



PARALLEL LÉVY-FLIGHT CUCKOO SEARCH FOR JOINT DG SITING/SIZING AND POWER-QUALITY ENHANCEMENT IN RADIAL DISTRIBUTION NETWORKS

Vinuta V Koluragi^{*1}, J P Sridhar²

¹Department of Electrical & Electronics Engineering, B.L.D.E.A's V. P. Dr. P. G. Halakatti College of Engineering & Technology, Vijayapur, India.

²Department of Electrical & Electronics Engineering, SJB Institute of Technology, Bengaluru, India.

¹<https://orcid.org/0009-0006-1966-3180>^{ID}, ²<https://orcid.org/0000-0003-0287-3203>^{ID}

Email: *vinutakoluragi@bldeacet.ac.in, srihdk@gmail.com

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ABSTRACT

This paper proposes a Parallel Lévy Flight Cuckoo Search (CS PLF) framework for joint siting and sizing of renewable distributed generation (DG) with power quality enhancement in radial distribution networks. The planning objective balances economic efficiency and operational security via a scalarized function combining the benefit to cost ratio (BCR), voltage stability factor (VSF), and a network security index (NSI) under standard power flow and equipment constraints. This article introduces two design elements that strengthen optimization results: (i) a parallelized Lévy flight update to accelerate global exploration without parameter inflation, and (ii) an integrated planning model that accounts for DG real/reactive support and UPQC driven reactive needs within the same optimization loop. In comparative experiments on an Indian 28 bus radial distribution system, CS PLF achieves lower composite objective values and stronger voltage profiles, while PSO provides lower total cost and faster runtime, highlighting a planning trade off between economy and robustness.



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I. INTRODUCTION

Growing penetration of renewable DG in distribution networks requires planners to co optimize siting/sizing decisions with power quality and voltage stability objectives. While metaheuristics (e.g., PSO, CSA, GWO) have been widely adopted, two persistent gaps remain: (1) most works treat DG allocation and power quality devices in separate stages; (2) search strategies often trade off exploration for speed, or vice versa. To address these, this article proposes CS PLF, a Cuckoo Search variant that parallelizes Lévy flight perturbations and embeds UPQC aware quality metrics in the objective, enabling joint economic–technical planning.

Contributions:

1. Integrated multi criteria formulation combining BCR, VSF, and NSI with standard AC constraints, capturing cost, voltage robustness, and thermal loading risk in one scalar objective
2. Parallel Lévy Flight Cuckoo Search (CS PLF): embarrassingly parallel Lévy flight updates accelerate global search while preserving CSA's low parameter count
3. DG and Power Quality co planning: decision variables include DG locations, counts, and ratings (P/Q), with UPQC considerations implicitly driving voltage profile/harmonic mitigation benefits.
4. Comparative study vs. PSO: highlights a cost–robustness trade off valuable for planners (CS PLF improves stability/security, PSO reduces cost/runtime).

Recent studies have significantly advanced the field of distributed generation (DG) sizing and placement, largely through the development of improved and hybrid optimization algorithms.

According to [1], [2] demonstrated the effectiveness of the Cuckoo Search Algorithm (CSA) in improving convergence speed and solution quality compared to classical methods. Further refinements to CSA were proposed by [3], who developed variants with reduced computational complexity and enhanced global search characteristics. Hybrid optimization frameworks have also shown considerable promise. According to [4] introduced a Grey Wolf–Cuckoo Search hybrid approach that improves robustness in identifying optimal DG placement, while by [5] applied PSO assisted techniques for DG allocation with reactive power support. Additional studies such as by [6] validate that hybrid metaheuristics offer performance gains in multi-DG integration. Research relating to Unified Power Quality Conditioner (UPQC) continues to expand due to its importance in mitigating voltage sag, harmonics, and reactive power imbalance. In [7], [8] evaluated multi objective and PSO based UPQC allocation methods, respectively. Benchmarking efforts such as that by Espinosa Gutiérrez and Aguila Téllez [9] demonstrated that exhaustive search can still serve as a useful reference for validating heuristic algorithms. In [10], [11] developed hybrid metaheuristic approaches to improve UPQC performance under varying grid conditions. Authors to [12] further explored combinations of genetic and dragonfly algorithms for enhanced UPQC placement efficiency. Machine learning integration for DG and UPQC optimization has also emerged as a growing theme, as highlighted by [13].

However, only a limited number of studies directly address combined DG and UPQC allocation. According to [14] proposed a hybrid Whale–Dragonfly strategy for simultaneous sizing and placement, improving both economic and technical indicators. Complementary insights regarding coordinated multi objective UPQC design are provided by [15]. Authors to [16] investigated UPQC operation within DG integrated networks and emphasized the need for coordinated control to ensure system stability. Comparative reviews, such as that by [17], reinforce that methods outperform deterministic techniques for DG sizing and placement. Additional work [18–21] further demonstrates the effectiveness of hybrid optimization, multi population heuristics, and swarm-based methods. Machine learning and deep learning assisted optimization strategies have also gained traction in recent years [22–24], and industry aligned reports such as by [25] confirm the continued relevance of PSO based DG planning. With the rapid growth of renewable integration, DG-based distribution systems are increasingly favored for their environmental and economic benefits. Earlier research primarily focused on real power-oriented DG placement using impact indices or classical evolutionary algorithms. In contrast, the present work proposes a CS PLF based approach for optimal DG allocation that simultaneously considers both real and reactive power contributions. This enables improved voltage stability and loss minimization, building upon the foundational contributions of prior studies.

II. MATERIALS AND METHODS

To address the limitations of existing approaches, this article proposes a novel CS-PLF that is compared with PSO. The method is designed to improve optimal results while maintaining computational efficiency. This section starts with objective constraints used for the optimal placement and followed by the PSO and CS-PLF. The objective is to minimize the total cost while maximizing voltage stability and network security. The cost model includes investment and operational expenses, while benefits are derived from improved power quality and reduced losses. Mathematical formulations include cost functions, benefit functions, voltage stability factor (VSF), network security index (NSI), and constraints for generation limits, voltage tolerances, and line capacities.

Decision Variables and Sets

- $\mathcal{N}$: set of buses; $i \in \mathcal{N}$.
- $l_i \in \{0,1\}$: DG location indicator.
- $n_i \in \mathbb{Z}_{\geq 0}$: count of DG units at bus i .
- $P_{ij}^{\text{DG}}, Q_{ij}^{\text{DG}}$: active/reactive rating of a type- j DG at bus i ; $j \in \{\text{solar, wind, biomass}\}$.
- AC state variables V_i, θ_i ; line flows S_{ij} .

Economic Model

DG cost (present-valued):

$$C_{\text{DG}} = \sum_i \sum_j (I C_{ij} n_i l_i + \text{OMC}_{ij} P_{ij}^{\text{DG}} n_i l_i) \cdot \text{CPV}, \quad (1)$$

$$\text{CPV} = \frac{1 - \text{PV}^{Ny}}{1 - \text{PV}} \quad (2)$$

$$\text{PV} = \frac{1 + \frac{\text{IF}}{100}}{1 + \frac{\text{IR}}{100}}. \quad (3)$$

(Standardized the present-value notation and ratio as used in discounted-cash-flow analysis).

DG benefit (energy value + loss reduction):

$$B_{\text{DG}} = \sum_i \sum_j (P_{ij}^{\text{DG}} + Q_{ij}^{\text{DG}}) n_i l_i + \Delta P_{\text{loss}}^{\text{DG}} \cdot C_{\text{hr}} \cdot 8760 \cdot \text{CPV}. \quad (4)$$

$$\text{BCR} = \frac{B_{\text{DG}}}{C_{\text{DG}}}. \quad (5)$$

(If Q is remunerated differently, consider a weighting or separate tariff.)

Robustness Metrics

Voltage Stability Factor (VSF) at bus $i + 1$:

$$VSF_{i+1} = 2V_{i+1} - V_i, \bar{VSF} = \frac{1}{|\mathcal{N}|-1} \sum_{i=1}^{|\mathcal{N}|-1} VSF_{i+1}. \quad (6)$$

Network Security Index (NSI) via loading level:

$$LL_i = \frac{S_i^{MVA}}{S_{i,max}^{MVA}}, \bar{NSI} = \frac{1}{|\mathcal{N}|-1} \sum_{i=1}^{|\mathcal{N}|-1} LL_i. \quad (7)$$

Lower $\bar{NSI}$ indicates a more secure network.

Objective and Constraints

Scalarized the multi-criteria planning objective as:

$$\min_{\{l_i, n_i, P_{ij}^{DG}, Q_{ij}^{DG}\}} f = -\alpha BCR - \beta \bar{VSF} + \gamma \bar{NSI}, \alpha, \beta, \gamma > 0. \quad (8)$$

Subject to standard AC power-flow equations; generator, voltage, and line limits:

(Corrected typographic inconsistencies in the reactive-power balance and clarified that both P_{loss} and Q_{loss} denote network losses.)

$$P_{slack} + \sum_{i,j} P_{ij}^{DG} n_i l_i - \sum_i P_{D,i} \quad (9)$$

$$Q_{slack} + \sum_{i,j} Q_{ij}^{DG} n_i l_i - \sum_i Q_{D,i} \quad (10)$$

$$P_{ij}^{min} \leq P_{ij}^{DG} n_i \leq P_{ij}^{max}, Q_{ij}^{min} \leq Q_{ij}^{DG} n_i \quad (11)$$

$$Q_{ij}^{DG} = P_{ij}^{DG} \tan(\cos^{-1}(\text{PF})) \quad (12)$$

$$V_i^{min} \leq V_i \leq V_i^{max} \quad (13)$$

$$|S_{ij}| \leq S_{ij}^{max}. \quad (14)$$

A. Particle Swarm Optimization Algorithm (PSO)

PSO is inspired by social behavior in animal groups. Each particle represents a potential solution and updates its position based on personal and global best experiences. The algorithm is efficient for static optimization problems and has been widely applied in power system planning. Figure 1 shows the flow chart of PSO algorithm flowchart.

B. Cuckoo Search- Parallel Levy Flights (CS-PLF)

CS-PLF mimics the brood parasitism of cuckoo birds. It uses Lévy flights for global search and probabilistic replacement of poor solutions. CS-PLF requires fewer parameters and offers robust performance in complex optimization landscapes. Below is a brief summary of the CS-PLF algorithm.

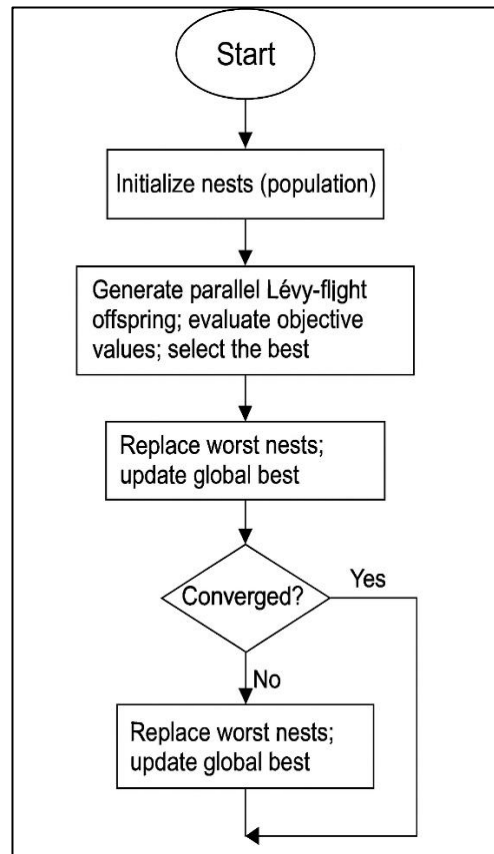


Figure 1: CS-PLF flowchart.
Source: Authors, (2026).

III. RESULTS AND DISCUSSIONS

The MATLAB 2025a m-file is used for the algorithm development and test. The laptop with 11th Gen Intel Core i7-11850H @ 2.50Ghz processor with 32 GB RAM is used. The proposed model is tested on the Indian 28-bus distribution system. DGs of solar, wind, and biomass types are considered over a 10-year planning horizon. Both PSO and CS-PLF are applied with identical population and iteration settings. CS-PLF yields superior voltage stability and network security, while PSO achieves lower total cost and faster convergence. Detailed results are presented in tabular and graphical formats. The test system employed here is Indian 28 distributed bus system [2]. The PSO method and the CS-PLF algorithm are used to minimize Equation (10). Six is assumed to be the constant number of DG installations ($N=6$). Additionally, the issue has been resolved for a period of ten years (yr) ($N_{yr}=10$). The three DG kinds selected are biomass, wind, and solar. In this case, solar is type 1, wind is type 2, and biomass is type 3. And it works for reactive power support also. The power factor considered here is 0.9.

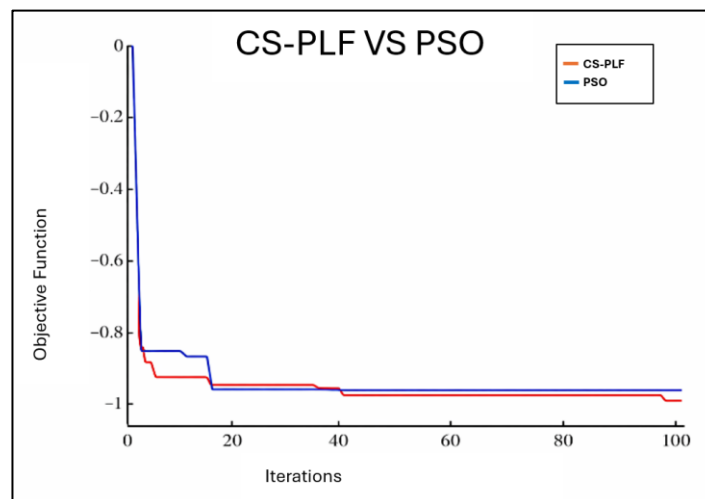


Figure 2: The graph of convergence between CS-PLF and PSO.
Source: Authors, (2026).

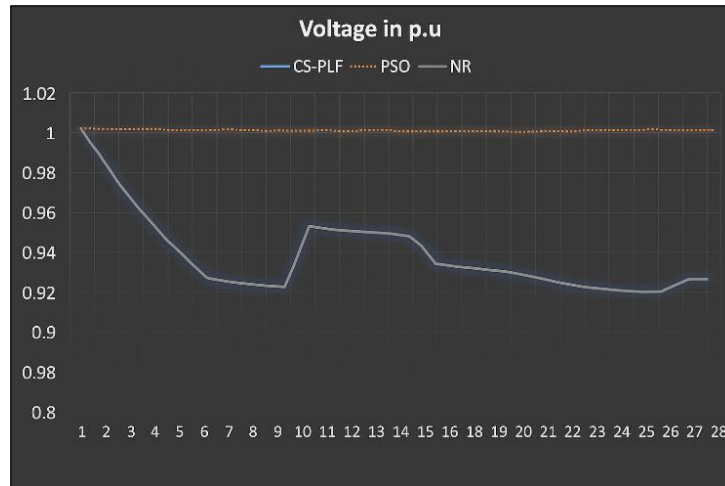


Figure 3: Indian 28-bus system voltage profile with renewable DG positioned ideally using CS-PLF and PSO and without renewable DG using the Newton-Raphson technique.
Source: Authors, (2026).

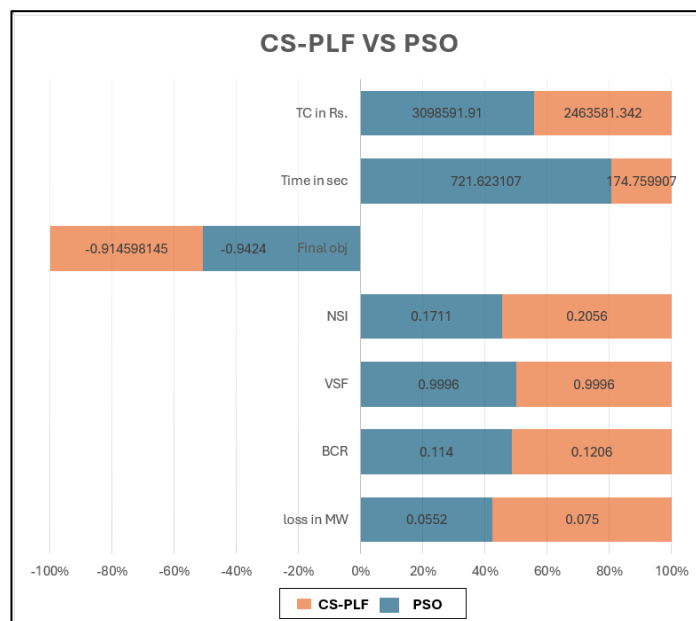


Figure 4: Comparing the CS-PLF with PSO using the following metrics: NSI, VSF, BCF, time spent, total cost, loss in MW, and end objective value.
Source: Authors, (2026).

Figure 2 shows the convergence graph. Where the figure 3 shows the Voltage profile of all the algorithms. The convergence graphs of the CS-PLF and PSO algorithms with the identical objective function are displayed in the above figure. In this case, the overall population is 60, and the number of algorithms for both algorithms is 100. The performance of PSO is shown by the blue line in the graph above, and that of CS-PLF by the red line. CS-PLF provides a superior minimum objective function for 100 iterations. Both meet the requirements. Figure 4 shows the comparison result. The research summarizes the allocation of renewable distributed generators across six buses, detailing their capacity, cost, and operational metrics. The total installed capacity is 4.475 MW and 2.2 MVar, with an overall investment cost of approximately ₹2.14 million and annual operation and maintenance (O&M) expenses of ₹0.33 million, resulting in a cumulative annual cost of ₹2.46 million. Bus 26 contributes the largest share, hosting six units with 1.2 MW capacity and incurring the highest total cost of ₹910,809.89, while Bus 24 is the most cost-efficient with a cost per MW of about ₹276,247. Type-3 DGs dominate the network, providing 3.6 MW capacity but at a higher cost per MW compared to type-2 units, which are more economical. O&M costs remain consistent at roughly 13–14% of total costs across all buses, indicating predictable maintenance scaling. Overall, the data highlights a trade-off between capacity and cost efficiency, suggesting that strategic placement of DGs is crucial for optimizing investment and operational performance. In comparison to the PSO method, the CS-PLF algorithm provides superior voltage profile, NSI, VSF, and BCR values. However, the PSO method is less expensive and takes less time to solve.

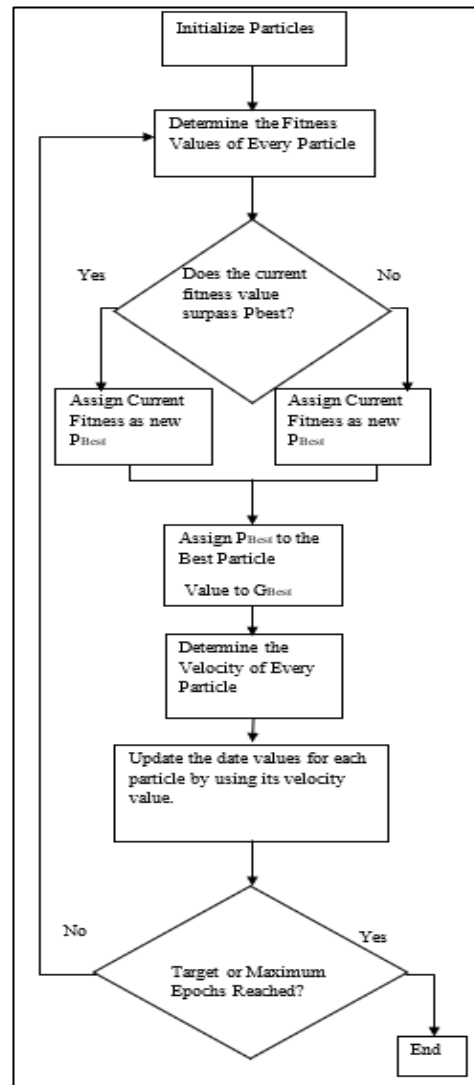


Figure 5: Particle swarm optimization Algorithm flowchart.
Source: Authors, (2026).

It is the logical presentation of the results that demonstrate the true contribution of the research and also justify the conclusion. The parts indicated above, Introduction, Material and Methods serve to explain how the results are obtained. Use tables and figures for your explanation. The results must be written in the past, in a brief and simple way. Avoid redundancy.

IV. CONCLUSIONS

This research demonstrates that renewable DGs, when optimally placed and sized, can significantly enhance distribution system performance by reducing losses, improving voltage stability, and maintaining power quality. A comparative analysis of two metaheuristic algorithms—PSO and CS-PLF—highlights the trade-offs between economic efficiency and technical performance. PSO proves more cost-effective, making it suitable for budget-driven planning, while CS-PLF delivers superior voltage profiles and system stability through advanced global search and parallelized updates. The integration of UPQC further strengthens power quality by mitigating harmonics and regulating voltage. Simulation results on standard IEEE test feeders validate the proposed framework and emphasize that operational priorities, such as minimizing cost or improving voltage stability, should guide algorithm selection. These findings provide actionable insights for smart grid expansion planning and real-time decision-making in renewable-rich networks, paving the way for more resilient and sustainable power systems.

V. AUTHOR'S CONTRIBUTION

Conceptualization: Vinuta V Koluragi

Methodology: Vinuta V Koluragi and J P Sridhar.

Investigation: Vinuta V Koluragi and J P Sridhar.

Discussion of results: Vinuta V Koluragi and J P Sridhar.

Writing – Original Draft: Vinuta V Koluragi.

Writing – Review and Editing: Vinuta V Koluragi and J P Sridhar.

Resources: J P Sridhar.

Supervision: Vinuta V Koluragi and J P Sridhar.

Approval of the final text: Vinuta V Koluragi and J P Sridhar.

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