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Optimal placement and sizing of distributed generation units in distribution networks using an enhanced particle swarm optimization framework

Introduction. *Optimal planning of distributed generation (DG) units is a critical research topic due to the growing integration of renewable energy and the need to enhance distribution network performance. Classical optimization methods often struggle with the nonlinear, nonconvex, and highly coupled nature of DG allocation problems.* ***Problem.*** *The IEEE 33-bus distribution network experiences significant voltage drops and high active and reactive power losses under normal operating conditions. Determining the optimal placement and sizing of DG units is a complex problem involving multiple interacting variables and operational constraints.* ***Goal.*** *This study aims to improve technical performance by minimizing total active power losses and voltage deviation while ensuring voltage stability and network reliability.* ***Methodology.*** *The particle swarm optimization (PSO) algorithm is enhanced using the Dehghani method (DM) – a population-based modification framework allowing all individuals, including the worst member, to contribute in improving the best solution. The improved PSO-DM algorithm is applied to the IEEE 33 bus system under four cases: the base case without DG and scenarios with 2, 3 and 4 DG units. The objective function includes active power loss minimization and total voltage deviation.* ***Results.*** *The 4-DG configuration significantly improves system performance: active power losses decrease from 210.67 kW to 53.9 kW (74.4 % reduction), reactive losses drop from 142.84 kVAr to 38.42 kVAr (73.1 % reduction), the minimum bus voltage rises from 0.9037 to 0.9741 p.u. and total voltage deviation decreases from 1.8037 p.u. to 0.5129 p.u. (71.6 % improvement). These results demonstrate that PSO-DM effectively balances exploration and exploitation, yielding superior DG allocation solutions.* ***Scientific novelty.*** *Integrating DM into PSO introduces a cooperative solution-refinement mechanism that enhances convergence speed and search accuracy.* ***Practical value.*** *The PSO-DM framework provides a reliable and computationally efficient tool for DG planning in modern smart distribution networks.* References 22, tables 1, figures 3.

Key words: **distributed generation, particle swarm optimization, Dehghani method, voltage deviation, power loss minimization, distribution networks.**

Вступ. *Оптимальне планування установок розподіленої генерації (DG) є критично важливою темою дослідження через зростаючу інтеграцію відновлюваної енергетики та необхідність підвищення продуктивності розподільчої мережі. Класичні методи оптимізації часто мають проблеми з лінійністю, опуклістю та сильно пов'язаною проблемою розміщення DG.* ***Проблема***. *Розподільна мережа з шинами IEEE 33 зазнає значних падінь напруги та високих втрат активної та реактивної потужності за нормальних умов експлуатації. Визначення оптимального розміщення та розмірів DG є складною проблемою, що включає численні взаємодіючі змінні та експлуатаційні обмеження.* ***Мета***. *Це дослідження спрямоване на покращення технічних характеристик шляхом мінімізації загальних втрат активної потужності та відхилення напруги, забезпечуючи при цьому стабільність напруги та надійність мережі.* ***Методика***. *Алгоритм оптимізації рою частинок (PSO) удосконалено за допомогою методу Dehghani (DM) – популяційної модифікації, що дозволяє всім особам, включаючи найгіршого члена, зробити свій внесок в отримання найкращого рішення. Удосконалений алгоритм PSO-DM застосовується до системи шин IEEE 33 у чотирьох випадках: базовий випадок без DG та сценарії з 2, 3 та 4 DG. Цільова функція включає мінімізацію втрат активної потужності та загальне відхилення напруги.* ***Результати***. *Конфігурація з 4 DG значно покращує продуктивність системи: втрати активної потужності зменшуються з 210,67 кВт до 53,9 кВт (зниження на 74,4 %), реактивної – з 142,84 кВАр до 38,42 кВАр (зниження на 73,1 %), мінімальна напруга на шині зростає з 0,9037 у.о. до 0,9741 у.о., а загальне відхилення напруги зменшується з 1,8037 у.о. до 0,5129 у.о. (покращення на 71,6 %). Ці результати демонструють, що PSO-DM ефективно балансує розвідку та експлуатацію, забезпечуючи кращі рішення для розміщення установок DG.* ***Наукова новизна***. *Інтеграція DM в PSO впроваджує механізм кооперативного уточнення рішень, який підвищує швидкість конвергенції та точність пошуку.* ***Практична значимість***. *Структура PSO-DM забезпечує надійний та обчислювально ефективний інструмент для планування DG у сучасних інтелектуальних розподільчих мережах.* Бібл. 22, табл. 1, рис. 3.

Ключові слова: **розподілена генерація, оптимізація рою часток, метод Dehghani, відхилення напруги, мінімізація втрат потужності, розподільні мережі.**

Introduction. The increasing penetration of distributed generation (DG) technologies has transformed the operational paradigms of modern distribution systems. Conventionally, radial distribution networks were designed to passively deliver electrical power from centralized power plants to end-users; however, the integration of DG units, such as photovoltaic (PV) systems, wind turbines, fuel cells and microturbines, has introduced new opportunities and challenges in enhancing the efficiency, stability, and sustainability of electrical networks [1]. DG units significantly improve system performance by reducing real power losses, supporting voltage profiles, increasing network reliability, and reinforcing resilience against disturbances [2]. Nevertheless, these benefits are achievable only when DG units are sited and sized optimally. Improper placement or inaccurate sizing may lead to voltage violations, reverse power flow, feeder congestion, or even deterioration of overall network performance. Consequently, the problem of optimal placement and sizing of DG units has become a central research topic in power system planning and operation [3].

DG refers to small-scale, decentralized power generation sources located near the load centers. Their integration offers multiple technical and economic advantages, including reduced transmission losses, deferred network expansion costs, enhanced voltage stability, and improved environmental sustainability [4–6]. As highlighted in recent studies, DG's impact on distribution power networks is highly sensitive to its location and capacity [7]. For instance, the work [8] emphasizes that uncertainty in load demand can significantly influence optimal DG decisions, advocating hybrid metaheuristic frameworks for more reliable solutions. Similarly, an improved salp swarm algorithm is employed to determine DG allocation in radial systems, showing that properly placed DGs minimize power losses and voltage deviations while delivering strong techno-economic gains [9]. In another relevant study, the jellyfish search algorithm is applied to the optimal placement of solar PV-based DGs, using a multi-objective formulation to concurrently reduce real power losses, improve voltage profile, and enhance system stability [10].

Additional literature also confirms the importance of combining analytical indicators with metaheuristic algorithms to improve DG optimization effectiveness. For instance, an integrated approach using an active power loss sensitivity index to identify candidate buses and a modified ant lion optimization algorithm to determine DG sizes is presented in [11]. The incorporation of Lévy flights significantly improves exploration ability and prevents premature convergence. Likewise, hybridized methodologies, such as the modified grey wolf optimization integrated with ETAP software [12], demonstrate the potential of advanced strategies in supporting protection coordination while optimizing DG allocation. Other perspectives in [2, 13–16] explore multi-objective DG-capacitor placement, optimal scheduling with electric vehicles, reconfiguration combined with DG and capacitors, DG placement in microgrids using enhanced differential evolution, and DG-energy storage co-optimization using genetic algorithms. Collectively, these studies reveal a consistent conclusion: metaheuristic algorithms are indispensable tools for addressing the highly nonlinear, multimodal, and constraint-intensive nature of DG allocation problems in modern distribution networks. Numerous metaheuristic algorithms have been introduced and developed to date, and they have found extensive applications in real-world and engineering optimization problems [17–19].

Despite the extensive contribution in the literature, achieving a balanced trade-off between exploration and exploitation remains a key challenge in metaheuristic-based DG optimization. Classical algorithms, such as the particle swarm optimization (PSO), are powerful yet often susceptible to premature convergence, especially when dealing with multimodal search spaces characteristic of DG planning. To address this gap, improved variants of PSO have been proposed to enhance convergence speed, robustness, and accuracy. Motivated by this need, an enhanced PSO algorithm augmented with Dehghani method (DM) is introduced in this study. DMeenhancement introduces adaptive update mechanisms that refine particle movement patterns, strengthen global exploration, and reduce the risk of stagnation. As a result, the DM-enhanced PSO exhibits superior capabilities in escaping local minima and identifying high-quality solutions, making it particularly suitable for DG placement tasks that involve complex operational constraints and nonlinear performance indices.

This **study aims** to improve the technical performance of the distribution network by minimizing total active power losses and voltage deviation while ensuring voltage stability and maintaining reliable system operation. To achieve this objective, the DM-enhanced PSO algorithm is applied to determine the optimal placement and sizing of DG units. The IEEE 33-bus radial distribution system is used as the test platform, and four scenarios are considered – one base case without DG and three cases with 2, 3 and 4 DG units – to comprehensively evaluate the impact of DG penetration on loss reduction, voltage improvement, and overall system performance.

The structure of the paper is organized as follows. Problem formulation, including the mathematical model for DG placement and sizing, objective functions, and system constraints are presented in section «**Problem definition**». The PSO algorithm and details of the enhancements incorporated through the Dehghani method are introduced in section «**Particle swarm optimization and Dehghani method**», and simulation studies and performance evaluation of the proposed method on the IEEE-33 bus system under all test scenarios are provided in section «**Simulation studies and performance analysis**». Finally, section «**Conclusions and future work**» concludes the paper and outlines future research directions, emphasizing the potential extension of DM-enhanced PSO to multi-objective DG planning, integration of storage systems, and real-time optimal operational strategies.

Problem definition. The optimal placement and sizing of DG units in radial distribution networks is a nonlinear, constrained optimization problem that aims to simultaneously improve the voltage profile and minimize active power losses. Let the distribution network consist of N buses and L branches. The objective is to determine the optimal locations $\{bk\}$ and corresponding DG sizes $\{P_{DG,k}, Q_{DG,k}\}$ for k = 1, ..., n_{DG}, such that network performance is enhanced while satisfying all power flow and operational limits.

Power flow model and loss formulation. For each branch $l \in L$ connecting bus i to j, the active power loss is calculated as:

$$P_{loss} = \sum_{i=1}^{L} R_l \frac{P_l^2 + Q_l^2}{V_i^2}, \tag{1}$$

where R_l is the line resistance; P_l, Q_l are the active and reactive power flows; V_i is the sending-end voltage magnitude.

Nodal active and reactive power balances are:

$$P_i = \sum_{j \in \Omega_i} P_{ij} - P_{D,i} + P_{DG,i} ; \tag{2}$$

$$Q_i = \sum_{j \in \Omega_i} Q_{ij} - Q_{D,i} + Q_{DG,i} , \tag{3}$$

where $P_{D,i}$, $Q_{D,i}$ denote loads; $P_{DG,i}$, $Q_{DG,i}$ denote DG injections at bus i.

Branch power flows in backward-forward sweep include:

$$P_{ij} = \sum_{m \in \Psi(j)} P_{jm} + P_{D,j} - P_{DG,j} ; \tag{4}$$

$$Q_{ij} = \sum_{m \in \Psi(j)} Q_{jm} + Q_{D,j} - Q_{DG,j} . \tag{5}$$

Bus voltages are updated using:

$$V_j = V_i - \frac{R_{ij} P_{ij} + X_{ij} Q_{ij}}{V_i} .$$

DG modeling. A DG unit can operate at unity power factor or supply reactive power depending on the technology. In general:

$$S_{DG,k} = P_{DG,k} + jQ_{DG,k}. \tag{6}$$

DG size constraints are:

$$P_{DG,k}^{\min} \le P_{DG,k} \le P_{DG,k}^{\max} . \tag{7}$$

Objective function. To simultaneously minimize active power loss and enhance voltage stability, a weighted multi-objective formulation is adopted:

$$\min F = \omega_1 P_{loss} + \omega_2 \left(\sum_{i=1}^{N} \left| V_i - 1 \right| \right), \tag{8}$$

subject to: 0.95 p.u. ≤ V_i ≤ 1.05 p.u., where: ω_1, ω_2 are the weight coefficients; the second term minimizes total voltage deviation ($VD = \sum_{i=1}^{N} |V_i - 1|$). This formulation provides a clear and mathematically rigorous representation of the DG placement and sizing problem, enabling the application of metaheuristic algorithms, such as the Dehghani-enhanced PSO, to effectively solve the problem under multiple DG penetration scenarios.

PSO and Dehghani method. PSO is a population-based stochastic optimizer [20]. Let a swarm consist of N_p particles, each with position $X_i \in R^D$ and velocity $V_i \in R^D$ at iteration *t*. Each particle retains a personal best $P_{best,i}$ and the swarm maintains a global best g_{best} (also denoted X_{best}). The standard PSO update rules are:

$$V_i^{t+1} = \omega V_i^t + C_1 r_1 \left(P_{best,i} - X_i^t\right) + C_2 r_2 \left(g_{best} - X_i^t\right); \quad (9)$$

$$X_i^{t+1} = X_i^t + V_i^{t+1}, \quad (10)$$

where ω is the inertia weight; C_1, $C_2 > 0$ are the cognitive/social coefficients; $r_1, r_2 \sim U(0, 1)$ are the uniform random vectors. Objective function $f(x)$ is minimized.

PSO is effective, but can suffer premature convergence and stagnation; the Dehghani method [21] is a population-level improvement operator that uses **component-wise contribution of all individuals** to refine the current best solution.

Dehghani method – concept and formalization. DM introduces an auxiliary vector X_{DM} initialized as the current best:

$$X_{DM} \leftarrow X_{best}. \quad (11)$$

For every particle $i = 1, ..., N_p$ and for each dimension $d = 1, ... , D$, DM attempts a component-wise replacement:

$$X_{DM}(d) \leftarrow X_i(d). \quad (12)$$

Compute the objective $f(X_{DM})$. If

$$f(X_{DM}) < f(X_{best}), \quad (13)$$

then accept the improvement:

$$X_{best} \leftarrow X_{DM}, \quad (14)$$

otherwise restore $X_{DM}(d) \leftarrow X_{best}(d)$ and continue. In words: each component of the global best is temporarily replaced by the corresponding component of every population member. If any such replacement yields a better objective, the global best is updated. This process leverages information in all members – including poor solutions – to explore promising coordinate-wise moves.

Algorithmically (pseudo-code):

1. $X_{DM} \leftarrow X_{best}$.
2. For $i = 1$ to N_p:
3. ;; For $d = 1$ to D:
4. ;;;; $X_{DM}(d) \leftarrow X_i(d)$ and evaluate $f(X_{DM})$.
5. ;;;;;\If $f(X_{DM}) < f(X_{best})$ then $X_{best} \leftarrow X_{DM}$. Else $X_{DM}(d) \leftarrow X_{best}(d)$.
6. ;; End for *d*.
7. End for *i*.

DM is parameter-light (no additional random numbers) and performs $O(N_p \cdot D)$ objective evaluations in the worst case per DM application.

Integration: DM-enhanced PSO. In DM-enhanced PSO, the standard PSO loop is preserved. After updating positions and personal/global bests at iteration *t*, apply DM to refine X_{best}. That is:

1. Update V_i^{t+1}, X_i^{t+1}.
2. Update $P_{best,i}$ and g_{best}.
3. Apply DM to attempt component-wise improvement of X_{best}.
4. Proceed to next iteration.

This hybridization preserves PSO dynamics while enabling coordinate-wise exploitation informed by the entire swarm. Empirically, DM-enhanced PSO increases the probability of escaping local minima and improves final solution quality for high-dimensional, constrained engineering tasks such as DG placement and sizing.

Simulation studies and performance analysis. Performance of the DM-enhanced PSO algorithm in solving the optimal placement and sizing of DG units in the IEEE 33-bus radial test system [22] is evaluated in this section. Four study cases are considered:

1) the base case without DG;
2) the optimal integration of 2 DG units;
3) the optimal integration of 3 DG units;
4) the optimal integration of 4 DG units.

The optimization objective simultaneously minimizes power losses and voltage deviation (*VD*). Lower values of *VD* indicate better voltage quality and improved network stability.

Global results obtained by the DM-enhanced PSO-DM are summarized in Table 1.

Table 1

Global results after optimum DG's placement in IEEE 33-bus test system

Parameters	Base	With 2 DG	With 3 DG	With 4 DG
P_{loss}, kW	210.67	183.37	136.5	53.9
Q_{loss}, kVAr	142.84	123.3	90.87	38.42
V_{min}, p.u.	0.903	0.9195	0.9344	0.9741
VD	1.8037	1.6278	1.3713	0.5129
DG locations (bus)	–	18,22	17,22,33	17,18,30,32
P_{DG}, kW	–	129.31 306.87	240.91 297.20 200	257.88 466.97 131.15 700
Q_{DG}, kVAr	–	62.63 148.62	116.68 143.95 96.86	124.90 226.16 63.52 339.02

The base network exhibits significant losses with an active power loss of 210.67 kW and a reactive power loss of 142.84 kVAr. Furthermore, the voltage deviation is relatively high (*VD* = 1.8037), confirming the weak voltage support typically observed in unreinforced radial systems. The introduction of DG units leads to noticeable performance improvement, and these enhancements intensify as the number of DG units increases.

Voltage profile analysis. Voltage profile across all buses for different scenarios is depicted in Fig. 1. In the base case, the minimum voltage drops to approximately 0.903 p.u., revealing the well-known voltage weakness around the mid-feeder section. With 2 DG units, the voltage profile rises uniformly, eliminating the deep dip and improving overall voltage stability. The placement of 3 DG units results in further enhancement, increasing the minimum voltage level and flattening the profile.

The most significant improvement occurs with 4 optimally located DG units. The entire voltage curve shifts upward, with all bus voltages remaining satisfactorily close to 1 p.u. This is also reflected in the voltage deviation value, which sharply decreases to *VD* = 0.5129, representing a 71.6 % improvement compared to the base case. This confirms that PSO-DM efficiently identifies optimal DG sites that contribute maximum voltage support.

Active power loss reduction. Active power loss for each bus is shown in Fig. 2. The integration of DG units remarkably reduces feeder losses by supplying power locally and minimizing line currents. Active loss decreases from 210.67 kW in the base case to 183.37 kW with 2 DGs and further to 136.5 kW with 3 DGs. The lowest loss, 53.9 kW, is achieved with 4 DGs, corresponding to a 74.4 % reduction compared with the base network. This significant decline clearly demonstrates the effectiveness of the DM-enhanced PSO optimization in loss minimization.

Reactive power loss reduction. Reactive power loss trends (Fig. 3) follow a similar pattern. The losses are reduced from 142.84 kVAr (base case) to 123.3 kVAr (2 DGs), 90.87 kVAr (3 DGs) and finally to 38.42 kVAr (4 DGs). The availability of reactive power support from optimally sized DGs directly enhances the voltage profile and lowers reactive currents, leading to substantial loss mitigation.

Overall performance discussion. The combined analysis of Table 1 and Fig. 1–3 clearly demonstrates that the DM-enhanced PSO algorithm delivers highly effective optimization solutions. The addition of DG units systematically improves voltage quality, reduces line loading, and significantly decreases both active and reactive losses. Among the investigated scenarios, the configuration with 4 DG units offers the best overall performance, affirming the strong capability of DM-enhanced PSO in identifying optimal DG allocation patterns.

These results confirm that incorporating DMe into PSO considerably enhances the exploration–exploitation balance, enabling superior DG planning outcomes in radial distribution systems.

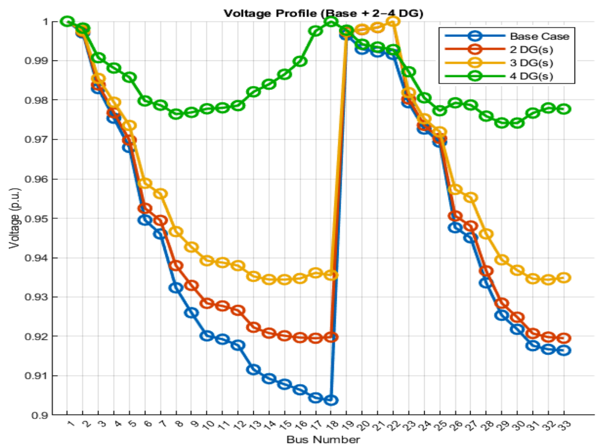

Fig. 1. Voltage profile without and with DGs integration

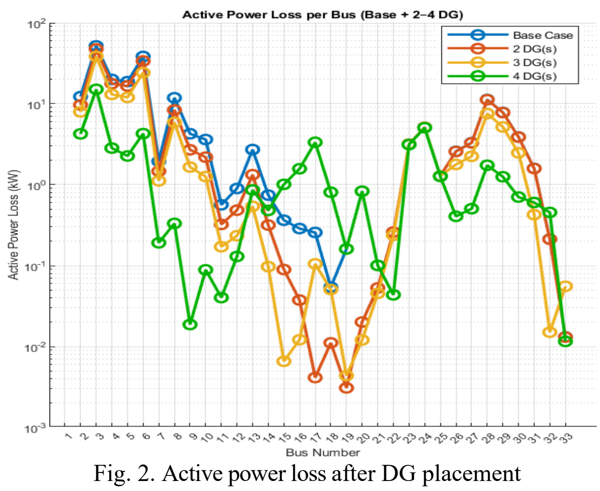

Fig. 2. Active power loss after DG placement

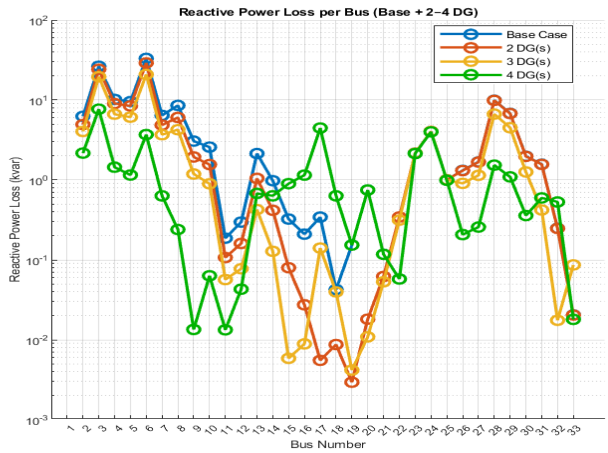

Fig. 3. Reactive power loss after DG placement

Conclusions and future work. An enhanced particle swarm optimization framework, augmented with the Dehghani method (DM-enhanced PSO), for determining the optimal placement and sizing of DG units in radial distribution networks is presented in this study. The mathematical formulation simultaneously minimized active power losses and voltage deviation while satisfying operational constraints, including power balance, voltage limits, and branch current ratings. Simulation results on the IEEE 33-bus system demonstrate that the proposed methodology significantly improves network performance across multiple technical criteria.

Simulation results on the IEEE 33-bus system demonstrate that the proposed DM-enhanced PSO methodology significantly improves network performance across multiple technical criteria. In particular, compared with the base case (no DG), the optimal 4-DG configuration reduces total active power loss from 210.67 kW to 53.9 kW, i.e. a reduction of 156.77 kW (≈74.4 %); and reduces total reactive power loss from 142.84 kVAr to 38.42 kVAr, i.e. a reduction of 104.42 kVAr (≈73.1 %). Voltage stability is also improved: the minimum bus voltage increases from 0.903 p.u. to 0.9741 p.u., and total voltage deviation VD decreases from 1.8037 to 0.5129 (≈71.6 % improvement). These quantitative results confirm that the DM-enhanced PSO reliably identifies DG placements and sizes that materially reduce both active and reactive losses while improving voltage quality.

Despite the promising results, several avenues remain open for future research. First, incorporating time-varying load models, renewable generation uncertainty, and probabilistic constraints can improve the realism of the optimization framework. Second, extending the model to multi-objective formulations – such as economic cost, emission minimization, and reliability enhancement – would enable more comprehensive planning. Additionally, applying advanced hybrid metaheuristics or reinforcement learning-based strategies may further improve convergence properties. Finally, validating the algorithm on larger and unbalanced distribution networks would provide a more extensive assessment of its scalability and practical applicability.

Conflict of interest. The authors declare that they have no conflicts of interest.

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