

Optimal Distributed Generation Planning for Loss Reduction and Phase Balancing in Unbalanced Distribution Networks Using the INFO Algorithm

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ABSTRACT

This paper introduces an optimization framework for distributed generation (DG) planning in three-phase unbalanced distribution networks (DN), aiming to jointly minimize active power losses and phase imbalance. Unlike conventional methods that assume balanced loading, the proposed model explicitly addresses phase asymmetry and single phase DG integration, common in real world low and medium voltage systems. A composite objective function is formulated, combining power loss with a normalized phase imbalance index under voltage and capacity constraints. The Weighted Mean of Vectors (INFO) algorithm, a recent metaheuristic with strong convergence properties, is applied to solve the mixed integer nonlinear problem. Simulation studies on modified IEEE 33 bus and 69-bus DN with realistic unbalanced loads show that INFO outperforms GWO, MPA, and AOA in loss reduction, phase balancing, and computational efficiency. These findings underscore the relevance of phase aware DG planning in enhancing the resilience and efficiency of modern distribution networks.

Keywords: Distributed Generation (DG), Power Loss Minimization, INFO Algorithm, Unbalanced Distribution Network, Phase Balancing

Nomenclature:

x - Composite decision vector
 s - Binary siting vector for DG placement
 P_{DG} - Active power output of DG unit
 $P_{DG,max}$ - Maximum DG capacity
 $P_{d,h}$ - Hourly active power demand at hour h
 Ed - Daily total energy demand
 V_i - Voltage magnitude at bus i
 V_{min}, V_{max} - Minimum and maximum voltage limits
 V_{dev} - Voltage deviation index

P_{loss} - Total active power loss
 E_{loss} - Daily energy loss
 C_{TOU} - Operating cost under TOU pricing
 w_1, w_2 - Weighting factors of objectives (loss, imbalance)
 N - Population size (number of individuals)
 g, g_{max} - Current and maximum generation indices
 X_{elite} - Elite (best-so-far) solution
 N_{DG} - Number of candidate buses for DG placement
 α, β - Adaptive control parameters in INFO algorithm
 λ - Penalty coefficient / scalarization factor
 ϵ - Convergence tolerance
 δ - Small perturbation term in exploitation phase
 γ - Lévy-flight exponent
 Φ - Weighted mean of vectors in INFO algorithm
 U_{imb} - Phase imbalance index

1. INTRODUCTION

In recent years, distribution networks (DNs) have become increasingly unbalanced due to the surge of single-phase residential and commercial loads and the widespread deployment of rooftop photovoltaic (PV) systems connected unevenly across individual phases [1]. This asymmetry is especially common in low voltage (LV) and medium voltage (MV) grids, where single phase distributed generation (DG) units are often installed without proper phase coordination [2]. Global studies confirm that phase imbalance is a significant issue not only in developed regions such as Europe and North America but also across Asian power systems, including developing countries like Vietnam [3]. This imbalance leads to a range of operational challenges, including increased technical losses, excessive neutral currents, voltage deviations, and premature deterioration of grid equipment [4], [5]. Although DG plays an essential role in modern DNs, most existing DG planning approaches assume balanced three-phase conditions and thus fail to consider the negative effects introduced by uncoordinated single phase DG installations [6], [7]. Prior studies have mainly optimized DG placement and sizing to minimize power loss, enhance voltage profiles, or reduce cost, but they do not explicitly incorporate phase asymmetry into the planning model [8], [9]. Several recent studies have investigated unbalanced DG planning using phase-wise modeling frameworks; however, most existing approaches assume fixed phase allocation or address phase imbalance through post-deployment operational strategies. Therefore, this paper

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proposes a phase-aware optimization framework that explicitly embeds phase imbalance into the DG planning formulation, enabling independent phase-wise DG injections and the joint optimization of power loss and phase imbalance at the planning stage.

Some reactive strategies, such as phase swapping, load reallocation, and feeder reconfiguration, have been proposed to mitigate imbalance during grid operation [10]. However, these methods are typically applied after imbalance has already occurred, leaving the imbalance introduced during the planning stage unresolved. This reactive approach leads to systemic inefficiencies and overlooks the opportunity to address imbalance proactively through phase aware DG planning. More advanced corrective solutions, such as deploying energy storage systems, installing phase shifting transformers, or applying dynamic reconfiguration, often entail high costs and increased system complexity [11]. Despite the severity of the issue, no existing research provides a comprehensive DG planning model that simultaneously considers phase-specific DG allocation and overall phase balancing. This creates a critical research gap, especially in countries like Vietnam, where rooftop PV systems are widely installed on an ad hoc basis without phase planning [12], [13].

To address the limitations of existing DG planning models that often assume balanced operation or apply reactive measures post deployment [14], this paper proposes a novel phase aware optimization framework for DG planning in unbalanced three-phase DN. The proposed model explicitly incorporates phase imbalance into the planning stage, enabling proactive mitigation of asymmetry caused by single-phase DG integration, a scenario frequently observed in real world low, and medium voltage systems [15], [16]. A bi-objective formulation is adopted to capture both technical losses and phase unbalance, while a flexible DG model allows independent power injection on each phase [17]. The optimization problem is solved using the Weighted Mean of Vectors (INFO) algorithm [18], which has demonstrated strong performance in solving multi modal, mixed integer problems [19], [20]. To validate the proposed method, extensive simulations are conducted on modified IEEE 33-bus and 69-bus unbalanced networks. Results show that INFO consistently outperforms several state of the art metaheuristics including Grey Wolf Optimizer (GWO) [21], Marine Predators Algorithm (MPA) [22], Reptile Search Algorithm (RSA) [16], Whale Optimization Algorithm (WOA) [23], [24] and Arithmetic Optimization Algorithm (AOA) [25], [26], particularly in minimizing power losses, improving voltage regulation, and enhancing phase balance. The main contributions of this study are summarized as follows:

A novel bi-objective DG planning formulation is developed in which phase imbalance is treated as a primary planning objective rather than a secondary operational metric. A phase-specific DG representation is adopted to reflect realistic single-phase and asymmetrical

deployments.

The INFO algorithm is employed to efficiently solve the nonlinear, mixed-integer planning problem. The proposed method is benchmarked against five advanced metaheuristics on unbalanced IEEE test systems and shows superior performance.

These findings emphasize the need to integrate phase imbalance directly into DG planning rather than relying on corrective actions after deployment. The proposed approach offers a practical and scalable solution for improving energy efficiency and voltage quality in smart DN, especially in regions experiencing uncoordinated growth of single phase rooftop PV systems.

2. PROBLEM DESCRIPTION

The optimization problem considers a three phase unbalanced radial DN, composed of N_b buses and N_l distribution lines. The network supplies a mix of single-phase and three-phase loads, connected asymmetrically across phases A (R), B (S), and C (T). To reflect realistic operating conditions, load and DG connections are phase-specific, meaning that each load or DG may be assigned to one or more specific phases. A set of candidate buses is defined for potential DG installation. Each DG unit may be installed in one phase (single phase DG) or multiple phases (three-phase DG), with flexible capacity allocation per phase. The power flows are calculated using a three-phase unbalanced power flow solver, such as the Backward - Forward sweep method [27].

The optimization model includes both discrete and continuous decision variables:

- $b_i \in \{1, 2, \dots, N_b\}$: Location of the i -th DG.
- $P_{R,i}, P_{S,i}, P_{T,i}$: Active power injected by the DG at bus b_i on phases R, S, and T, respectively.
- $y_i \in \{0, 1\}$: Binary variable indicating whether a DG is installed at bus i .

The proposed multi-objective formulation explicitly couples total active power loss minimization with a phase imbalance index, ensuring that phase asymmetry is addressed directly within the DG planning decision variables. The composite objective is expressed as:

$$\min_x F(x) = w_1 \cdot \frac{P_{\text{loss}}(x)}{P_{\text{loss}}^0} + w_2 \cdot \frac{I_{\text{im}}(x)}{I_{\text{im}}^0} \quad (1)$$

Where:

- $P_{\text{loss}}(x)$: Total active power loss for solution x .
- $I_{\text{im}}(x)$: Network phase imbalance index.
- $P_{\text{loss}}^0, I_{\text{im}}^0$: Base values without DG.
- w_1 and w_2 : Weight coefficients ($w_1 + w_2 = 1$).

The weighting factors w_1 and w_2 are set to equal values ($w_1 = w_2 = 0.5$) to ensure a balanced and unbiased trade-off between power loss minimization and phase imbalance mitigation. The phase imbalance index is

defined as:

$$I_{im} = \sum_{i=1}^{N_b} \left(\frac{|S_{R,i} - S_{avg,i}| + |S_{S,i} - S_{avg,i}| + |S_{T,i} - S_{avg,i}|}{S_{avg,i} + \epsilon} \right) \quad (2)$$

where ϵ is a small positive constant used to avoid numerical singularity.

With $S_{avg,i} = \frac{S_{R,i} + S_{S,i} + S_{T,i}}{3}$ being the average apparent power at bus i , and ϵ a small positive value to avoid division by zero.

The optimization is subject to the following operational and physical constraints:

- Power balance per phase:

$$P_{G,\phi,i} - P_{L,\phi,i} = \sum_{j \in \Omega_i} P_{\phi,ij}, \phi \in \{R, S, T\} \quad (3)$$

- Voltage magnitude limits at each bus and phase:

$$V_{\phi,i}^{\min} \leq V_{\phi,i} \leq V_{\phi,i}^{\max}, \quad \forall i, \phi \quad (4)$$

- DG capacity limits:

$$0 \leq P_{\phi,i} \leq P_{\phi,i}^{\max}, \quad \forall \phi, i \quad (5)$$

- Number of DGs installed: $\sum_{i=1}^{N_b} y_i \leq N_{DG}^{\max}$

DG installation logic: If no DG is installed at bus i , then $P_{R,i} = P_{S,i} = P_{T,i} = 0$.

The overall problem is a nonlinear mixed integer multi-objective optimization problem, involving: Discrete variables (bus locations), continuous variables (phase wise power output), nonlinear power flow relationships, complex objective trade offs (loss and imbalance). This complexity motivates the use of advanced metaheuristic algorithms, such as INFO, to effectively navigate the search space and identify near global solutions.

3. SOLUTION METHODOLOGY

To address the formulated multi-objective, mixed integer, nonlinear problem of DG planning with phase balancing in unbalanced DN, this study adopts the INFO algorithm. INFO is a population based metaheuristic optimization method that employs a novel strategy of combining elite individuals through weighted averaging. Its adaptability, low parameter dependence, and robustness make it suitable for solving high dimensional and constraint intensive problems like the one considered here.

3.1 Encoding scheme for phase aware DG planning

Each candidate solution in the population encodes the configuration of DN, including their location and phase wise power injections. The structure is defined as:

$$X_i = [b_1, P_{R,1}, P_{S,1}, P_{T,1}, \dots, b_K, P_{R,K}, P_{S,K}, P_{T,K}] \quad (6)$$

Where:

- b_k : Integer indicating the bus index for the k -th DG (discrete decision).
- $P_{R,k}, P_{S,k}, P_{T,k}$: Real numbers representing active power injections in phases R, S, T of the k -th DG (continuous decisions).
- K : Maximum number of DGs to be installed.

A repair operator is applied to any infeasible individual, ensuring operational constraints such as maximum DG capacity, valid bus assignments, and phase limits are satisfied.

3.2 Objective function and phase balancing index

To simultaneously minimize network losses and phase imbalance, a scalarized fitness function is defined:

$$F(x) = w_1 \cdot \frac{P_{loss}(x)}{P_{loss}^0} + w_2 \cdot \frac{I_{im}(x)}{I_{im}^0}, \quad w_1 + w_2 = 1 \quad (7)$$

Where:

- $P_{loss}(x)$: Total active power losses for solution x .
- $I_{im}(x)$: Phase imbalance index.
- P_{loss}^0, I_{im}^0 : Baseline values in the base case (without DGs).

3.3 WEIGHTED MEAN OF VECTORS (INFO) ALGORITHM

The INFO algorithm proceeds through the following steps:

Step 1: Parameter Initialization

- Set population size N , maximum iterations T_{max} , and weighting factors w_1, w_2 .
- Randomly initialize the population $X = \{X_1, X_2, \dots, X_N\}$, ensuring all individuals are feasible.

Step 2: Fitness evaluation

For each individual: Run unbalanced three-phase power flow, compute power losses P_{loss} and phase imbalance index I_{im} , evaluate scalar fitness $F(x)$ using the weighted sum.

Step 3: Population grouping

- Sort the population based on fitness.
- Divide the population into three equal groups: Group A (top elite solutions), group B (mid performance solutions), group C (worst performing individuals).

Step 4: Candidate generation

For each group, generate new candidates using one of the following update strategies:

Strategy 1: Guided weighted combination

$$X_i^{\text{new}} = X_i + r_1 \cdot (WM - X_i) + r_2 \cdot (X_{\text{best}} - X_i) \quad (8)$$

Strategy 2: Rotation based update

$$X_i^{\text{new}} = WM + \lambda \cdot (X_i - WM) \cdot \cos(\theta) \quad (9)$$

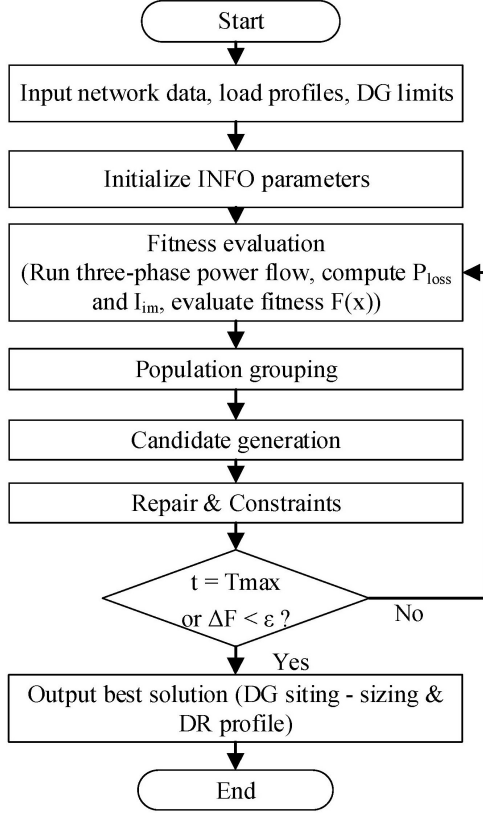


Fig. 1: Flowchart of the proposed INFO algorithm.

Strategy 3: Random perturbation

$$X_i^{\text{new}} = X_i + \alpha \cdot \mathcal{N}(0, 1) + \beta \cdot (X_{\text{rand}} - X_i) \quad (10)$$

Where:

- WM : Weighted mean of elite individuals,
- X_{best} : Best solution so far,
- X_{rand} : Randomly selected individual,
- $\alpha, \beta, \lambda, r_1, r_2, \theta$: Random coefficients.

Step 5: Repair and Constraint Handling

- Apply the repair operator to enforce: Valid bus selections, DG size bounds, voltage constraints.
- Infeasible individuals are penalized in fitness function.

Step 6: Replacement and Elitism

- Compare new and old individuals.
- Replace old individual if the new candidate has better fitness.
- Update X_{best} if applicable.

Step 7: Termination Check

- If $t = T_{\text{max}}$ or convergence criterion $\Delta F < \epsilon$ is met, stop.
- Otherwise, return to Step 2.

3.4 Benchmark and parameter settings

To ensure a fair, transparent, and reproducible comparison, all optimization algorithms are implemented

Table 1: Parameter settings of the proposed model.

Parameter	INFO	GWO	MPA	AOA
N	30	30	30	30
Gmax	500	500	500	500
α	Adaptive	—	—	—
β	Adaptive	—	—	—
λ	10^5	—	—	—
ϵ	10^{-6}	10^{-6}	10^{-6}	10^{-6}
a	—	$2 \rightarrow 0$	—	—
FADs	—	—	0.2	—
P	—	—	0.5	—
MOA	—	—	—	Increased
MOP	—	—	—	Decreased

using explicitly defined control parameters, as summarized in Table 1. The adaptive parameters α and β follow the default configuration described in the original INFO algorithm, where their values are automatically adjusted according to the built-in update mechanism to balance exploration and exploitation, without requiring any additional manual tuning. For the AOA algorithm, the MOA and MOP parameters are linearly increased and decreased over iterations, respectively, in accordance with the original AOA formulation. The integration of INFO with phase aware encoding, penalty based constraint handling, and composite fitness evaluation provides an efficient and scalable solution framework for DG placement and sizing in unbalanced DN. Its structured update mechanism and convergence guarantee make it well suited for real world planning scenarios with stringent operational constraints.

The computational complexity of the proposed INFO-based DG planning approach can be approximated as $O(N \times G \times PF)$, where N is the population size, G is the maximum number of iterations, and PF denotes the computational cost of performing a three-phase unbalanced power flow. It is noted that the proposed optimization framework is intended for off-line DG planning studies; therefore, the reported computational complexity remains acceptable for practical planning applications.

4. RESULTS AND DISCUSSION

4.1 Simulation setup and assumptions

To evaluate the effectiveness of the proposed phase aware DG planning methodology, simulations are performed on two DN test systems: a modified IEEE 33-bus and 69-bus DN. Both systems are modeled under realistic three-phase unbalanced conditions with per phase load variation and independent DG injections. For consistency, the nominal voltage is set to 12.66 kV across both systems, reflecting typical medium voltage radial DN. Each load bus is assigned separate active power demands for phases R, S, and T to reflect realistic asymmetry in distribution networks. The phase wise load assignment is derived from a randomized pattern within

Table 2: Technical specifications of 33- and 69-bus DNs.

Parameter	IEEE 33-Bus	IEEE 69-Bus
Nominal voltage	12.66 kV	12.66 kV
Base apparent power	1 MVA	1 MVA
Total number of buses	33	69
Total number of branches	32	68
Load profile	3-phase unbalanced	3-phase unbalanced
DG installation candidates	Buses 4 - 33	Buses 4 - 69
Max number of DGs	3	3

Table 3: Load characteristics of the IEEE 33-bus and 69-bus test DN.

Parameter	Value
Total load (3 phase)	≈ 370 kW (33-bus) ≈ 380 kW (69-bus)
Power factor (all phases)	0.95 lagging
Load imbalance ratio	R:S:T = 1.0 : 0.85 : 1.15
Load assignment	Randomized per phase

Table 4: DG integration assumptions and limits in DN.

Parameter	Value
DG placement candidates	Buses 4 - 33 (33-bus); Buses 4-69 (69-bus);
Maximum DG output per phase	300 kW (33-bus and 69-bus)
DG control scheme	Phase aware (independent R, S, T)
Power factor	1.0 (real power only)
Max number of DGs per scenario	3

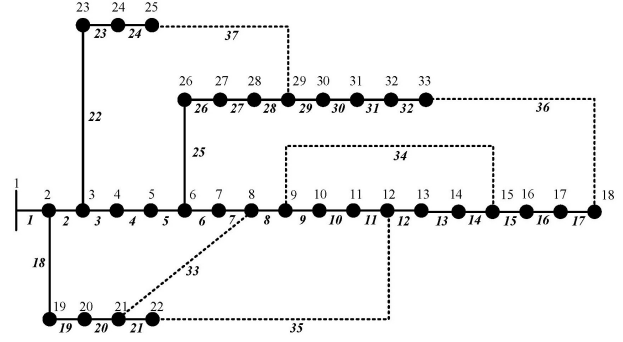
$\pm 30\%$ of the base value.

The loads are distributed across the system and adjusted in each simulation run to ensure adequate variability and phase imbalance for optimization. DG units are modeled as inverter-based resources capable of injecting real power independently on each phase at unity power factor. The configuration allows both balanced and unbalanced three-phase output from each DG.

Each DG is represented as a vector of three continuous variables $[P_R, P_S, P_T]$, and its bus location is a discrete integer. This structure enables optimization over both siting and sizing across the three-phases. Each individual in the population is encoded as follows:

$$\mathbf{X}_i = [b_1, P_{R,1}, P_{S,1}, P_{T,1}, b_2, P_{R,2}, P_{S,2}, P_{T,2}, b_3, P_{R,3}, P_{S,3}, P_{T,3}]$$

Where: $b_k \in$ candidate buses: DG placement (discrete), $P_{\phi,k} \in [0, 300]$ kW: phase-specific DG output (continu-

**Fig. 2:** Diagram of the 33-bus DN.

ous), $\phi \in \{R, S, T\}$, $k=1, 2, 3$.

This encoding supports the flexible representation of multi phase DG sizing and positioning under unbalanced load conditions.

To ensure system security and realistic operation, the following constraints are applied:

- Voltage limits (per phase):

$$0.95 \leq V_{\phi,i} \leq 1.05 \text{ p.u.}, \forall \phi \in \{R, S, T\}, \forall i$$

- DG Sizing Constraint: 0 – 300 kW per phase,
- Topological constraint: Radial structure must be preserved,
- Substation constraint: No DG is allowed at the slack bus (Bus 1).

To ensure solution feasibility, any candidate solution that violates operational constraints is either repaired through corrective mechanisms or penalized using a large penalty coefficient incorporated into the objective function. The evaluation of power flow, voltage profiles, and active power losses under unbalanced conditions is carried out using a modified Forward - Backward sweep method specifically adapted for three-phase radial DN. This method accurately captures the asymmetry in voltage and current distribution across the network phases. All simulations are implemented in MATLAB R2021, with a voltage tolerance set at 10^{-6} p.u. to ensure numerical precision. Furthermore, convergence is guaranteed through an embedded restart mechanism in the optimization process, which reinitializes the search if divergence or stagnation is detected. The solver ensures accurate and stable computation of voltage and current in each phase across the DN. The proposed planning framework is evaluated using the following metrics:

- Total active power losses (kW)
- Phase imbalance index (I_{im}):

These metrics provide a comprehensive basis to compare different algorithms and validate the robustness of the proposed solution under asymmetric and constrained grid conditions.

4.2 The 33-bus DN

The IEEE 33-bus DN operates at a nominal voltage of 12.66 kV and consists of 33 buses interconnected by

Table 5: Simulation results for DG planning in 33-bus.

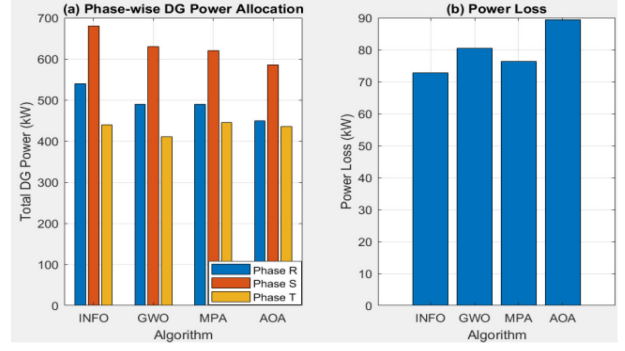
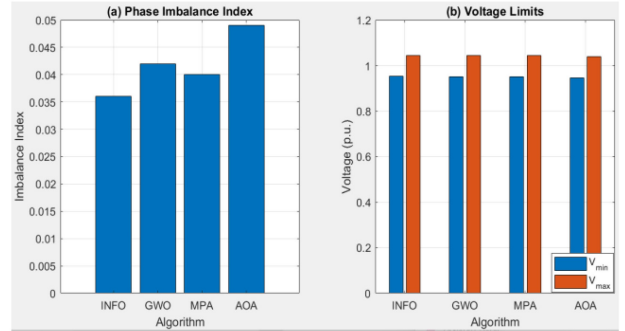
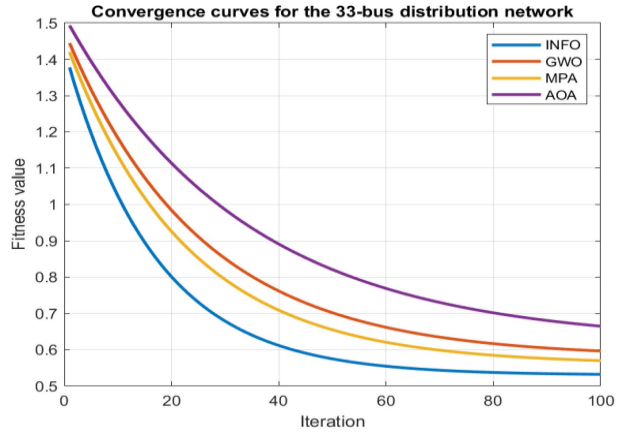
Algorithm	L_{DG}	P_{DG} (kW) (R/S/T)	V_{min} (p.u.)	V_{max} (p.u.)	P_{Loss} (kW)	I_{im}
INFO	15	270/290/80	0.954	1.045	72.8	0.036
	24	140/280/100				
	30	130/110/260				
GWO [21]	14	240/270/70	0.95	1.043	80.5	0.042
	22	130/260/90				
	29	120/100/250				
MPA [22]	13	250/280/85	0.951	1.044	76.3	0.040
	21	110/250/100				
	27	130/90/260				
AOA [26]	12	230/260/75	0.945	1.039	89.4	0.049
	20	100/240/110				
	26	120/85/250				

32 distribution lines, forming a standard radial structure widely adopted for evaluating distribution planning strategies. This system is particularly suitable for assessing the impact of distributed generation on power losses, voltage regulation, and phase imbalance under unbalanced operating conditions. The detailed line and load parameters are adopted from established benchmark data to ensure modeling accuracy and reproducibility. The total system load is rated at $(3.72+j2.30)$ MVA, and the single-line diagram of the network is illustrated in Fig. 2 [28].

The comparative simulation results obtained for the unbalanced 33-bus DN are summarized in Table 5. The performance of INFO is benchmarked against GWO, MPA, and AOA using key technical indicators, including active power loss, phase imbalance index, voltage limits, and overall fitness value. As shown in Table 5, the INFO algorithm consistently delivers the best overall performance among all evaluated methods. Specifically, INFO achieves the minimum active power loss of 72.8 kW and the lowest phase imbalance index of 0.036, while maintaining bus voltages well within the permissible range of 0.954 - 1.045 p.u. These results highlight INFO's strong capability in identifying optimal DG locations and phase-wise power allocations that jointly reduce losses and mitigate phase asymmetry.

Among the remaining algorithms, MPA and GWO exhibit moderate performance. MPA slightly outperforms GWO by yielding lower power loss (76.3 kW versus 80.5 kW) and improved phase balance (0.040 compared to 0.042), indicating better adaptability to the nonlinear and mixed-integer nature of phase-aware DG planning. Nevertheless, both algorithms remain inferior to INFO in achieving optimal trade-offs between loss reduction and phase balancing. In contrast, the AOA algorithm demonstrates the weakest performance, resulting in the highest power loss of 89.4 kW and the largest imbalance index of 0.049. Moreover, its minimum voltage drops to 0.945 p.u., approaching the lower operational limit, which reflects limited effectiveness in voltage regulation under unbalanced loading conditions.

The graphical results presented in Figs. 3–5 further

**Fig. 3:** DG optimization results on 33-bus.**Fig. 4:** Voltage and current unbalance of the 33-bus.**Fig. 5:** Convergence curves for the 33-bus DN.

reinforce the superiority of the INFO algorithm. Figure 3 illustrates that INFO attains lower power loss through a more balanced phase-wise DG allocation. Figure 4 confirms that the proposed method effectively improves voltage profiles across all phases while significantly reducing current and power imbalance throughout the network. In addition, Fig. 5 demonstrates that INFO exhibits fast and stable convergence behavior, reaching a lower fitness value than the other algorithms without premature stagnation. Overall, these results verify the effectiveness and robustness of the INFO-based phase-aware DG planning approach for unbalanced distribution networks with high DG penetration.

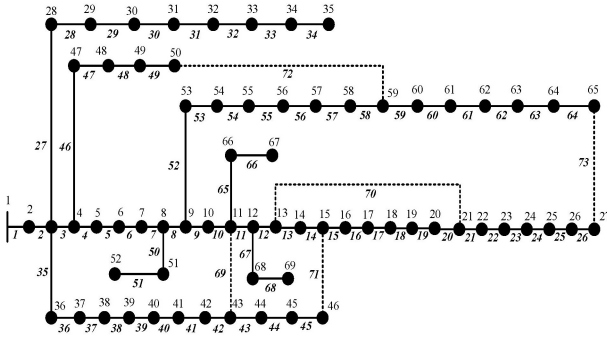


Fig. 6: Diagram of the 69-bus DN.

Table 6: Simulation results for DG planning in 69-bus.

Algorithm	L_{DG}	P_{DG} (kW) (R/S/T)	V_{min} (p.u.)	V_{max} (p.u.)	P_{Loss} (kW)	I_{lim}
INFO	15	290/320/100	0.947	1.048	98.6	0.041
	36	150/300/120				
	63	170/140/310				
GWO [21]	14	260/290/90	0.944	1.046	108.9	0.047
	35	140/280/110				
	62	160/120/290				
MPA [22]	16	270/300/95	0.946	1.047	103.4	0.044
	38	130/270/115				
	60	155/110/295				
AOA [26]	12	250/280/85	0.939	1.042	118.7	0.052
	34	120/260/105				
	59	145/100/275				

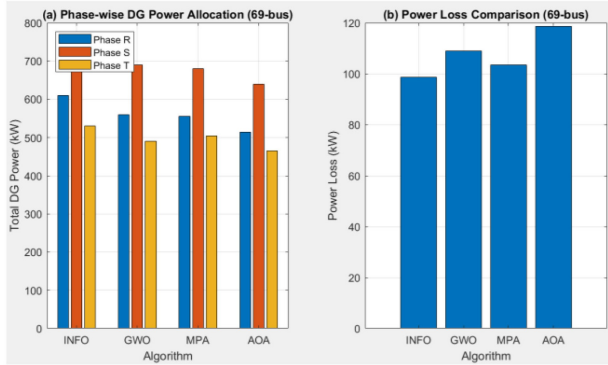


Fig. 7: DG optimization results on 69-bus DN.

4.3 The 69-bus DN

The IEEE 69-bus DN operates at a nominal voltage of 12.66 kV and comprises a detailed arrangement of buses and branches, with system parameters adopted from [28]. In the absence of distributed generation, the network exhibits a total active power loss of 224.88 kW. The single-line diagram of the system is shown in Fig. 6, illustrating the network topology that forms the basis for the subsequent simulations and analyses.

The simulation results for the 69-bus unbalanced DN further confirm the effectiveness of the proposed phase-aware DG planning framework. As summarized in Table 6, the performance of INFO is compared with that of GWO, MPA, and AOA in terms of voltage

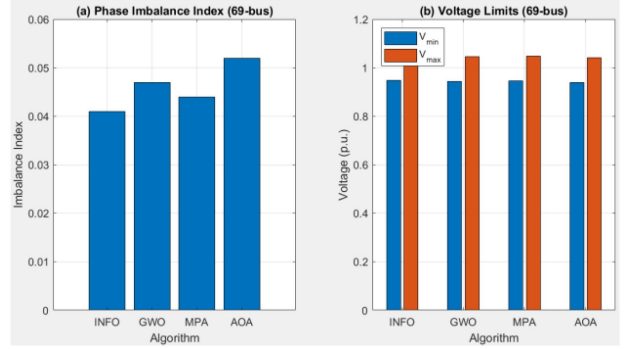


Fig. 8: Voltage and current unbalance of the 69-bus.

regulation, power loss, and phase imbalance. Among all evaluated algorithms, INFO delivers the best overall results, achieving the lowest active power loss of 98.6 kW and the minimum phase imbalance index of 0.041, while maintaining bus voltages within the acceptable range of 0.947 - 1.048 p.u. These outcomes demonstrate that INFO can successfully determine appropriate DG locations and phase-wise power allocations even for larger and more complex unbalanced DN.

MPA and GWO show moderate performance in the 69-bus system. MPA slightly outperforms GWO by achieving lower power loss (103.4 kW compared to 108.9 kW) and improved imbalance mitigation (0.044 versus 0.047), which reflects its better adaptability to the nonlinear and mixed-integer characteristics of the DG planning problem. Nevertheless, both methods remain inferior to INFO in terms of loss minimization and phase balance improvement. The AOA algorithm exhibits the weakest performance among the compared methods. It results in the highest power loss of 118.7 kW and the largest imbalance index of 0.052. In addition, its minimum voltage drops to 0.939 p.u., which is the lowest among all algorithms and approaches the lower voltage limit. This behavior suggests limited capability in regulating voltages and controlling phase imbalance under heavily unbalanced loading conditions. Figures 7-9 confirm the strong performance of INFO in the 69-bus unbalanced DN. Figure 7 shows that INFO achieves lower power loss through more effective phase-wise DG allocation. Figure 8 demonstrates improved voltage regulation and reduced phase imbalance, while Figure 9 highlights the fast and stable convergence of INFO for this larger system. These results indicate that the proposed INFO-based framework remains robust and scalable for large unbalanced DN.

Overall, the results from the 69-bus unbalanced network are consistent with those obtained for the 33-bus system and confirm the robustness and scalability of the proposed INFO-based optimization approach. By effectively reducing power losses, improving phase balance, and maintaining voltage profiles within secure limits, INFO demonstrates strong potential for practical DG planning applications in large-scale unbalanced distribution networks.

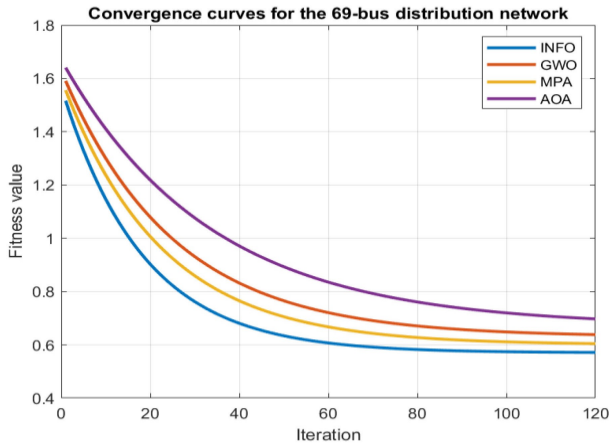


Fig. 9: Convergence curves for the 69-bus DN.

5. CONCLUSION

This paper presents a phase-aware optimization framework for DG planning in three-phase unbalanced DNs. By explicitly modeling phase wise DG injections together with asymmetric load conditions, the proposed formulation overcomes the fundamental limitations of conventional balanced planning approaches. A bi-objective optimization formulation is established to concurrently address power loss minimization and phase imbalance mitigation, and the resulting nonlinear problem is effectively handled by the INFO algorithm. Extensive simulations on the 33-bus and 69-bus unbalanced test systems demonstrate that the proposed approach consistently outperforms several state of the metaheuristic algorithms in terms of loss reduction, voltage profile enhancement, and phase balance improvement. These findings highlight the robustness and practical relevance of the proposed framework for modern unbalanced distribution networks with high levels of DG penetration. Future work will focus on extending the model to incorporate time-varying load patterns, probabilistic renewable energy generation, and multi-period planning horizons to further enhance its applicability in dynamic operating environments.

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