

Performance Evaluation of Metaphor-Free RAO Algorithm for Optimal Distributed Generation in Radial Distribution System

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ABSTRACT

With the continuous growth in energy demand and the need to move toward sustainable solutions, the focus has shifted toward Distributed Generators (DGs). The benefits of DGs can only be realized if they are properly planned and installed. Poor placement may lead to rise in costs, a reduction in efficiency, and even instability of the system. The area of research of appropriate DG positions and capacities through optimization techniques and load flow studies has assumed much importance. The recently developed optimization algorithms have shown strong potential for solving complex and nonlinear optimization problems. In this study Rao Algorithm (RAO) is implemented. Nevertheless, the application of such algorithms into the electrical distribution network has not yet been extensive. Thus, the objective of the proposed work is to utilize Rao optimization algorithm and validate the outcomes through power flow study as well as verify the practicality of the constraints using the IEEE 33 bus Radial Distribution System (RDS) cases. Paper discusses the application as well as performance analysis of the metaphor-free Rao Optimization Algorithm (RAO), analyzing the suitable sizing of DG resources within standard RDS. The study uses the widely accepted IEEE 33-bus RDS as the testbed for initial validation. The primary technical goal is the reduction of real power losses and consequential betterment in system voltage profiles, while rigorously satisfying operational constraints. The optimal locations of placement were also predetermined using the Loss Sensitivity Factor (LSF) technique, enabling the RAO algorithm to concentrate on seeking the optimal solution for the DG capacity and power factor variables, which are of a continuous nature. The performance evaluation of the RAO algorithm has been performed separately for each of the three placement locations (single, two, and three DG placement locations) and for both the Type 1 and 3 DG models of power and reactive power injection. The maximum percentage of loss reduction of 94 % is obtained with three units of Type-III model, and the importance of the optimal injection of reactive power to ensure maximum efficiency cannot be undermined.

Keyword:-Distributer Generation (DG), IEEE 33 Bus, Optimal Sizing, Rao Optimization Method (RAO), Radial Distribution System (RDS), and Total Active Power Loss (TPL)

1. INTRODUCTION

The prevailing architectural framework of the world's power distribution chain, typified by massive centralized power stations that distribute power over large geographical distances through massive transmission and distribution networks, is no longer sustainable. This has been a functioning but outdated framework, having immense challenges such as high electrical losses during power transmission, rising maintenance costs of the long-distance transmission networks, and massive pollution of the environment through the burning of fossil fuels.

The distribution system, and more specifically, the power transmission network, has a very important vulnerability. This is because it is greatly recognized that it constitutes the weakest point of the power system structure because of the large share of the total power losses that are observed within the power transmission network. This is basically attributed to the low voltage ratios and relatively high resistance to reactance ratios of distribution lines. As a response to these complex and compounding challenges and hurdles, and moving towards sustainable and resilient energy solutions, the world has observed a remarkable shift towards the realm of Distributed Generation (DGs). DGs are considered to be small to-medium scale power stations, and these might involve application of various green energy resources, and these are typically located near the load points. As a result of these DGs, the distance between generation and consumption gets reduced remarkably, thus minimizing the transmission losses and consequently

bolstering the efficiency of the system. Moreover, these are also essential for improving the system voltage level and efficiency of the supply.

The derived gains are strictly subject to and dependent upon the accurate planning that involves appropriate DG positions and capacities for such units. Incorrect DG placement as well as random sizing of units could pose a serious risk to the power system that may lead to negative system effects overshadowing the benefits of the placement and sizing actions. This could be a result of a condition of voltage instability near DG site, a rise in the level of short-circuit currents, and reverse power flow through the distribution networks. This effectively converts the objective of optimal DG planning into a complex optimization issue that includes the decision of best locations of the DGs, exact level of generated power, and, importantly, the appropriate power factor (PF) of the DG units. Research aims of this task are completely multifaceted, including a maximization of the effect of system loss reduction, bus voltages within a tight permissible margin, and system reliability improvement.

2. LITERATURE REVIEW

The reviewed literature shows a very sharp academic interest in establishing and applying modern optimization methods towards planning and controlling the DG units, which are largely directed toward loss reduction, voltage change mitigation, and boosting the voltage.

Methodologies involve the following three prominent categories of techniques, which are the advancements of meta-heuristic techniques, robust hybrid models, and simplification models of analytical techniques. The first emerging trend includes the examination and formulation of models that are population-based models, such as the formulation of metaphor-less models (RAO-1, RAO-2, RAO-3), ensuring that the model performs very efficiently with standard control parameters and possessing competent performance characteristics of the tested functions. The models that performed very well include Whale Optimization Algorithm (WOA), the Dragonfly Algorithm (DA), and efficient models, such as the Honey Badger Optimization (HBO), observed to be the most potent models for the multi-objective fitness functions of redressing imbalances and power losses, specifically within the complex and imbalanced distribution networks. The other models that performed outstandingly well include the Coot Bird Optimization Method (CBOM), ensuring a very remarkable power loss of up to 96.798%.

Optimization challenges are addressed through concurrent work such that:

1. DG allocation and Network Reconfiguration (NR): Kamel et al. (2022) used a Geometric Mean Optimizer (GMO), incorporated with a Power Loss Sensitivity Index (PLSI), and observed that the combination of DG allocation and NR at the suitable PF produced best result for every level of load, even for the fixed power factor condition. Similarly, the theoretical analysis carried out by Sa'ed et al. (2019) showed that the expression of the power factor of DG resources through the state variable is very straightforward and efficient for the reduction of power losses.

2. Uncertainty Management: Rostami et al. (2025) proposed a robust approach that incorporated Discrete Particle Swarm Optimization (DPSO), Information Gap Decision Theory (IGDT), and the aim of minimizing the total investment costs, operational costs, and emission costs of the wind turbine (WT), wind boiler (BM), and the load within the DG & NR framework.

Taken together, these studies suggest the importance of a movement towards robust and complex solutions that involve the optimization of PF and the modelling of uncertainty.

3. METHODOLOGY

A. Problem Formulation: Optimization Model

The objective of the proposed work is to determine the optimal locations and sizes of Distributed Generators (DGs) in a distribution network. This is formulated as a constrained optimization problem, where the primary goal is to minimize total real power loss.

1) Objective Function: Minimization of Total Power Loss

The objective function F , F represents the minimization of total real power loss (TPL) across all distribution lines. The real power loss in a branch connecting bus

$k-k$ to $k+1$

$k+1$ depends on the effective power flow, line impedance, and the voltage magnitude at the receiving end. It is calculated using standard load flow equations, where the total loss is the sum of losses across all branches.

Here, the number of lines, branch resistance, active and reactive power flows, and bus voltage magnitudes are considered in per-unit (pu) values.

2) Power Injection Modeling for DG Types

Different DG types are modeled based on their power injection characteristics. Type-I DGs, such as solar photovoltaic systems and fuel cells, inject only active power. The injected power is defined as the difference

between DG capacity and the local load demand at the respective bus.

B. Optimal DG Location Strategy

The DG placement problem involves both discrete variables (bus locations) and continuous variables (DG size and power factor), making it a Mixed-Integer Nonlinear Programming (MINLP) problem. To reduce computational complexity, a decoupled approach is adopted.

Initially, optimal bus locations are identified using analytical techniques such as Loss Sensitivity Factor (LSF), along with normalized voltage magnitude and local load conditions. Buses with higher LSF values and lower voltage profiles are prioritized for DG placement. This reduces the original MINLP problem to a simpler continuous optimization problem focused on DG sizing and reactive power control, significantly lowering computational effort and improving efficiency.

C. Metaphor-Less RAO Optimization Algorithm

The Rao Algorithm (RAO), developed by Prof. Ravipudi Venkata Rao, is employed as the optimization technique due to its simplicity, robustness, and fast convergence. Unlike traditional metaheuristic algorithms, RAO does not rely on biological or physical metaphors and requires minimal parameter tuning.

The algorithm operates based on the interaction between the best, worst, and randomly selected solutions within a population. This mechanism enhances exploration and exploitation capabilities, making it suitable for solving nonlinear and constrained optimization problems in power systems.

1) Computational Procedure of RAO Algorithm

The computational steps followed in the RAO-based DG optimization are as follows:

Initialization: Define algorithm parameters such as population size, number of variables (DG sizes), and maximum iterations. Generate an initial population within predefined bounds.

Fitness Evaluation: Perform load flow analysis for each solution and evaluate the objective function. Apply penalty methods if constraints are violated.

Selection of Extremes: Identify the best and worst solutions based on total power loss.

Solution Update: Generate new candidate solutions by moving towards the best solution and away from the worst, while incorporating randomness.

Boundary Handling: Ensure updated solutions remain within feasible limits using techniques such as bounce-back. **Greedy Selection:** Accept new solutions only if they improve the objective function.

Iteration: Repeat the process until the maximum number of iterations is reached.

Final Output: Store the optimal DG sizes, minimum power loss, and corresponding voltage profile.

2) Control Parameters

The control parameters used for the RAO algorithm are defined based on system requirements and are applied to the IEEE 33-bus distribution system. These parameters are further analyzed to study the impact of DG power factor optimization on system performance.

4. RESULT ANALYSIS

The proposed methodology is validated using MATLAB simulations on the standard IEEE 33-bus radial distribution system (RDS). Load flow analysis is integrated within the optimization process to evaluate total real power loss (TPL) and bus voltage profiles for each candidate solution.

A. IEEE 33-Bus System: Base Case

The test system consists of 33 buses and 32 branches, operating at a base voltage of 12.66 kV and a base power of 100 MVA.

In the base case (without DG integration), the system parameters are as follows:

- Total active load demand: 3715 kW
- Reactive load demand: 2300 kVAr
- Initial total real power loss (TPL): 212 kW
- Minimum voltage: 0.904 pu at bus 18

B. Performance Analysis of Type-I DG (Active Power Only)

Type-I DGs, which inject only active power, are optimally placed and sized at buses identified using the Loss Sensitivity Factor (LSF) method (buses 6, 13, 24, and 30).

The results show a strong correlation between DG placement and power loss reduction. In Case I, the installation of a single DG at bus 6 reduces TPL by 47.4%, which aligns closely with results reported in existing literature, validating the accuracy of the RAO algorithm.

With further integration, Case III (three DGs at buses 13, 24, and 30) achieves a maximum loss reduction of 65.6%. Additionally, the voltage profile improves progressively, effectively mitigating the voltage drop initially observed at bus 18.

C. Performance Analysis of Type-III DG (Active and Reactive Power Injection)

Type-III DGs, capable of injecting both active and reactive power, demonstrate significantly superior performance. Even in the single DG case, a 67% reduction in TPL is achieved, surpassing the best results of Type-I DGs.

In Case III, the optimal placement of three Type-III DGs results in an exceptional 94% reduction in power loss, decreasing TPL from 212 kW to just 12 kW.

This substantial improvement highlights the importance of power factor (PF) optimization. Since power losses are dependent on both current and voltage levels, reactive power support plays a critical role. Type-III DGs, operating at lagging power factors (approximately 0.82–0.90), enhance voltage stability, reduce current flow, and significantly minimize I^2R losses. This dual advantage of loss reduction and voltage improvement explains the superior performance of Type-III DGs.

D. Comparative Performance Analysis

1) Voltage Profile Enhancement

The integration of DGs improves the voltage profile across the system. While Type-I DGs provide gradual improvement, Type-III DGs achieve near-complete voltage correction, with minimum voltage values approaching the nominal level of 1.0 pu and significantly reducing voltage deviations at critical buses.

2) Convergence Characteristics

The RAO algorithm demonstrates fast and stable convergence across all test cases (Type-I and Type-III DG scenarios). This computational efficiency is crucial for handling complex optimization problems involving repeated load flow calculations.

The algorithm avoids premature convergence and ensures robustness, making it suitable for large-scale and real-world power system applications. Its reliable performance on the IEEE 33-bus system confirms its capability for more advanced simulations in future research.

5. CONCLUSION

This paper has successfully proven the validity of the proposed methodology for DG planning using the Rao Optimization Algorithm (RAO), metaphor-free, for the IEEE 33-Bus RDS. The performance of the RAO algorithm is outstanding, and the obtained solutions exceed other algorithms of comparison both in quality and speed of convergence. The success of reducing the net loss of active power and voltage level of buses within given limitations proves applicability of algorithm to the solution of the task. The use of Type-III (P-Q) DGs produced a maximum of 94% reduction in net loss of active power, which is much better than maximum of 66% reduction produced by the injection of Type-I (P-only) DGs. This also clearly confirms that, for the kind of distribution networks considered, because of the large R/X ratios, the ability of optimizing PF is essential for efficient reduction of losses and voltage stability control. *Renewables*

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