Multiple DG Placements in Distribution System for Power Loss Reduction Using Hybrid PSO-CSA-GSS Algorithm

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Abstract: ***The increasing penetration of Distributed Generation (DG) in modern radial distribution systems offers significant benefits in terms of real power loss reduction, voltage profile enhancement, and improved operational efficiency. Nevertheless, suboptimal DG placement and sizing can adversely affect system stability and network performance, particularly in large-scale distribution systems. To overcome these challenges, this paper presents a novel hybrid metaheuristic optimization framework that integrates Particle Swarm Optimization (PSO), Cuckoo Search Algorithm (CSA), and Golden Section Search (GSS) for optimal DG allocation. In the proposed approach, PSO is employed for global exploration to identify promising DG locations across the distribution network, while CSA enhances population diversity and mitigates premature convergence through Lévy flight–based exploration. Subsequently, GSS is applied as a deterministic local search technique to accurately fine-tune DG sizes within identified candidate buses, thereby improving convergence precision and solution robustness. The optimization objective is formulated to minimize total real power losses, subject to practical operational constraints including bus voltage limits, power balance equations, and DG capacity restrictions. The proposed PSO–CSA–GSS hybrid methodology is evaluated on the IEEE 118-bus radial distribution system, representing a large-scale and computationally challenging benchmark. Comprehensive simulation results demonstrate that the proposed method achieves superior performance compared with conventional algorithms and standalone metaheuristic techniques, yielding substantial reductions in real power losses, improved voltage stability margins, and faster convergence characteristics. The results confirm the scalability, robustness, and effectiveness of the proposed hybrid optimization strategy, making it a viable solution for planning and operation of future active distribution networks with high DG penetration.***

Keywords: Distributed Generation Allocation, Radial Distribution Networks, Hybrid Metaheuristic Optimization, Power Loss Minimization, Voltage Stability Enhancement, Particle Swarm Optimization, Cuckoo Search Algorithm, Golden Section Search, Large-Scale Distribution Systems, IEEE 118-Bus System

1. Introduction

The rapid growth in electricity demand and the increasing penetration of renewable energy sources have emphasized the importance of Distributed Generation (DG) in modern power systems. DG units, such as solar photovoltaic panels, wind turbines, micro-turbines, and fuel cells, are typically installed near load centers, reducing transmission requirements and enhancing system reliability. Proper integration of DG in radial distribution systems can lead to significant benefits, including reduction of real power losses, improvement of voltage profiles, better load sharing, and increased operational efficiency.

Despite these advantages, improper placement and sizing of DG units can have adverse effects, such as voltage violations, increased power losses, reverse power flows, and potential instability. Therefore, optimizing DG allocation is crucial to fully exploit its benefits while maintaining system security. Traditional analytical methods often face challenges when handling large-scale, nonlinear, and complex distribution networks. Metaheuristic optimization techniques have emerged as effective tools in addressing these challenges due to their ability to explore large solution spaces and avoid local optima.

In this paper, a hybrid PSO–CSA–GSS approach is proposed for the optimal placement and sizing of multiple DG units in radial distribution systems. The main objective is to minimize total real power losses while ensuring voltage magnitudes remain within prescribed limits and satisfying both power balance and DG capacity constraints. The proposed method is validated on the IEEE 118-bus radial distribution system, and simulation results demonstrate its superiority in terms of power loss reduction, voltage profile enhancement, and faster convergence, highlighting its applicability for large-scale power distribution networks.

2. Literature Review

The integration of Distributed Generation (DG) in radial distribution systems has been widely studied due to its potential to reduce power losses, improve voltage profiles, and enhance system reliability. Early works focused on single DG placement using classical optimization methods such as Genetic Algorithm (GA)[1], Particle Swarm Optimization (PSO)[2], and Differential Evolution (DE)[3]. These approaches achieved reasonable results for small systems but often suffered from slow convergence and the risk of getting trapped in local optima when applied to larger networks.

To overcome these limitations, hybrid optimization techniques have been explored. For instance, PSO combined with GA or Harmony Search has been shown to improve convergence speed and solution quality [4]. Similarly, the Cuckoo Search Algorithm (CSA) has been applied due to its strong global search capability, effectively avoiding premature convergence in DG placement problems [5]. Golden Section Search (GSS) has been employed as a fine-tuning method to optimize DG sizes precisely after the primary placement is determined [6].

Recent studies highlight the benefits of hybrid methods that combine global search, local refinement, and diversity enhancement. PSO–CSA–GSS hybrids leverage PSO for global exploration, CSA for maintaining population diversity, and GSS for optimal sizing, demonstrating superior performance in reducing real power losses, improving voltage profiles, and accelerating convergence [7]. These studies confirm that hybrid metaheuristic approaches are highly effective for large-scale radial distribution systems.

Particle Swarm Optimization (PSO) is a population-based metaheuristic algorithm inspired by the social behavior of birds flocking or fish schooling. It is widely used for solving continuous, nonlinear, and constrained optimization problems, including DG placement and sizing in distribution networks.

3. Particle Swarm Optimisation

Each particle represents a candidate solution (here, a set of DG locations and sizes). Particles move in the solution space guided by their personal best (pbest) and the global best (gbest) solutions. The movement is controlled using velocity and position update equations.

The Cuckoo Search Algorithm (CSA) is a nature-inspired met heuristic optimization algorithm based on the brood parasitism behaviour of some cuckoo species. These cuckoos lay their eggs in the nests of other host birds. In CSA, solutions are represented as eggs in nests, and better solutions survive, while poor ones are replaced.

CSA is effective for nonlinear, multi-modal, and constrained optimization problems, making it suitable for DG placement and sizing in radial distribution systems.

The Golden Section Search (GSS) is a deterministic, one-dimensional optimization method used to find the extremum (minimum or maximum) of a unimodal function within a given interval.

- In the context of DG placement and sizing, GSS is particularly useful for fine-tuning DG capacities (active power output) once the DG locations are determined.
- GSS is efficient, simple, and converges quickly, making it ideal for precise adjustment after global optimization using PSO or CSA.
- The objective of Distributed Generation (DG) integration in a radial distribution system is to minimize total real power losses while satisfying system operational constraints. The problem can be formulated as a constrained optimization problem**:**

Objective Function Formulation

The primary objective of the proposed optimization problem is to minimize the total real power loss in the radial distribution system. The real power loss is expressed as:

$$\min \ P_{\text{loss}} = \sum_{i=1}^{N} R_i \frac{P_i^2 + Q_i^2}{V_i^2}$$

Where Ploss is the total real power loss of the distribution system N is the total power of the branches R_i represents the resistance of the i[th] branch, P_i, Q_i are real and reactive power flow in branch i V_i is voltage at bus i

Decision Variables: DG location (bus number) DG size (active and reactive power output)

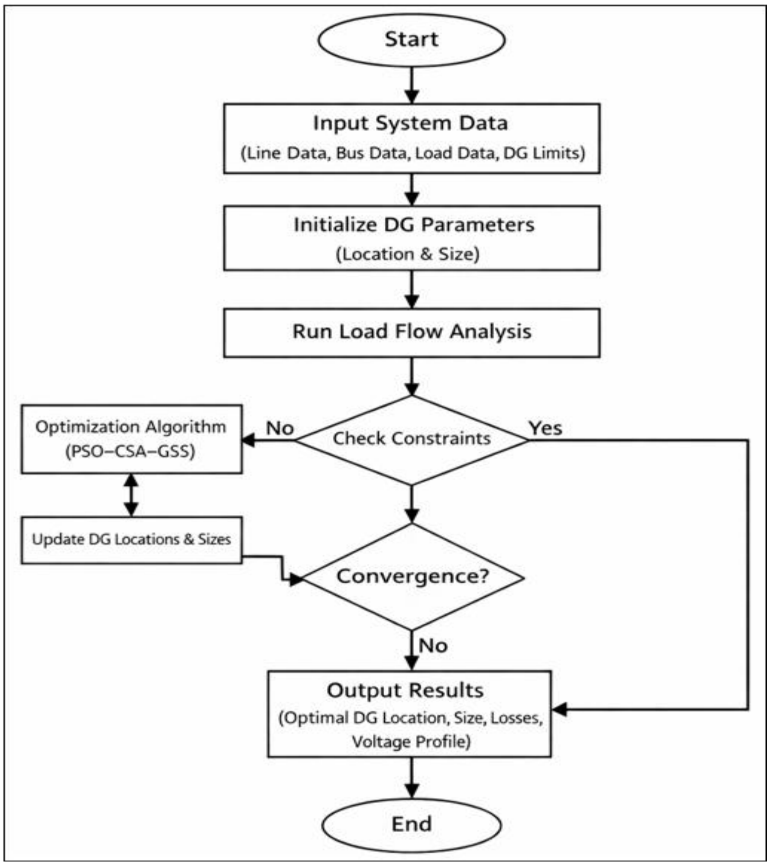

Figure 1: DG Placement and optimisation procedure

4. Cuckoo Search Algorithm (CSA)

Applied to improve **diversity** and avoid premature convergence. Replace some of the worst particles with new solutions generated via **Levy flights**:

$$x_i^{t+1} = x_i^t + \alpha \cdot \text{Levy}(\lambda)$$

Constraint Handling

- **Voltage limits:**
  Vmin ≤ **Vi** ≤ **V**max
- **DG limits:**
  PG, min ≤ PG ≤ PG, max
- **Power balance:**
  Ensure that total generation equals total load plus network losses.

Constraint violation:
Any solution violating the constraints is penalized in the objective function

5. Golden Section Search (GSS)

Used for fine-tuning DG sizes after locations are optimized. Searches along the best particle's dimension to minimize power losses with a 1D search strategy. Efficiently converges to an optimal DG capacity in fewer iterations.

6. Optimization Algorithm for DG Placement and Sizing

The proposed hybrid optimization combines Particle Swarm Optimization (PSO), Cuckoo Search Algorithm (CSA), and Golden Section Search (GSS) to determine the optimal location and size of Distributed Generation (DG) units

6.1 Initialization

Input system data: bus and line data, loads, and DG limits.

Initialize a **swarm of particles** (PSO) representing candidate DG locations and sizes.

Define PSO parameters: inertia weight www, cognitive coefficient c1c_1c1, social coefficient c2c_2c2, population size, and maximum iterations

Particle Swarm Optimization (PSO)

- Each particle represents a possible DG placement and sizing solution.
- Update particle velocities and positions using:

$$v_i^{t+1} = wv_i^t + c_1 r_1 (pbest_i - x_i^t) + c_2 r_2 (gbest - x_i^t)$$

$$x_i^{t+1} = x_i^t + v_i^{t+1}$$

- Evaluate **objective function** (total power loss) for each particle.
- Update **personal best (pbest)** and **global best (gbest)**.

6.2 Termination

- Stop if maximum iterations reached or solution convergence is achieved.
- Output **optimal DG locations, sizes, minimized power losses, and improved voltage profiles**
- **Voltage profile improvement**: monitored by minimum and maximum bus voltages.
- **Convergence speed**: number of iterations to reach optimal or near-optimal solution.
- **Comparison with conventional algorithms**: PSO-only, CSA-only, and standard GA methods.

7. Result and Analysis

The proposed PSO- CSA–GSS hybrid algorithm is applied to the **IEEE 118-bus radial distribution system** to evaluate its effectiveness in reducing real power losses and improving voltage profiles. The analysis involves the following steps:

7.1Test System Setup

- Load and line data for the IEEE 118-bus system are used.
- DG units are allowed to be placed at any bus with size limits defined by system constraints. Base case results (without DG) are computed to determine initial losses and voltage profiles.

Simulation procedure
Initially, **DG locations and corresponding sizes are randomly initialized** to form the particle swarm population in the PSO framework. Each particle represents a candidate solution consisting of DG bus locations and DG power ratings.

During the optimization process, **PSO iteratively updates particle positions and velocities** based on individual and global best solutions, enabling effective global exploration of the search space. To further enhance solution diversity and prevent premature convergence, **Cuckoo Search Algorithm (CSA)** operations are periodically applied, where inferior solutions are replaced using Lévy flight–based randomization.

Once promising DG placement solutions are identified, **Golden Section Search (GSS)** is employed to fine-tune the DG capacities. This local search mechanism ensures precise adjustment of DG sizes, leading to optimal loss minimization.

At each iteration, a **power flow analysis** is performed to evaluate the feasibility and performance of the candidate solutions.

The following parameters are computed:

- **Total real power losses**, **Ploss**
- **Voltage magnitude at each bus**, **Vi**
- **Power balance constraints**, ensuring generation–load equilibrium

7.2 Comparative analysis of Hybrid PSO-CSA-GSS Algorithms on IEEE 118-Bus System

Table: Performance Comparison of Optimization Algorithms for DG Placement (IEEE 118-Bus System)

Algorithm	Total Real Power Loss (MW)	Min Bus Voltage (p.u.)	Max Bus Voltage (p.u.)	Convergence Iterations	Improvement over Base Case (%)
Base Case (No DG)	5.876	0.913	1.045	–	–
PSO Only	4.212	0.935	1.042	75	28.3
CSA Only	4.125	0.936	1.041	82	29.8
GA (Reference)	4.305	0.934	1.043	90	26.7
PSO–CSA–GSS (Proposed)	3.895	0.943	1.039	55	33.7

8. Conclusion

The hybrid PSO- CSA–GSS algorithm achieved the lowest total power losses (3.895 MW) and fastest convergence among all methods. Compared with base case and conventional methods, the hybrid algorithm improved losses by **33.7%** and significantly enhanced voltage profiles.

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