$$

2.2. Backward and forward sweep method (BFS)

The BFS method is a robust power flow technique for RDS [18]. It consists of two steps: Backward Sweep: starting from the end buses toward the reference bus, the branch current is calculated using (7).

$$I_{brk} = I_{k+1} + \sum_{m \in M} I_m \quad (7)$$

With I_m is the branch current connected downstream of bus $(k+1)$, and M is the set of branches connected to bus $(k+1)$. Forward Sweep: After obtaining the branch currents, the bus voltages are updated from the reference bus to the end buses using (6) [19].

2.3. Direct approach method (DA)

The DA method is based on two matrices: the bus injection to branch current (BIBC) matrix and BCBV matrix the branch current to bus voltage [17]. The steps are as follows: The branch current vector $[I_{Br}]$ is calculated using (8).

$$[I_{Br}]_{nb*1} = [BIBC]_{nb*(N-1)} * [I_k]_{(N-1)*1} \quad (8)$$

Where nb is the number of branches, N is the number of buses, and $[I_{\boldsymbol{k}}]$ is the load currents vector at each bus except the reference bus. The voltage drop vector $[\Delta V]$ is calculated using (9).

$$[\Delta V]_{(N-1)*1} = [Z]_{(N-1)*nb} * [I_{Br}]_{nb*1} \quad (9)$$

The relationship between branch currents and voltage drops is expressed as (10).

$$[\Delta V] = [BCBV] * [BIBC] * [I_{Br}] \quad (10)$$

The bus voltages are updated iteratively using (11).

$$\left[V_k^{(n)}\right] = [V_s] - \left[\Delta\, V_k^{(n)}\right] \quad (11)$$

The maximum error for all buses is verified using (12).

$$\begin{cases} e_k^{(n)} = V_k^{(n)} - V_k^{(n-1)} \\ e_{Max}^{(n)} = Max\left(e_2^{(n)}, e_3^{(n)}, \dots e_N^{(n)}\right) \end{cases} \quad (12)$$

2.4. Newton-raphson method (NR)

The NR method is widely used for power flow calculations due to its strong convergence characteristics [19]. The steps are as follows: The active and reactive power equations at bus k are:

$$\begin{cases} \mathrm{P_k} = \sum_{k=1}^{N} |V_k|\,|V_{k+1}|(G_{k,k+1}\cos\delta_{k,k+1} + B_{k,k+1}\sin\delta_{k,k+1}) \\ \\ \mathrm{Q_k} = \sum_{k=1}^{N} |V_k|\,|V_{k+1}|(G_{k,k+1}\sin\delta_{k,k+1} - B_{k,k+1}\cos\delta_{k,k+1}) \end{cases} \quad (13)$$

with G and B are the admittance matrix. The active and reactive power losses are evaluated as (14).

$$\begin{cases} \Delta P_k = P_{k_{Load}} - P_{k_{calc}} \\ \Delta Q_k = Q_{k_{Load}} - Q_{k_{calc}} \end{cases} \quad (14)$$

The new values of complex voltages are calculated using (15).

$$\begin{cases} |\bar{V}_i|^{k+1} = |\bar{V}_i|^k + \Delta|\bar{V}_i|^k \\ \theta_i^{k+1} = \theta_i^k + \Delta\theta_i^k \end{cases} \quad (15)$$

3. LOCATION AND SIZING OF THE DG IN THE RDS

Maximizing the benefits of DG requires optimal placement and sizing. This study introduces an innovative approach that integrates voltage stability index (VSI) values as dynamic weights within a multi-objective function. The method optimizes DG allocation while accounting for load variations and network operating conditions. By embedding VSI directly into the optimization, it precisely evaluates the impact of DG on voltage stability, yielding more robust and efficient solutions and motivating new strategies for DG integration.

3.1. Selection of performance indices

The selection of a VSI is critical, as it fundamentally guides the optimization framework for DG integration. A wide array of VSIs exists in the literature [5], [20], with effectiveness being highly context-dependent. Impedance-based indices are common in academic studies for their direct relationship to network parameters. However, they are less practical for real-world systems where line impedance data is often uncertain or unavailable. In contrast, measurement-based indices, which use real-time quantities like voltage, current, and power, are better suited for modern distribution networks. Their reliance on readily available measurements makes them robust for systems with high renewable DG penetration and limited parameter observability their effectiveness.

- Line stability index: This index (Lmn) is applied to assess the stability of the line between two buses in an interconnected system reduced to a single-line network [5]. The expression for the index is given by (16).

  $$L_{mn} = \frac{4XQ_r}{|V_s|^2 \sin(\theta-\delta)^2} \leq 1 \quad (16)$$

  A line is considered close to instability when the value of Lmn approaches 1. On the other hand, if the value of Lmn is strictly less than one (1), then the system is said to be stable [5].

- Fast voltage stability index (FVSI). The stability index of the FVSI line is calculated by (17).

  $$FVSI_{k,k+1} = \frac{4Z_k^2 Q_{k+1}}{V_k^2 X_k} \quad (17)$$

  The line with an FVSI value nearest to 1 is the most critical and may trigger system instability [5].

- Load voltage stability index (VSLI): The VSLI is calculated by applying the principle of setting the discriminant of the power quadratic equation to be greater than or equal to zero [5]. This method yields the following formula for obtaining the VSLI:

  $$VSLI = \frac{4\left(V_k V_{k+1} \cos\delta - V_{k+1}^2 \cos\delta\right)}{V_k^2} \quad (18)$$

  stability is ensured when $VSLI < 1$, while values exceeding 1 indicate possible voltage collapse.

3.2. Formulation of the VSI–LSF based objective function

This study proposes a hybrid optimization framework that integrates the loss sensitivity factor (LSF) with three voltage stability indices (Lmn, FVSI, and VSLI). The LSF identifies buses with the greatest impact on active and reactive power losses, while the VSIs evaluate both local and global voltage stability margins. To enable a fair combination, all indices are normalized into the range [0,1]. The resulting normalized values are then assigned as dynamic weights (w_1 for Lmn, w_2 for FVSI, and w_3 for VSLI). A bus with a low VSI receives a small weight, signaling low priority for corrective action, whereas a bus with a high VSI receives a dominant weight, marking it as critical for DG placement. This integrated, weighted approach overcomes the limitations of conventional optimization techniques like PSO and GA [21], which often suffer from slow convergence, parameter sensitivity, and premature convergence to suboptimal results

[5], [19], [22]. The resulting multi-objective function (F1) combines the active and reactive LSF components P_{lsf} and Q_{lsf} with the standardized VSI-based weights (w_1, w_2, w_3), guiding the optimization toward DG locations that simultaneously minimize losses and enhance system stability.

$$F_1 = w_1 * P_{lsf} + w_2 * Q_{lsf} - w_3 * [\sum_{m=1}^{nb}((V_m - V_{min})^2 + (V_m - V_{max})^2)] \quad (19)$$

Sensitivity calculations: The partial derivatives of active and reactive power losses with respect to equivalent powers are as (20) and (21).

$$\begin{cases} \frac{\partial P_{line,loss}}{\partial P_{eq}} = 2 * \frac{P_{eq(k+1)}}{V_{(k+1)}^2} * r_l \\ \frac{\partial P_{line,loss}}{\partial Q_{eq}} = 2 * \frac{Q_{eq(k+1)}}{V_{(k+1)}^2} * r_l \end{cases} \quad (20)$$

$$\begin{cases} \frac{\partial Q_{line,loss}}{\partial P_{eq}} = 2 * \frac{P_{eq(k+1)}}{V_{(k+1)}^2} * x_l \\ \frac{\partial Q_{line,loss}}{\partial Q_{eq}} = 2 * \frac{Q_{eq(k+1)}}{V_{(k+1)}^2} * x_l \end{cases} \quad (21)$$

Active P_{lsf} and reactive Q_{lsf} loss sensitivity factors can be obtained by (22) and (23).

$$P_{lsf} = \frac{2*r_l}{V_{(k+1)}^2}(Q_{eq}(k+1) + P_{eq}(k+1)) \quad (22)$$

$$Q_{lsf} = \frac{2*x_l}{V_{(k+1)}^2}(Q_{eq}(k+1) + P_{eq}(k+1)) \quad (23)$$

The overall computational framework for optimal DG placement and sizing is summarized in Figure 2, which begins by performing an initial load flow analysis and calculating the VSI. The algorithm then follows an iterative process where the multi-objective function (19) identifies the bus with the highest sensitivity to update DG parameters until the stopping criteria are met.

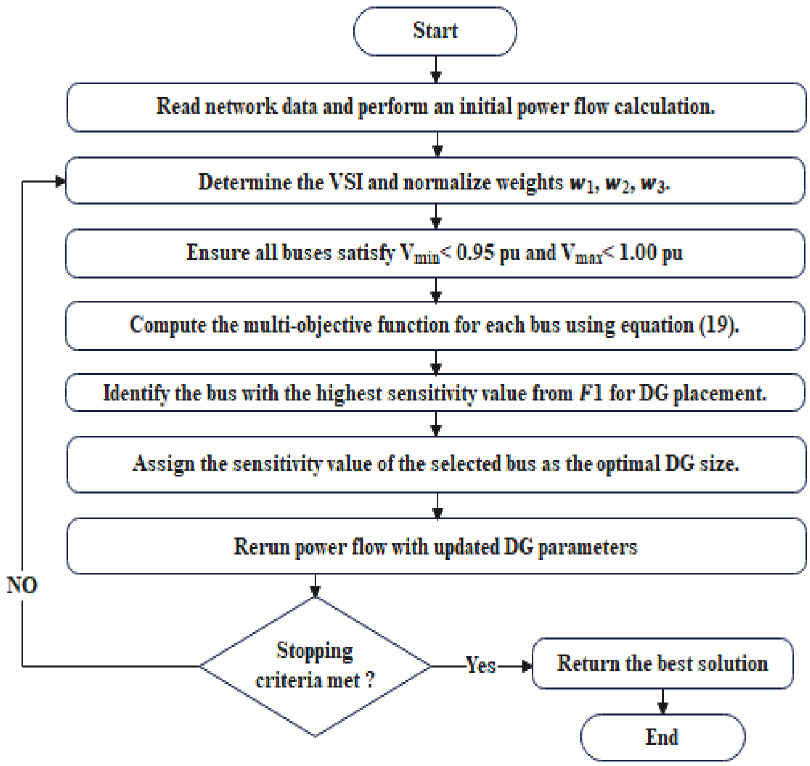

Figure 2. Step-by-step flowchart for optimal DG placement and sizing

Boundary and optimization constraints: The system must meet certain conditions to ensure stability and feasibility: voltage limits:

$$V\_min \leq V\_k \leq V\_max \quad (24)$$

The value of V_{min} is set to 0,95 p.u., and the value of V_{max} is 1.05 p.u. Power balance equations:

$$\begin{cases} \sum P_{load} = P_{DG} + P_{grid} + P_{loss} \\ \sum Q_{load} = Q_{DG} + Q_{grid} + Q_{loss} \end{cases} \quad (25)$$

DG power limits are given by (26).

$$\begin{cases} 0 \leq P_{DG} \leq \sum(P_{load}) - P_{grid} \\ 0 \leq Q_{DG} \leq \sum(Q_{load}) - Q_{grid} \end{cases} \quad (26)$$

Loss reduction with DG integration: The percentage reduction in power losses due to DG integration is calculated as (27).

$$\Delta P(\%) = \frac{\Delta P_{Loss\ without\ DG} - \Delta P_{Loss\ with\ DG}}{\Delta P_{Loss\ without\ DG}} . 100 \quad (27)$$

4. SIMULATION RESULTS

The proposed DG optimization methodology is validated on the standard IEEE 33-bus RDS [23]. The performance is evaluated under two scenarios: base case analysis: The initial network state without DG integration, establishing baseline voltage profiles, current flow, and total power losses. Optimized DG integration: The network state after implementing the optimal DG placement and sizing strategy from section 3, demonstrating the achieved performance improvements.

4.1. Analysis of results without DG

The initial network state was assessed without DG, revealing critical voltage issues. As shown in Figure 3, 21 buses exhibited voltages below 0.95 p.u. threshold, with the lowest value of 0.9174 p.u. at bus 18. This underscores a significant need for voltage support. Figure 4 illustrates the voltage deviations across the methods, demonstrating the superior performance of the direct method in maintaining voltages within an acceptable range.

Figure 5 illustrates the branch currents in the network, showcasing the current distribution across different lines. The DA gives a more balanced current profile which proves that the method is intended for the radial network. Figures 6 and 7 display the active and reactive power losses before DG integration.

The results show significant losses across the network, further emphasizing the need for DG placement to improve overall efficiency. Table 1 presents a comprehensive comparison of the three methods concerning power losses, along with the voltage levels recorded before the integration of DG. The results show that the DA method surpasses the other two methods by achieving the lowest total power losses in the network and maintaining higher minimum voltage levels.

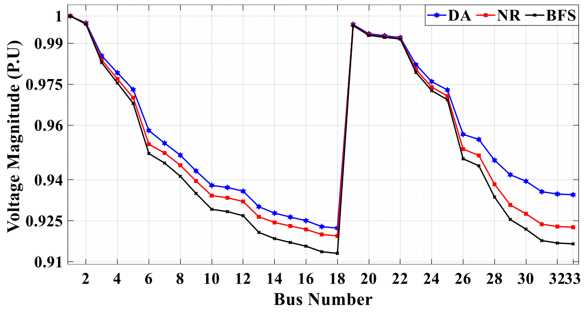

Figure 3. Voltage profile before DG integration

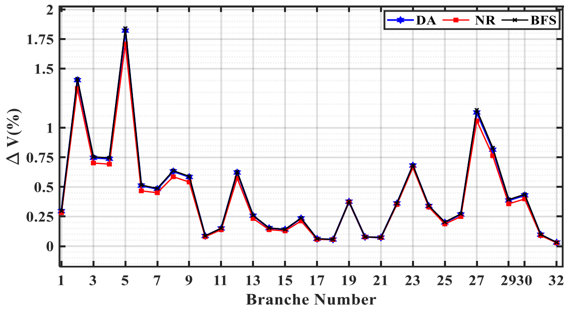

Figure 4. Voltage drop profile without DG

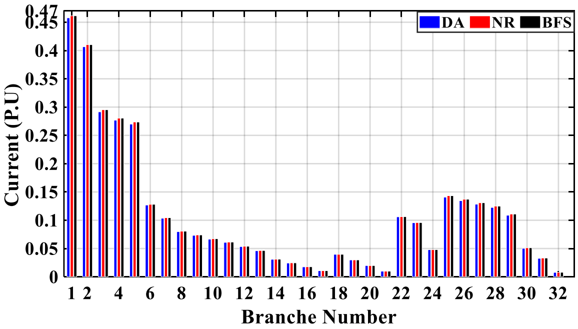

Figure 5. Currents in the branches without DG

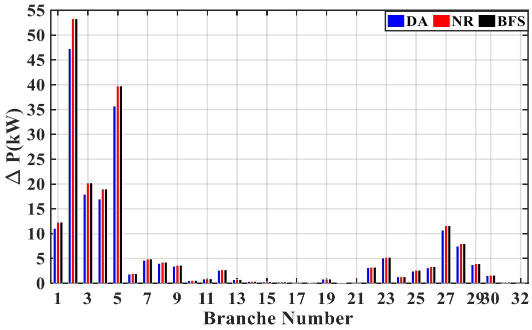

Figure 6. Active power losses without DG

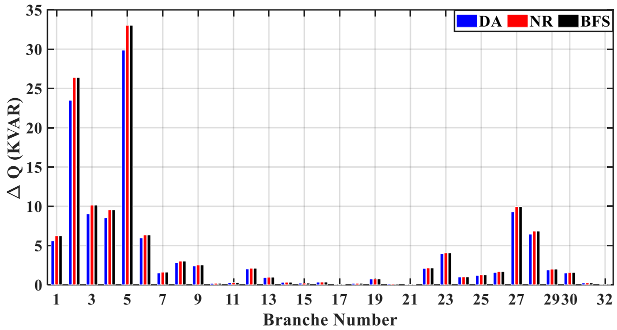

Figure 7. Reactive power losses without DG

Table 1. Comparative analysis between the methods treated without DG

Selected method	DA	NR	BFS
Vmax (p.u.)	1	1	1
Vmin (p.u.)	0.92233	0.91309	0.91309
Total active power loss (kW)	188.0873	207.1485	207.1485
Total reactive power loss (kVAR)	123.7433	135.0796	135.0796

4.2. Analysis of results with optimal DG

The simulation results in Figure 8 demonstrate the complementary roles of the VSI and LSF in optimizing DG placement. While each index provides weighting factors for bus selection, their effectiveness in determining the optimal DG size depends on the applied constraints. The combined VSI-LSF approach, however, offers a more accurate assessment of both location and capacity, thereby improving the reliability of DG allocation. It is also observed that bus 6 records the highest sensitivity value (0.26), marking it as a critical node for voltage stability. Identifying such vulnerable points is essential for strengthening network resilience and supporting effective DG integration strategies.

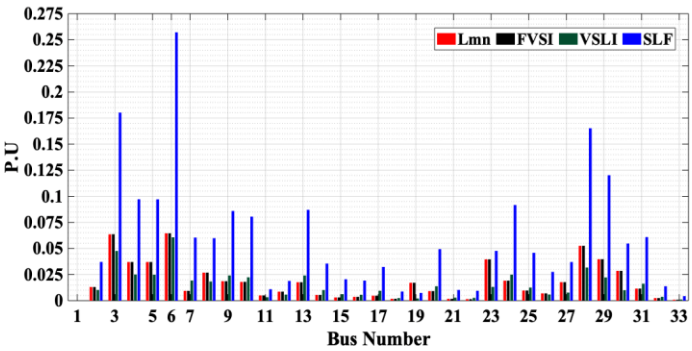

Figure 8. Voltage stability indices (VSI) in the optimization process

Figure 9 further validates the optimization approach by illustrating the impact of DG integration on power losses. At a 70% penetration rate, active power losses decrease to 60 kW, and reactive power losses to 47 kVAR, demonstrating a substantial improvement in network efficiency. These findings emphasize the importance of a well-structured multi-objective optimization strategy, where the combined use of VSI and LSF leads to a more effective and cost-efficient DG implementation. As determined by the procedure in section 3.2, bus 6 was confirmed as the optimal location for DG. Its integration yielded a 4.5% reduction in voltage drops (Figure 10), a 69.23% integration rate, and a substantial reduction in power losses, over 68% for the proposed method and 65% for the others, demonstrating the high efficiency of the proposed methodology.

Figures 11 and 12 highlight the substantial reduction in active and reactive power losses across the branches after DG integration. Additionally, Figure 13 reveals changes in both the intensity and direction of current flow within the network. Specifically, the direction of current flow is reversed in branches 3, 4, and 5, while the current intensity is significantly reduced in branches 1 and 2. These changes reflect the positive impact of DG placement at the optimal location, contributing to improved overall network efficiency. Figure 14 highlights the optimal power losses and the adjusted integration rate according to location, demonstrating the effectiveness of the selected multi-objective function, which balances three criteria: total system losses and the integration rate, both influenced by DG location.

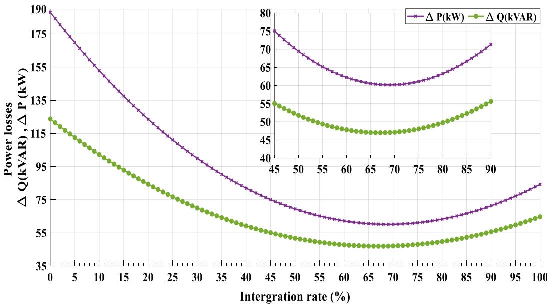

Figure 9. Total active and reactive power losses as a function of the integration ratio

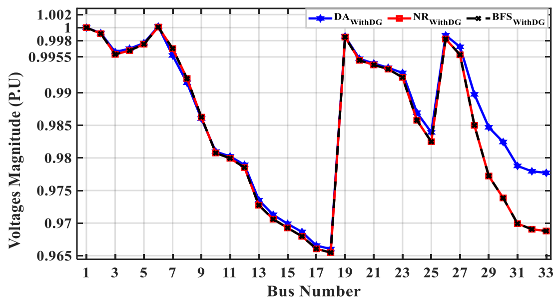

Figure 10. Voltage profile with DG

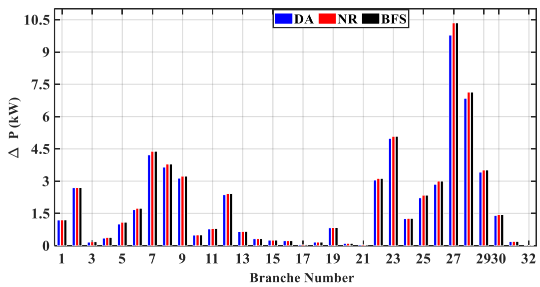

Figure 11. Active power losses with DG

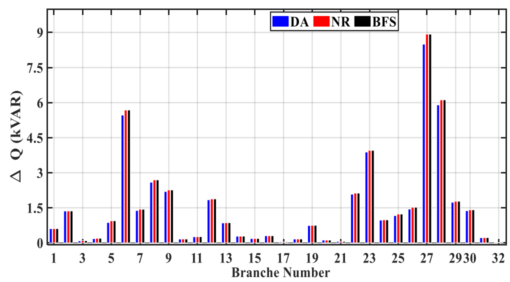

Figure 12. Reactive power losses with DG

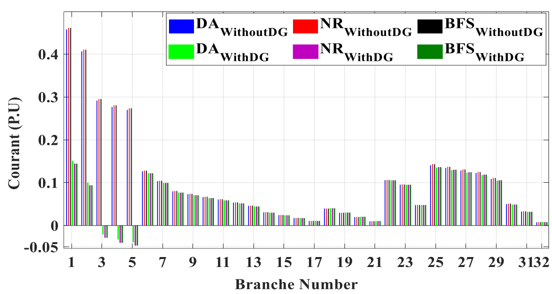

Figure 13. Current flow without and with DG

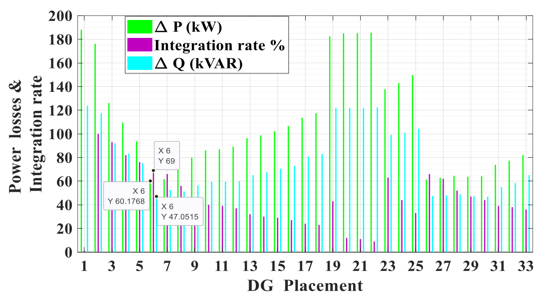

Figure 14. Total power loss and integration rate depending on the location of the DG

The effectiveness of $F1$ for optimizing DG integration is summarized in Table 2. All methods result in the same DG location (bus 6) and produce very similar voltage profiles, ensuring stability across the network. The DA shows a slightly lower DG integration rate (69.23%) compared to the NR and BFS methods, both of which achieve the maximum integration rate (70.47%). However, the DA is the most effective at reducing power losses, as it more efficiently lowers both active and reactive power losses.

Table 2. Benchmark analysis of methods with DG

Method chosen	DA	NR	BFS
DG location	6	6	6
Vmax (p.u.)	1.00143	1.0012	1.0012
Vmin (p.u.)	0.96732	0.96664	0.96664
Integration rate	69.232	70.467	70.467
DG size (MW)	2.572	2.618	2.618
Loss reduction %	68.0048	65.982	65.982
Total active power losses (kW)	60.17	62.33	62.33
Total reactive power losses (kVAR)	47.06	48.63	48.63

5. COMPARATIVE EVALUATION OF THE PROPOSED VSI-LSF METHOD

The proposed hybrid VSI-LSF method is benchmarked against 15 established algorithms for DG placement and sizing on the IEEE 33-bus system. The comparison in Table 3 evaluates four key metrics, power loss reduction, location consistency, sizing optimality, and operational robustness, demonstrating VSI-LSF's performance relative to the state of the art. The VSI-LSF method achieves a 68% reduction in active power losses with a 69.18 % integration rate using a single, optimally-sized DG unit (2.57 MW at bus 6). Other methods, such as ant colony optimization (ACOA, 80.73%) and Jellyfish Search (JS, 94.44%), achieve higher loss reductions but require three DG units, significantly increasing infrastructure and operational costs. As illustrated in Figure 9, the power losses exhibit a parabolic trend with respect to the DG integration rate. Losses decrease up to an optimal penetration level (around 70%) and then begin to rise when this threshold is exceeded. This behavior confirms that excessive DG integration can overload feeders and degrade network performance.

Table 3. Comparing proposed methods with literature methods for the IEEE-33 bus

Method	Optimal location	Size of DG %	Size of DG (MW)	Losses reduction %	Total active power losses (kw)
AD (VSI-LSF)	6	69.18	2.57	68.00	60.17
NR (VSI-LSF)	6	70.25	2.61	65.9	62.33
BFS (VSI-LSF)	6	70.25	2.61	65.9	62.33
I-DBEA [17]	13, 24,30	105.32	3.91	53.21	94.85
MALO [24]	7, 16, 31	85.57	3.18	54.54	92.15
ACOA [25]	7, 24, 30	97.73	3.63	80.73	40.18
ASFLA [12]	24, 29, 12	51.57	1.91	67.00	66.87
IMRFO [23]	6	68.50	2.54	69.70	61.36
Jellyfish search (JS) [11]	13, 24, 30	77.87	2.89	94.44	11.74
PSO [6]	6, 32	58.78	2.18	65.22	71.85
Crayfish optimization algorithm (COA) [3]	7	17.76	0.66	10.18	164.1
PSO [14]	8	43.01	1.59	60.01	84.35
AHA [4]	8, 29, 16	79.32	2.99	83.80	30.30
(I-GWOPSO) [22]	14, 24, 30	78.38	2.91	66.37	70.64
GA [8], [21]	6	69.98	2.60	47.39	111.03
	29, 8, 32	53.83	2.00	62.52	78.92
SMA [14]	7	62.98	2.34	67.30	68.83

The VSI-LSF method accurately identifies the optimal integration point, enabling maximum performance using only a single DG unit. From a protection standpoint, the impact of DG penetration is highly dependent on both the number and placement of the installed units. When a single DG is strategically located, the direction and magnitude of fault currents remain limited and predictable, significantly reducing the likelihood of relay misoperation. Conversely, deploying multiple DG units increases the aggregate fault current contribution and may introduce bidirectional power flows. This condition often leads to protection blinding, false or nuisance tripping, and sympathetic tripping, thereby complicating coordination schemes and compromising protection reliability.

A key strength of VSI-LSF is its consistency in identifying the optimal DG location that balances voltage stability, power losses, and protection coordination. It uniquely selected bus 6 across all scenarios, a result confirmed by sensitivity indices. While methods like IMRFO also converged on bus 6, they achieved lower loss reductions (69.70%). Multi-DG approaches, including I-DBEA, AHA, and I-GWOPSO, demonstrated poor consistency, proposing variable and sub-optimal bus combinations (e.g., 13–24–30 or 14–24–30), which complicates planning and reduces practical applicability.

In summary, the hybrid VSI-LSF method offers an economically efficient and operationally robust framework for DG integration. It achieves substantial loss reduction with a single, cost-effective unit, simplifies grid protection, and ensures consistent siting accuracy by explicitly accounting for the network's parameters and topology. These features position VSI-LSF as a reliable and practical solution for modern distribution system planning.

6. CONCLUSION

This study presented a hybrid optimization approach for the optimal placement and sizing of DG units in medium-voltage radial distribution systems. By integrating weighted sensitivity indices into a multi-objective framework, the proposed method achieves a balanced trade-off among loss reduction, voltage stability, and renewable energy integration. Simulation results demonstrate that the approach enhances voltage profiles, reduces active power losses, and improves both stability and loadability, while maintaining high computational efficiency compared with existing techniques. Future research could extend this framework to incorporate dynamic operating conditions, fault and protection coordination, and uncertainty modeling of renewable energy sources. Furthermore, integrating electric vehicle charging effects and real-time adaptive control strategies would enhance the robustness and applicability of the method to next-generation smart distribution networks.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request. The research is based on computer simulations of the standard IEEE 33-bus radial distribution test system, a well-established public benchmark in power systems research [23].

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