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ORIGINAL ARTICLE
Electrica 2023; 23(2): 177-191

# Metaphor-Less RAO-3 and Sine Cosine Algorithm for Optimal Sizing of Distributed Generations of Multiple Types in Radial Distribution System

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**Cite this article as:** S. Shyamkant Halve, R. Arya and A. Koshti, "Metaphor-less RAO-3 and sine cosine algorithm for optimal sizing of distributed generations of multiple types in radial distribution system," *Electrica*, 23(2), 177-191, 2023.

## ABSTRACT

In this article, a method for the selection of buses in a radial distribution system (RDS) to locate different types of distributed generation (DG) is proposed. The buses have been identified based on the loss sensitivity factor. Line flow constraints have been considered using the load flow program. Type-I DG, that is, solar and fuel cell and Type-III DG, that is, small hydro turbine, cogeneration, and gas turbine have been considered for the study. Determination of optimum capacity for Type-I and Type-III DGs to minimize active power losses is selected as an optimization function. Metaphor-less RAO-3 algorithm has been used to evaluate the optimum DG capacity and results have been validated with sine cosine algorithm. Results are also compared with already existing algorithms in literature like hybrid technique, novel heuristic approach, etc. The statistical inference has been provided and results obtained for IEEE-33 and -69 bus RDS using RAO-3 algorithm is found better and has fast convergence characteristic.

***Index Terms***—Distributed generation, loss sensitivity factor, metaphor-less algorithm, radial distribution system, sine cosine algorithm

## I. INTRODUCTION

The power system is divided into three parts: generation, transmission, and distribution. The most important structural difference between transmission and distribution systems is that the transmission systems are interconnected while distribution systems are mostly radial or weekly meshed types. The distribution system is considered the weakest link in the power system because a larger percentage of power losses take place in it. The main objective of many researchers is to reduce power losses in the radial distribution system (RDS). To achieve this, load flow analysis plays an important role. It is required for taking various decisions during the operating stage as well as the design stage of the distribution system and effective planning of load transfer. Several load flow methods specially designed for distribution systems have been presented in the literature [1-4]. Now a days integration of distributed generations (DGs) in RDS has experienced considerable attention in power system research. The main purpose of DG integration is to reduce power losses and improve voltage profiles that indirectly improve the efficiency of the power system [5]. But the improper placement of DGs may lead to an increase in losses. Hence, the optimal location of DG plays a crucial role [6]. Various optimization algorithms have been used in literature to identify the optimal location and sizing of multiple DGs in RDS such as improved analytical (IA) [7], particle swarm optimization (PSO) [8], hybrid technique [9], dragonfly algorithm (DA) [10], whale optimization algorithm (WOA) [11], heuristic technique [12], efficient analytical [13], ant lion [14], chaotic symbiotic organisms search [15], novel student psychology-based [16] and quadratic curve fitting technique [17]. A complete analysis of the optimal location and size of Type-I DGs with a comparison of different optimization methods is highlighted in the literature [18]. The work in [19] implemented Enhanced Coyote algorithm for stability and reduction in power loss. Mostly four types of DGs are integrated with RDS [18]. The proper location of these DGs is addressed using voltage stability index, and optimal size is found using differential evolution [20].

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**Received:** February 2, 2022
**Revised:** June 3, 2022
**Accepted:** June 21, 2022
**Publication Date:** September 23, 2022
**DOI:** 10.5152/electrica.2022.22019

Research in [21] addressed the capacity, type, and location of DG optimization considering environmental safety and reliability of RDS. Kavya and Bozkurt [22] developed an algorithm to minimize power loss and deviation in voltage profiles**.** It was implemented to real RDS and tested at different loading conditions. Different optimization algorithms were developed for optimal sizing and siting of the induction generator model of DG for the sub-transmission system discussed in the literature [23-24]. Different optimization problems associated with practical engineering problems can be solved by various nature-inspired optimization algorithms focused on literature [25-28].

In this article, metaphor-less RAO-3 and sine cosine algorithm (SCA) are applied for optimal sizing of multiple DGs in RDS. In this work, two types of DGs considered are given as follows [18]:

Type-I: Inject active power only.

Type-III: Inject active and reactive power.

The basic objectives of this article are as follows:

1) To identify the optimal location of buses for placement of DGs using loss sensitivity factor (LSF).
2) Application of optimization techniques like RAO-3 method and SCA to minimize active power losses in RDS subjected to line flow and capacity constraints and eventually leading to improvement in the voltage profile of the system.
3) To provide statistical inferences for both proposed methods RAO-3 and SCA.
4) To evaluate the performance of RAO-3 and SCA as compared to existing algorithms and techniques.

This article is structured as a formulation of the objective function in Section II. Section III describes an algorithm for optimal capacity evaluation of DGs using RAO-3. Section IV represents the algorithm for optimal capacity evaluation of DGs using SCA. Section V gives results for two standard RDS. Section VI describes the conclusion.

## II. PROBLEM FORMULATION

### A. Objective Function

The core objective is to minimize total real power loss (TPL) in RDS. Fig. 1(a) shows the representation of a small section of a distribution line without integration of DG. Consider a branch “m” connected between bus “k” and “k+1.” Let $r_m$ and $x_m$ be the resistance and reactance of branch “m” in ohm (Ω). $I_m$ is the current flowing through branch “m” in Ampere.

The real power loss of branch (m) can be calculated using (1) as [10],

$$P_{loss(m)}=r_m\left(\frac{P^2_{eff(k+1)}+Q^2_{eff(k+1)}}{V_{k+1}{}^2}\right) \tag{1}$$

where $P_{eff(k+1)}$ and $Q_{eff(k+1)}$ are effective real, reactive power supplied beyond the bus (k+1) in kW and kVAR, respectively. $V_{k+1}$ is the voltage at (k+1)th bus in per unit (p.u).

The TPL minimization in RDS with DG connected is considered an objective function which is given by (2),

$$\min(TPL)=\min\left(\sum_{m=1}^{NL} I_m^2\times r_m\right) \tag{2}$$

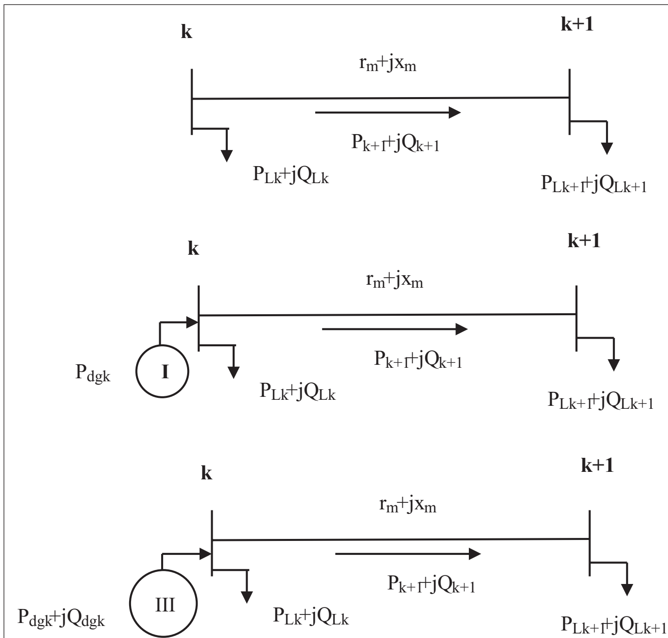


**Fig. 1.** Small section of a distribution system without integration of DG, with integration of Type-I DG at kth bus, and with integration of Type-III DG at $k^{th}$ bus.

where $P_k$ and $Q_k$ are active and reactive power injection at kth bus in kW and kVAR, respectively. $P_{Lk}$ and $Q_{Lk}$ are active and reactive power load at kth bus in kW and kVAR, respectively. $P_{Lk+1}$ and $Q_{Lk+1}$ are active and reactive power load at (k+1)th bus in kW and kVAR, respectively, and NL denotes the number of lines.

Consider a Type-I DG integrated at a bus k as shown in Fig. 1(b). Active power injection at bus k is calculated as

$$P_k = P_{dgk} - P_{Lk} \tag{3}$$

where $P_{dgk}$ is DG capacity at the kth bus in kW.

Consider a Type-III DG integrated at a particular bus k as shown in Fig. 1(c). Active power injection is calculated using (3) and reactive power injection at bus k is expressed as

$$Q_k = Q_{dgk} - Q_{Lk} \tag{4}$$

where $Q_{dgk}$ is DG capacity at the kth bus in kVAR.

The following constraints are considered to minimize the objective function:

i. Power flow equations

$$f(V,\delta)=0 \tag{5}$$

ii. Line power flow constraints

$$f_m \le f_m^{max} \quad \text{with } m = 1, 2, ..., NL \tag{6}$$

where $f_m$ and $f_m^{max}$ are mth line power flow and its maximum limit in kVA.

iii. Bus voltage limits

$$V_k^{min} \le V_k \le V_k^{max}$$
$$\text{with } k = 1,2,\ldots,\text{NBS(Number of buses)} \tag{7}$$

where $V_k^{min}$ is considered as 0.95 p.u and $V_k^{max}$ is considered as 1.05 p.u.

iv. DG capacity limits

$$P_{dgk}^{min} \le P_{dgk} \le P_{dgk}^{max} \tag{8}$$

where $P_{dgk}^{min}$ and $P_{dgk}^{max}$ are DG active power limits in kW.

**B. Loss Sensitivity Factor-Based Approach**
Optimal locations for placement of DG are located based on LSF [10].

LSF is calculated for all buses except reference bus as follows:

$$\frac{\partial P_{loss(m)}}{\partial Q_{eff(k+1)}} = \frac{2 \times Q_{eff(k+1)} \times r_m}{V_{(k+1)}^{2}}. \tag{9}$$

At these buses, normalized voltage magnitude $V_{norm(k+1)}$ is calculated as follows:

$$V_{norm(k+1)} = \frac{|V_{k+1}|}{0.95}. \tag{10}$$

The descending order of LSF, $V_{norm(k+1)}$ whose value is less than 1.01 p.u, and the load connected at that bus will decide the siting of DGs.

## III. OPTIMAL CAPACITY EVALUATION OF DISTRIBUTED GENERATIONS USING METAPHOR-LESS RAO-3 ALGORITHM

A simple metaphor-less RAO-3 optimization algorithm is developed by Ravipudi Venkata Rao in 2020 [28]. The author claims the results obtained using the proposed algorithm are based on best and worst solutions obtained during the optimization process and random interaction between the candidate solutions.

RAO-3 is used to evaluate optimal DG capacities at optimal locations. Type-I and Type-III DGs are selected for integration with RDS. A computational algorithm applied for optimal DG capacities evaluation using the RAO-3 method is explained in the following steps.

**Step 1:** Define population size (NP), number of design variables (NDG), and maximum number of iterations ($t_{max}$). Generate initial population of size "NP" randomly using (11).

$$S_0 = [X_{1,0}, X_{2,0}, X_{3,0}, \ldots, X_{NP,0}] \tag{11}$$

$$X_{k,0} = [P_{dg,1,k,0}, P_{dg,2,k,0}, \ldots, P_{dg,NDG,k,0}]^T \tag{12}$$

where i = 1, 2, …, NP and NDG is the numbers of DG at optimal locations.

$P_{dg,j,k,0}$ is the value of the jth element for kth individuals obtained using the equation as,

$$P_{dg,j,k,0} = P_{dg,j,min} + (P_{dg,j,max} - P_{dg,j,min}) \times rand_j \tag{13}$$

where $P_{dg,j,min}$ and $P_{dg,j,max}$ are lower and upper bounds on variable $P_{dg,j}$ and $rand_j$ is a random number in the range [0, 1]. Each $P_{dg,j,k}$ is randomly generated and regulated by (8). These generated samples of DG capacity must be chosen in a viable region and satisfy the constraints mentioned in (6).

**Step 2:** Evaluate objective function, that is, TPL in RDS for all populations using (2) with the help of load flow program, and in case of violation of inequality constraints, these are handled by [29] devised by Lampinen.

**Step 3:** Sort out the worst and best solutions from the current population based on their TPL values.

**Step 4:** Locate a new solution for all populations (k = 1,2,3, ..., NP) during $t^{th}$ iteration. Let $P_{dg,j,k,t}$ is the old value of a jth variable for a kth individual in $t^{th}$ iteration, $P_{dg,j,b,t}$ and $P_{dg,j,w,t}$ are the old values of jth variable for best and worst individual in $t^{th}$ iteration, respectively. $P'_{dg,j,k,t}$ is the updated value of $P_{dg,j,k,t}$.

**Step 5:** Modify each candidate solution using (14) for RAO-3

$$P'_{dg,j,k,t} = \left\{ \begin{array}{l} P_{dg,j,k,t} + r_{1,j,t}\left(P_{dg,j,b,t} - \left|P_{dg,j,w,t}\right|\right) \\ + r_{2,j,t}\left(\left|P_{dg,j,k,t} \text{ or } P_{dg,j,l,t}\right|\right) - \left(P_{dg,j,l,t} \text{ or } P_{dg,j,k,t}\right) \end{array} \right\} \tag{14}$$

$P_{dg,j,k,t}$ or $P_{dg,k,l,t}$ indicates that the $k^{th}$ candidate solution is compared with any randomly picked $l^{th}$ candidate solution and information is exchanged based on their TPL value. Select $k^{th}$ solution if its objective function value is minimum as compared to that of $l^{th}$ solution, then the term $P_{dg,j,k,t}$ or $P_{dg,j,l,t}$ becomes $P_{dg,j,k,t}$ else $P_{dg,j,l,t}$.

**Step 6:** If any control variable generated using (14) violates the bound then apply the bounce back technique [24] to bring within limits the violated variables.

**Step 7:** Is solution corresponds to $P'_{dg,j,k,t}$ is better than $P_{dg,j,k,t}$, then accept the new candidate solution and replace the previous solution with it. If not then keep the previous one.

**Step 8:** TPL is evaluated and increase iteration t = (t+1) and repeat from steps 4–7 until termination criteria is not achieved.

**Step 9:** Store the optimal solution along with TPL and voltage profile at each bus.

## IV. OPTIMAL CAPACITY EVALUATION OF DISTRIBUTED GENERATIONS S USING SINE COSINE ALGORITHM

Sine cosine algorithm is a population-based and nature-inspired algorithm. It is inspired by the mathematical features of sine and cosine trigonometric functions [25].

**TABLE I.** CONTROL PARAMETERS FOR SCA AND RAO-3 METHOD

| Control Parameter | Value |
|---|---|
| Population size (NP) | 30 |
| Maximum iterations specified ($t_{max}$) | 100 |
| Constant (C) for SCA | 2 |
| Upper bound limit of DG capacity $P_{dg,k}$ (kW) | 3000 |
| Lower bound limit of DG capacity $P_{dg,k}$ (kW) | 0 |

SCA, sine cosine algorithm.

**TABLE II.** COMPARISON OF OBTAINED RESULTS USING SCA, RAO-3, AND EXISTING METHODS FOR TYPE-I DG ON IEEE-33 BUS RDS

| Algorithm | Optimal DG Location | Optimal DG Size (kW) | Total DG Capacity (kW) | TPL (kW) | % RPL |
|---|---|---|---|---|---|
| Base case | - | - | - | 211.0058 | - |
| **Case 1** | | | | | |
| DA [10] | 6 | 2590.2000 | 2590.20 | 111.0338 | 47.3773 |
| IA [7] | 6 | 2601.0000 | 2601.00 | 111.1000 | 47.3900 |
| Hybrid [9] | 6 | 2490.0000 | 2490.00 | 111.1700 | 47.3100 |
| Heuristic [12] | 6 | 2593.6000 | 2593.60 | 111.0300 | 47.3791 |
| WOA [11] | 6 | 2589.6000 | 2589.60 | 111.0000 | 47.3900 |
| SCA | 6 | 2590.6800 | 2590.68 | 111.0329 | 47.3790 |
| RAO-3 | 6 | 2590.2100 | 2590.21 | 111.0329 | 47.3790 |
| **Case 2** | | | | | |
| IA [7] | 6 | 1800.0000 | 2520.00 | 91.6300 | 56.61 |
| | 14 | 720.0000 | | | |
| Hybrid [9] | 13 | 830.0000 | 1940.00 | 87.2800 | 58.6400 |
| | 30 | 1110.0000 | | | |
| Heuristic [12] | 13 | 840.0000 | 1974.00 | 87.1900 | 58.6770 |
| | 30 | 1134.0000 | | | |
| SCA | 13 | 846.6160 | 2010.82 | 87.1709 | 58.6879 |
| | 30 | 1164.2100 | | | |
| RAO-3 | 13 | 851.5000 | 2009.13 | 87.1691 | 58.6887 |
| | 30 | 1157.6334 | | | |
| **Case 3** | | | | | |
| IA [7] | 6 | 900.0000 | 2520.00 | 81.0500 | 61.62 |
| | 12 | 900.0000 | | | |
| | 31 | 720.0000 | | | |
| Hybrid [9] | 13 | 790.0000 | 2870.00 | 72.8900 | 65.4500 |
| | 24 | 1070.0000 | | | |
| | 30 | 1010.0000 | | | |
| Heuristic [12] | 13 | 792.0000 | 2887.00 | 72.8400 | 65.4786 |
| | 24 | 1068.0000 | | | |
| | 30 | 1027.0000 | | | |
| WOA [11] | 30 | 1072.8300 | 2701.99 | 73.7500 | 65.0500 |
| | 25 | 772.4880 | | | |
| | 13 | 856.6780 | | | |
| SCA | 13 | 800.0630 | 2980.02 | 72.8128 | 65.4925 |
| | 24 | 1135.5150 | | | |
| | 30 | 1044.4480 | | | |
| RAO-3 | 13 | 801.7059 | 2946.66 | 72.78890 | 65.5038 |
| | 24 | 1091.3126 | | | |
| | 30 | 1053.6491 | | | |

SCA, sine cosine algorithm; RDS, radial distribution system; DG, distributed generation; WOA, Whale Optimization Algorithm. TPL, total real power loss.

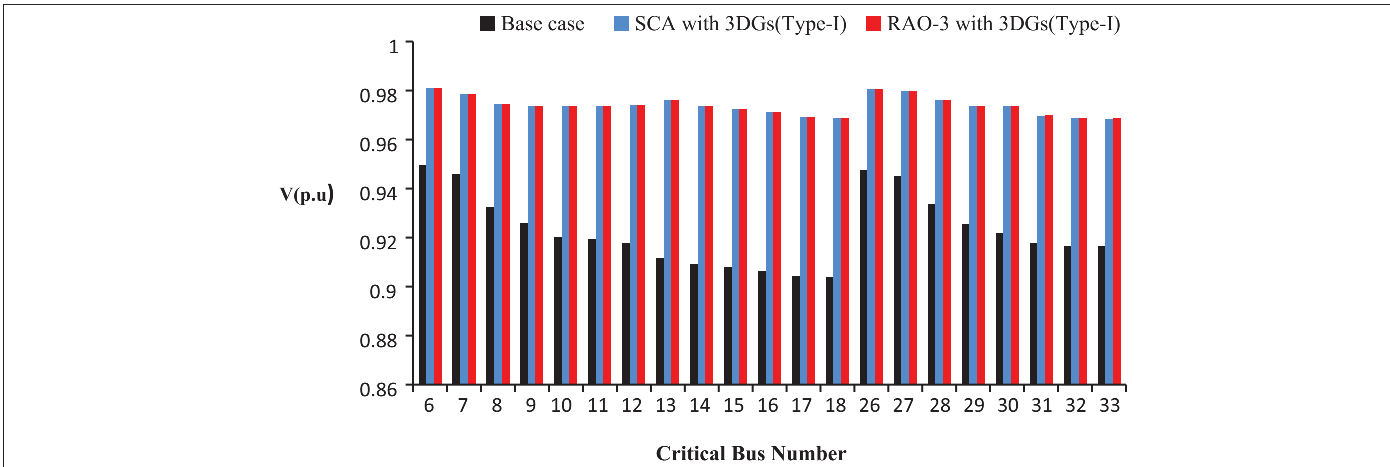


**Fig. 2.** Comparison of voltage profile with and without integration of Type-I DG for IEEE-33 RDS.

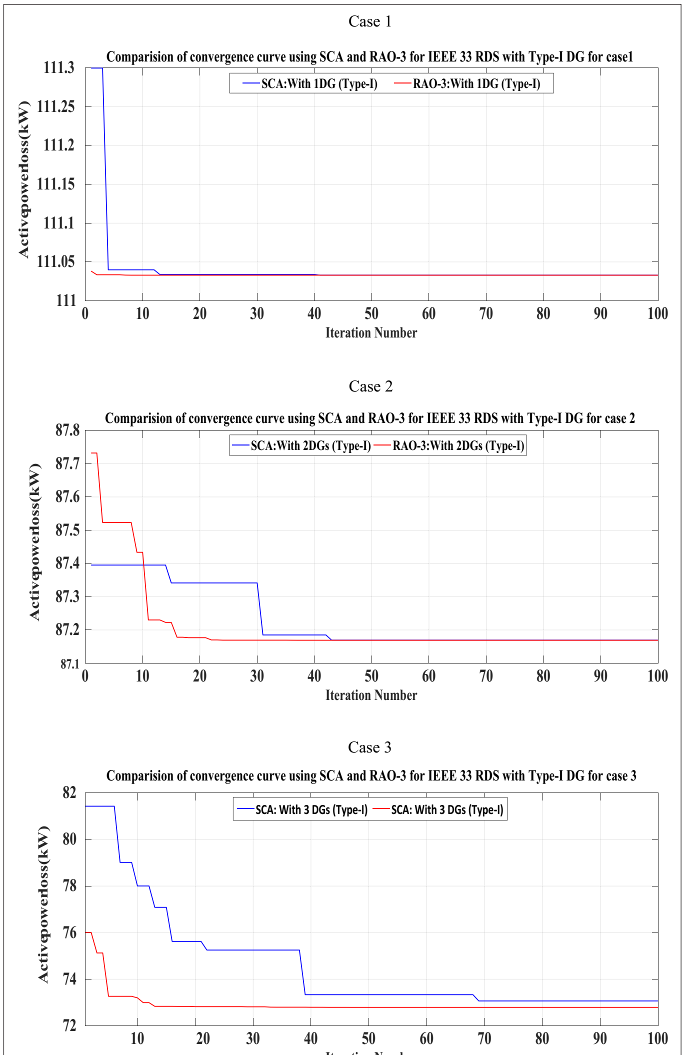


**Fig. 3.** Comparison of convergence curve using SCA and RAO-3 algorithms with Type-I DG in IEEE-33 RDS for different cases 1–3.

Sine cosine algorithm is implemented for optimal DG capacity evaluation using the following steps:

**Step 1:** Generate the initial population of size "NP" randomly using (11), (12), and (13).

Obtain objective function, that is, .e. TPL in RDS using (2).

**Step 2:** Let iteration count t = 1.

**Step 3:** Best candidate solution ($P_{dg,j,b,t}$) is obtained which gives minimum value TPL.

**TABLE III.** COMPARISON OF SCA AND RAO-3 FOR IEEE-33 BUS RDS BASED ON STATISTICAL INFERENCE FOR TYPE-I DG

| Type of DG | Cases | Statistical Inference for 20 Runs (kW) | Optimization Methods | |
|---|---|---|---|---|
| | | | SCA | RAO-3 |
| Type-I | 1 | M | 111.0329 | 111.0329 |
| | | B | 111.0329 | 111.0329 |
| | | W | 111.0329 | 111.0329 |
| | | SD | 0 | 0 |
| | 2 | M | 87.1868 | 87.1691 |
| | | B | 87.1709 | 87.1691 |
| | | W | 87.2190 | 87.1691 |
| | | SD | 0.00298 | 0 |
| | 3 | M | 73.0177 | 72.7889 |
| | | B | 72.8128 | 72.7889 |
| | | W | 73.9351 | 72.7889 |
| | | SD | 0.05378 | 0 |

SCA, sine cosine algorithm; RDS, radial distribution system; DG, distributed generation.

**Step 4:** Initialize $t_{max}$ and calculate $r_{l,t}$ as,

$$r_{1,t} = C - C \times \frac{t}{t_{max}} \tag{15}$$

where t, $t_{max}$ is the current iteration number and the maximum number of iterations, respectively.

**Step 5:** Update each candidate solution using,

$$P'_{dg,j,k,t} = \begin{cases} \left\{P_{dg,j,k,t} + r_{1,t}\sin(r_{2,j})\left|r_{3,j}P_{dg,j,b,t} - P_{dg,j,k,t}\right|\right\} & (r_{4,j,t} < 0.5) \\ \left\{P_{dg,j,k,t} + r_{1,t}\cos(r_{2,j})\left|r_{3,j}P_{dg,j,b,t} - P_{dg,j,k,t}\right|\right\} & \text{otherwise} \end{cases} \tag{16}$$

where $P_{dg,j,k,t}$ and $P'_{dg,j,k,t}$ represents $k^{th}$ solution vector at t and $(t+1)^{th}$ iteration. $P_{dg,j,b,t}$ is the best candidate solution obtained up to iteration t. $r_{2,j}$, $r_{3,j}$ and $r_{4,j}$ are random numbers generated between [0,1]. The random number $r_{3,j}$ provides weightage to $P_{dg,j,b,t}$. $r_1$ is the random

**TABLE IV.** COMPARISON OF OBTAINED RESULTS USING SCA, RAO-3 AND EXISTING METHODS FOR TYPE-III DG ON IEEE-33 BUS RDS

| | Optimal DG Capacity | | | | | | |
|---|---|---|---|---|---|---|---|
| **Algorithm** | **OptimalDG Location** | **kVA** | **Power factor** | **kW** | **kVAR** | **TPL (kW)** | **% RPL** |
| Base case | - | - | - | - | - | 211.0058 | - |
| **Case 1** | | | | | | | |
| DA [10] | 6 | 3073.500 | 0.9000 | 2766.1500 | 1339.7075 | 70.8652 | 66.4145 |
| Hybrid [9] | 6 | 3028.000 | 0.8200 | 2482.9600 | 1733.1167 | 67.9000 | 67.8200 |
| WOA [11] | 6 | 3105.795 | 0.8235 | 2557.6000 | 1762.0000 | 67.8600 | 67.8400 |
| SCA | 6 | 3111.250 | 0.8237 | 2562.8200 | 1764.0422 | 67.8687 | 67.8356 |
| RAO-3 | 6 | 3106.140 | 0.8236 | 2557.6000 | 1761.3656 | 67.8684 | 67.8357 |
| **Case 2** | | | | | | | |
| Hybrid [9] | 13 | 1039.000 | 0.9100 | 945.4900 | 430.7779 | 28.6000 | 86.4400 |
| | 30 | 1508.000 | 0.7200 | 1085.7600 | 1046.5128 | | |
| SCA | 13 | 902.340 | 0.9086 | 819.9300 | 376.7390 | 28.5771 | 86.4567 |
| | 30 | 1588.470 | 0.7397 | 1175.1300 | 1068.7820 | | |
| RAO-3 | 13 | 934.890 | 0.9045 | 845.5830 | 398.7644 | 28.5041 | 86.4913 |
| | 30 | 1557.920 | 0.7303 | 1137.7000 | 1064.3139 | | |
| **Case 3** | | | | | | | |
| Hybrid [9] | 13 | 873.000 | 0.9000 | 785.7000 | 380.5318 | 11.7000 | 94.4500 |
| | 24 | 1186.000 | 0.8900 | 1055.5400 | 540.7691 | | |
| | 30 | 1439.000 | 0.7100 | 1021.6900 | 1013.3462 | | |
| WOA [11] | 24 | 1324.507 | 0.8904 | 1179.3800 | 602.8110 | 16.2800 | 92.2800 |
| | 13 | 1092.008 | 0.8075 | 881.8800 | 644.0270 | | |
| | 30 | 1213.215 | 0.7860 | 953.6200 | 750.0000 | | |
| SCA | 13 | 913.1880 | 0.8926 | 815.4380 | 411.0620 | 12.2265 | 94.2050 |
| | 24 | 1146.630 | 0.9511 | 1090.6500 | 353.8690 | | |
| | 30 | 1403.260 | 0.6842 | 960.0570 | 1023.4500 | | |
| RAO-3 | 13 | 877.270 | 0.9049 | 793.8600 | 373.3630 | 11.699 | 94.4556 |
| | 24 | 1188.400 | 0.9004 | 1070.0500 | 517.1600 | | |
| | 30 | 1443.400 | 0.7134 | 1029.7300 | 1011.520 | | |

SCA, sine cosine algorithm; RDS, radial distribution system; DG, distributed generation; WOA, Whale Optimization Algorithm. TPL, total real power loss.

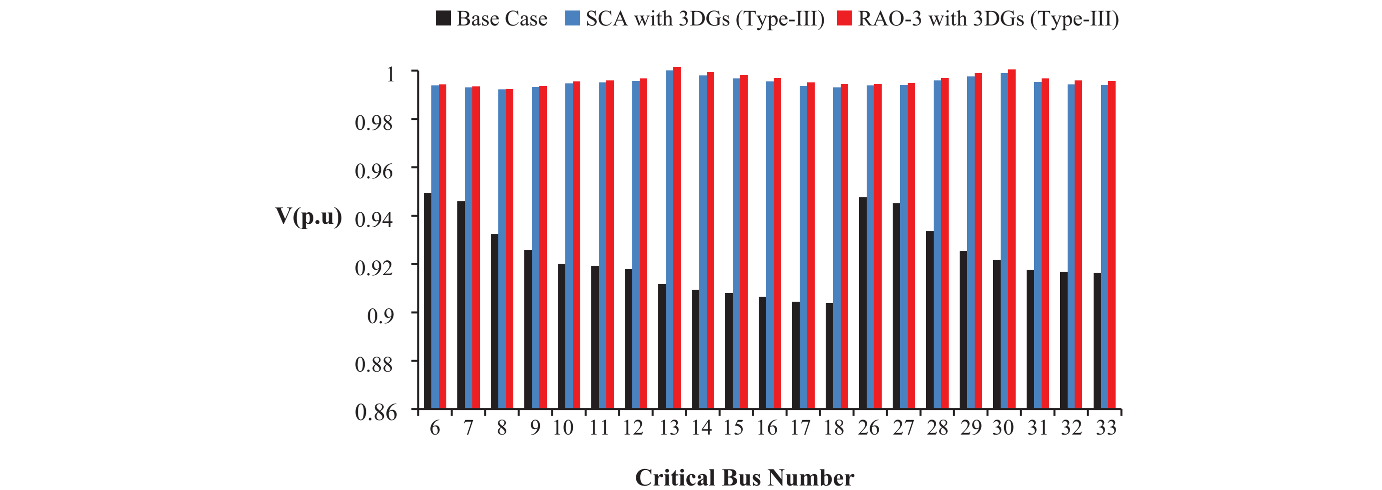


**Fig. 4.** Comparison of voltage profile with and without integration of Type-III DG for IEEE-33 RDS.

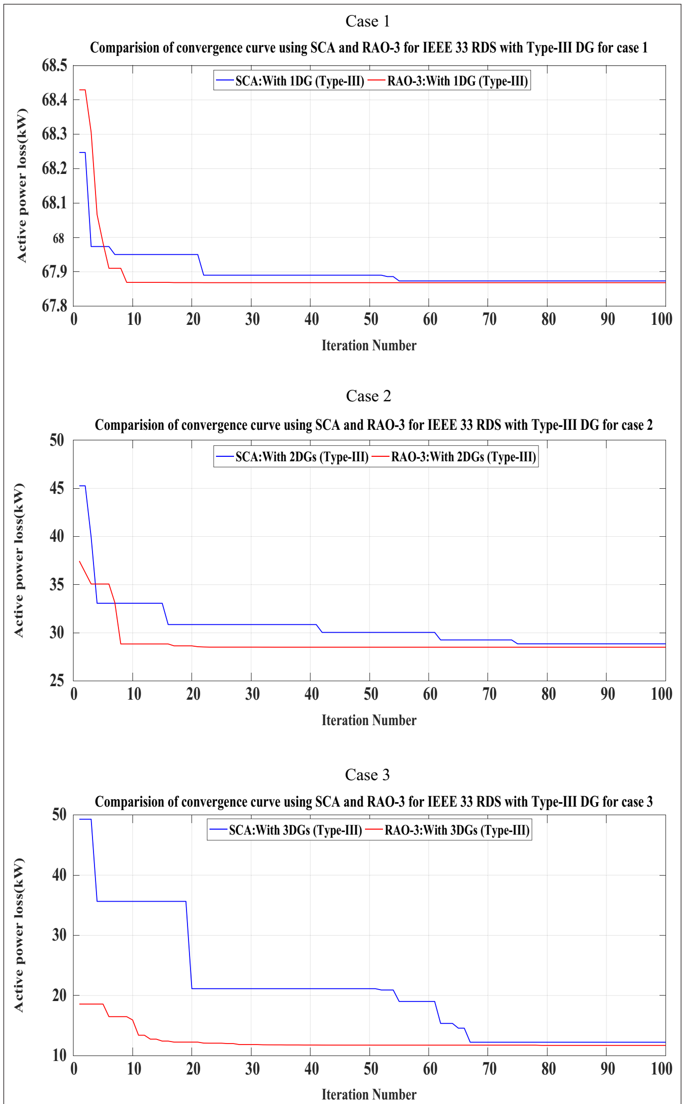


**Fig. 5.** Comparison of convergence curve using SCA and RAO-3 algorithms with Type-III DG in IEEE-33 RDS for different cases 1–3.

number that controls exploration and exploitation during the search process.

**Step 6:** If any control variable generated using (16) violates the bound, then apply the bounce back technique [24]. Update control parameter $r_{1,t}$ using (15).

**Step 7:** TPL is evaluated and increase generation $t = (t+1)$ and repeat from steps 3–6 till $t = t_{max}$.

**Step 8:** Store the optimal solution, TPL, and voltage profile at each bus.

**TABLE V.** COMPARISON OF SCA AND RAO-3 FOR IEEE-33 BUS RDS BASED ON STATISTICAL INFERENCE FOR TYPE-III DG

| Type of DG | Cases | Statistical Inference for 20 Runs (kW) | Optimization Methods | |
|---|---|---|---|---|
| | | | SCA | RAO-3 |
| Type-III | 1 | M | 67.8743 | 67.8684 |
| | | B | 67.8687 | 67.8684 |
| | | W | 67.9004 | 67.8684 |
| | | SD | 0.001579 | 0 |
| | 2 | M | 28.9943 | 28.5041 |
| | | B | 28.5771 | 28.5041 |
| | | W | 29.6386 | 28.5041 |
| | | SD | 0.05148 | 0 |
| | 3 | M | 13.5059 | 11.699 |
| | | B | 12.2265 | 11.699 |
| | | W | 15.8467 | 11.699 |
| | | SD | 0.1902 | 0 |

SCA, sine cosine algorithm; RDS, radial distribution system; DG, distributed generation.

**TABLE VI.** COMPARISON OF OBTAINED RESULTS USING SCA, RAO-3 AND EXISTING METHODS FOR TYPE-I DG ON IEEE-69 BUS RDS.

| Algorithm | Optimal DG Location | Optimal DG Size (kW) | Total DG Capacity (kW) | TPL (kW) | % RPL |
|---|---|---|---|---|---|
| Base case | - | - | - | 224.9584 | - |
| **Case 1** | | | | | |
| DA [10] | 61 | 1872.7000 | 1872.7000 | 83.2200 | 63.0133 |
| PSO [9] | 61 | 1870.0000 | 1870.0000 | 83.2200 | 63.0100 |
| Hybrid [9] | 61 | 1810.0000 | 1810.0000 | 83.3700 | 62.9500 |
| Heuristic [12] | 61 | 1823.0000 | 1823.0000 | 83.3000 | 63.0200 |
| WOA[11] | 61 | 1856.100 | 1856.1000 | 83.1800 | 63.0200 |
| SCA | 61 | 1872.6149 | 1872.6149 | 83.1889 | 63.0203 |
| RAO-3 | 61 | 1872.6445 | 1872.6445 | 83.1889 | 63.0203 |
| **Case 2** | | | | | |
| PSO [9] | 61 | 1780.0000 | 2310.0000 | 71.6800 | 68.14 |
| | 17 | 530.0000 | | | |
| Hybrid [9] | 61 | 1720.0000 | 2240.0000 | 71.8000 | 68.0900 |
| | 17 | 520.0000 | | | |
| Heuristic [12] | 61 | 1733.0000 | 2253.0000 | 71.8000 | 68.0800 |
| | 17 | 520.0000 | | | |
| SCA | 17 | 530.888 | 2308.689 | 71.6561 | 68.1469 |
| | 61 | 1777.801 | | | |
| RAO-3 | 17 | 531.168 | 2312.626 | 71.6550 | 68.1474 |
| | 61 | 1781.458 | | | |
| **Case 3** | | | | | |
| PSO [9] | 61 | 1700.0000 | 2600.0000 | 69.5400 | 69.09 |
| | 17 | 440.0000 | | | |
| | 11 | 460.0000 | | | |
| Hybrid [9] | 61 | 1670.0000 | 2560.0000 | 69.5400 | 69.0900 |
| | 17 | 380.0000 | | | |
| | 11 | 510.0000 | | | |
| Heuristic [12] | 61 | 1689.0000 | 2472.0000 | 69.7000 | 69.022 |
| | 21 | 312.0000 | | | |
| | 12 | 471.0000 | | | |
| WOA [11] | 11 | 489.0200 | 2645.8000 | 69.7200 | 69.0000 |
| | 18 | 476.4800 | | | |
| | 61 | 1680.3000 | | | |
| SCA | 11 | 504.497 | 2682.051 | 69.4199 | 69.1410 |
| | 18 | 392.878 | | | |
| | 61 | 1784.676 | | | |
| RAO-3 | 11 | 526.782 | 2625.795 | 69.4072 | 69.1466 |
| | 18 | 380.056 | | | |
| | 61 | 1718.957 | | | |

SCA, sine cosine algorithm; RDS, radial distribution system; DG, distributed generation; WOA, Whale optimization algorithm; PSO, particle swarm optimization; TPL, total real power loss.

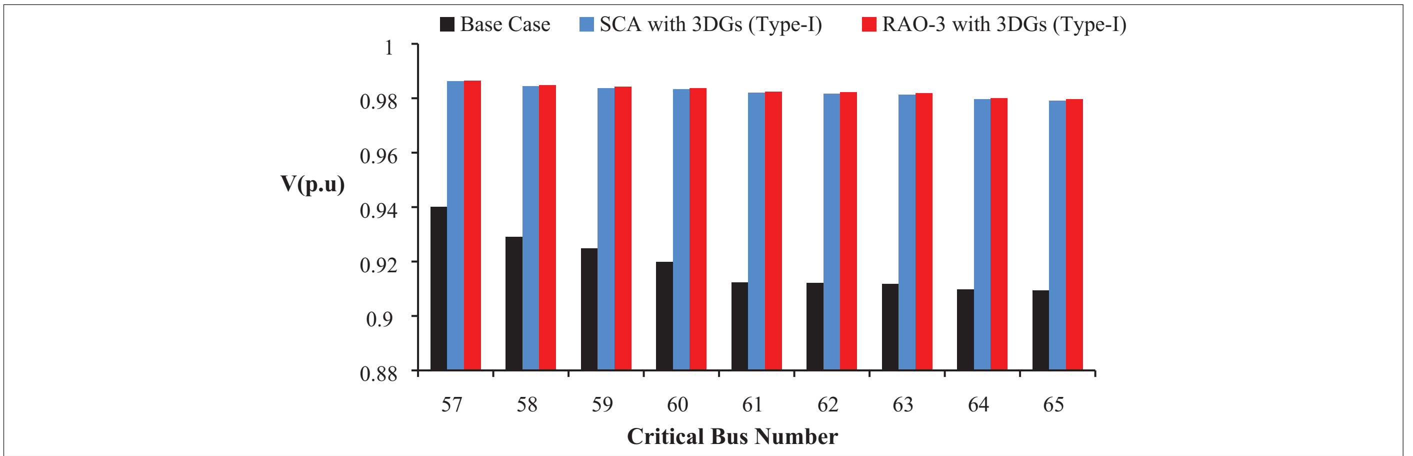


**Fig. 6.** Comparison of voltage profile with and without integration of Type-I DG for IEEE-69 RDS.

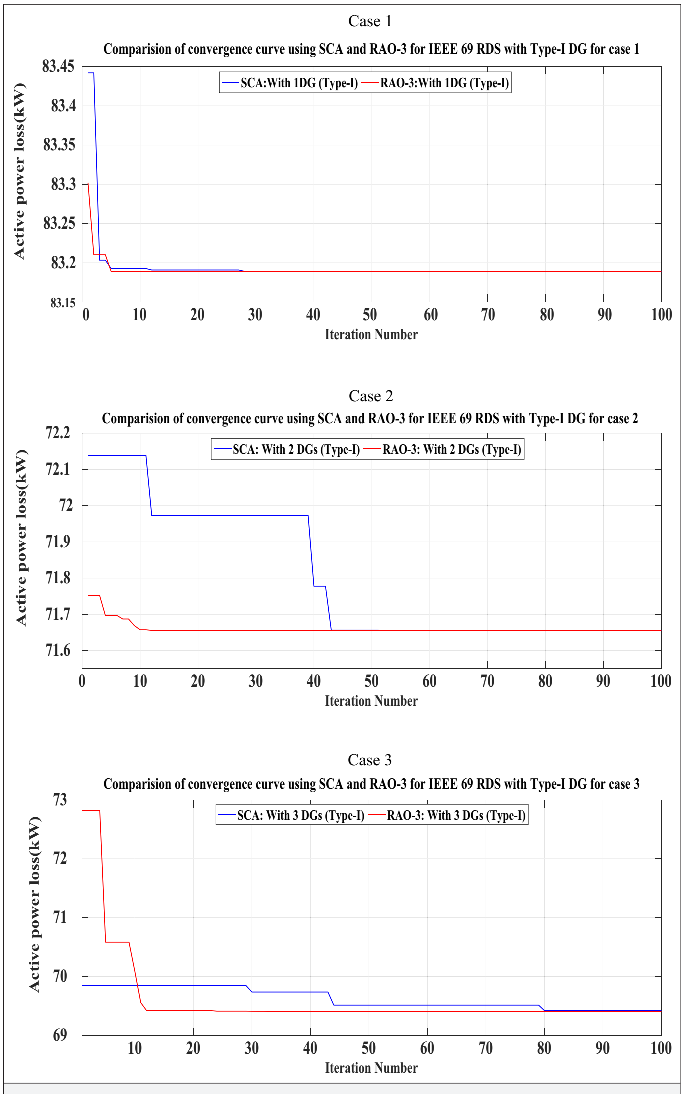


**Fig. 7.** Comparison of convergence curve using SCA and RAO-3 algorithms with Type-I DG in IEEE-69 RDS for different cases 1–3.

## V. RESULTS AND DISCUSSION

Optimal capacities of DGs with minimum active power loss are evaluated at optimal bus locations using the RAO-3 algorithm and validated by using SCA and compared with results for existing algorithms from the literature. These algorithms are tested on two test systems, that is, IEEE-33 and -69 bus RDS. Both systems have base voltage and apparent power of 12.66 kV and 100 MVA. The following three cases are considered for both test systems with two types of DGs (Type-I and Type-III) integrated at optimal locations.

Case 1: Integrating one DG of Type-I or Type-III

**TABLE VII.** COMPARISON OF SCA AND RAO-3 FOR IEEE-69 BUS RDS BASED ON STATISTICAL INFERENCE FOR TYPE-I DG.

| Type of DG | Cases | Statistical Inference for 20 Runs (kW) | Optimization Methods | |
|---|---|---|---|---|
| | | | SCA | RAO-3 |
| Type-I | 1 | M | 83.1889 | 83.1889 |
| | | B | 83.1889 | 83.1889 |
| | | W | 83.1889 | 83.1889 |
| | | SD | 0 | 0 |
| | 2 | M | 71.6718 | 71.655 |
| | | B | 71.6561 | 71.655 |
| | | W | 71.7172 | 71.655 |
| | | SD | 0.0036 | 0 |
| | 3 | M | 70.3585 | 69.4072 |
| | | B | 69.4199 | 69.4072 |
| | | W | 73.586 | 69.4072 |
| | | SD | 0.2677 | 0 |

SCA, sine cosine algorithm; RDS, radial distribution system; DG, distributed generation.

Case 2: Integrating two DGs of Type-I or Type-III

Case 3: Integrating three DGs of Type-I or Type-III

For all the cases, direct load flow method is used to obtain the voltage profile and total real power losses [4]. The control parameters used for optimization using RAO-3 and SCA are given in Table I.

### A. IEEE 33-Bus Radial Distribution System

This system consists of 32 branches and 33 buses [11]. Total active and reactive power loads are 3715 kW and 2300 kVAR, respectively. Total real power loss before integration of any type of DG is 211.0058 kW. Critical buses are those buses that violate their upper and lower bound voltage limits given in (7). It is observed that for this test system, critical bus numbers are 6–18 and 26–33.

#### *1) Integrating Type-I* Distributed Generations for IEEE-33 Bus Radial Distribution System

Table II shows results obtained for optimal capacity of Type-I DG with minimum real power loss and percentage reduction in active power loss (RPL) at the optimal locations for cases 1–3 using RAO-3, SCA, and other existing algorithms.

**TABLE VIII.** COMPARISON OF OBTAINED RESULTS USING SCA, RAO-3 AND EXISTING METHODS FOR TYPE-III DG ON IEEE-69 BUS RDS

| | | Optimal DG Capacity | | | | | |
|---|---|---|---|---|---|---|---|
| **Algorithm** | **Optimal DG Location** | **kVA** | **Power factor** | **kW** | **kVAR** | **TPL (kW)** | **% RPL** |
| Base case | - | - | - | - | - | 224.9584 | - |
| **Case 1** | | | | | | | |
| DA [10] | 61 | 2217.300 | 0.9000 | 1995.5700 | 966.4986 | 27.9636 | 87.5717 |
| Hybrid [9] | 61 | 2240.000 | 0.8100 | 1814.4000 | 1313.6029 | 23.1900 | 89.7000 |
| WOA [11] | 61 | 2239.478 | 0.8090 | 1811.8000 | 1316.3000 | 23.1500 | 89.7100 |
| SCA | 61 | 2239.440 | 0.8150 | 1825.2200 | 1297.5572 | 23.1452 | 89.7113 |
| RAO-3 | 61 | 2243.740 | 0.8149 | 1828.4000 | 1300.4990 | 23.1448 | 89.7115 |
| **Case 2** | | | | | | | |
| Hybrid [9] | 17 | 630.000 | 0.8200 | 516.6000 | 360.5890 | 7.2100 | 96.7955 |
| | 61 | 2120.000 | 0.8100 | 1717.2000 | 1243.2313 | | |
| SCA | 17 | 616.495 | 0.8234 | 507.5960 | 349.8757 | 7.2544 | 96.7752 |
| | 61 | 2104.58 | 0.8202 | 1726.2200 | 1203.9126 | | |
| RAO-3 | 17 | 630.258 | 0.8283 | 522.034 | 353.138 | 7.1995 | 96.7996 |
| | 61 | 2131.36 | 0.8138 | 1734.66 | 1238.402 | | |
| **Case 3** | | | | | | | |
| Hybrid[9] | 18 | 480.000 | 0.7700 | 369.6000 | 306.2610 | 4.3000 | 98.088 |
| | 61 | 2060.000 | 0.8300 | 1709.8000 | 1149.0000 | | |
| | 66 | 530.000 | 0.8200 | 434.6000 | 303.3526 | | |
| WOA [11] | 61 | 1888.735 | 0.8366 | 1580.52 | 1034.0600 | 5.6300 | 97.4900 |
| | 21 | 361.164 | 0.7789 | 281.3300 | 226.4800 | | |
| | 11 | 783.170 | 0.8854 | 693.4300 | 364.0200 | | |
| SCA | 11 | 539.176 | 0.6991 | 376.945 | 385.517 | 4.4481 | 98.0220 |
| | 18 | 501.053 | 0.8642 | 433.028 | 252.073 | | |
| | 61 | 2084.62 | 0.8250 | 1719.85 | 1178.035 | | |
| RAO-3 | 11 | 607.821 | 0.8134 | 494.428 | 353.536 | 4.2650 | 98.1040 |
| | 18 | 454.604 | 0.833 | 378.836 | 251.292 | | |
| | 61 | 2057.39 | 0.8138 | 1674.42 | 1195.46 | | |

SCA, sine cosine algorithm; RDS, radial distribution system; DG, distributed generation; WOA, whale optimization algorithm; TPL, total real power loss.

Results show that RPL for case 1 with the integration of one DG at optimal bus location 6 is 47.379% using RAO-3 which is observed as in close agreement with SCA and other existing algorithms. RPL for case 2, that is, integrating two DGs at optimal bus locations 13 and 30 is 58.6887% using RAO-3 which is slightly good as compared with SCA and others. Similarly, for case 3 with integrating 3 DGs at optimal bus locations 13, 24, and 30 using RAO-3, a reduction in a real power loss of 65.5038% is better than all other algorithms.

Figure 2 represents a comparison of voltage profiles at critical buses with and without the integration of three DGs (Case 3) of Type-I using SCA and RAO-3 algorithms. By integrating one, two, and three DGs at optimal locations of Type-I, voltages are improved gradually but it shows much improvement for case 3, that is, with the integration of three DGs.

Figure 3 shows a comparison of convergence characteristics of SCA and RAO-3 for cases 1, 2, and 3 with Type-I DGs at optimal locations for IEEE-33 bus RDS. It is observed that the RAO-3 algorithm requires fewer iterations to converge as compared to SCA.

Table III represents the performance of the proposed algorithms SCA and RAO-3 based on statistical inference such as mean value (M), best value(B), worst value (W), and standard deviation (SD) of the objective function as active power loss minimization of RDS. Twenty runs are taken for each statistical inference and the RAO-3 method yields the same optimal solution without any deviation which is advantageous as compared to other algorithms.

***2) Integrating Type-III Distributed Generations for IEEE-33 Bus Radial Distribution System***

From Table IV, it is noticed that with the integration of one DG of Type-III at optimal bus location 6 for case 1, RPL is obtained as 67.8357% which is nearly the same as that of SCA but better than that of Dragonfly and Hybrid methods. While integrating two DGs of the same kind at optimal bus locations 13 and 30 for case 2, RPL by RAO-3 method is 86.4913 % which is better than that of SCA and hybrid approach. Similarly, while integrating three DGs of Type-III at optimal bus locations 13, 24, and 30 for case 3, RPL is observed as 94.4556% which is much better compared to that of SCA and WOA.

Figure 4 indicates improvement in voltage profiles at critical buses while integrating three DGs of Type-III for case 3 using SCA and RAO-3 as compared to the base case.

Figure 5 gives comparison of convergence characteristics of SCA and RAO-3 for cases 1, 2, and 3 of Type-III DG at optimal locations for IEEE-33 bus RDS. It is notified that the RAO-3 algorithm has fast convergence characteristic as compared to SCA.

Table V presents a comparison of SCA with the RAO-3 algorithm based on statistical inference and zero SD is obtained with the RAO-3 method.

**B. IEEE-69 Bus Radial Distribution System**

This system consists of 68 branches and 69 buses [11]. Total active and reactive power loads are 3801 kW and 2694 kVAR, respectively. Total real power losses for base case means without integration of any type of DG is 224.9584 kW. It is observed that critical bus numbers for this test system are 57–65 whose voltage magnitude is less than 0.95 per unit as expressed in (7).

***1) Integrating Type-I Distributed Generation for IEEE-69 Bus Radial Distribution System***

Table VI shows a comparison of TPL, DG capacities, and RPL at optimal locations using RAO-3, SCA, and other existing algorithms for Type-I DG on IEEE-69 bus RDS for all cases. The RPL with RAO-3 and SCA is 63.0203% for case 1 at optimal bus location 61. This value of RPL is very close on the better side as compared to other algorithms. The RPL for case 2 with the RAO-3 method when 2 DGs are placed at optimal bus locations 17 and 61 is 68.1474% which shows better results as compared to SCA and other existing methods. Similarly, RPL with the RAO-3 method for case 3, that is, when three DGs are placed at optimal bus locations 11, 18, and 61 is 69.1466 % which is higher compared to that of SCA and other optimization methods.

Figure 6 shows improvement in voltage profiles at critical buses while integrating three DGs of Type-I for case 3 using SCA and RAO-3 with respect to the base case. For cases 1–3 with the integration of Type-I DGs at optimal locations, voltages are improved gradually but this improvement is much better for case 3.

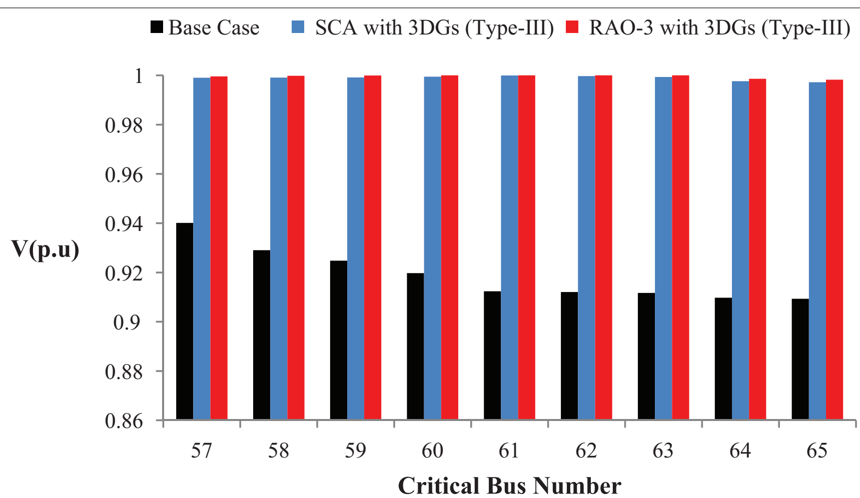


**Fig. 8.** Comparison of voltage profile with and without integration of Type-III DG for IEEE-69 RDS.

Figure 7 illustrates the comparison of the convergence curve representing TPL for cases 1–3 when Type-I DGs have been integrated into IEEE-69 bus RDS with the SCA and RAO-3 method.

Statistics of TPL for 20 runs with SCA and RAO-3 method for IEEE-69 RDS with Type-I DGs for all cases are presented in Table VII and again zero SD advantage is observed with the RAO-3 method.

***2) Integrating Type-III Distributed Generation for IEEE-69 Bus Radial Distribution System***

From Table VIII, it is observed that while integrating Type-III DG at optimal bus location 61 for case 1, a reduction in active power loss is obtained as 89.7115% which is nearly the same as that of SCA but better than Dragonfly and hybrid algorithms. For case 2 with two DGs of Type-III at optimal bus locations 17 and 61, a reduction in active power loss is obtained as 96.7996% by the RAO-3 method which is in close agreement with the hybrid method but better than SCA. While integrating three DGs for case 3 of Type-III at optimal bus locations 11, 18, and 61 the reduction in real power loss is 98.104%, which is better compared to SCA, Hybrid method, and WOA.

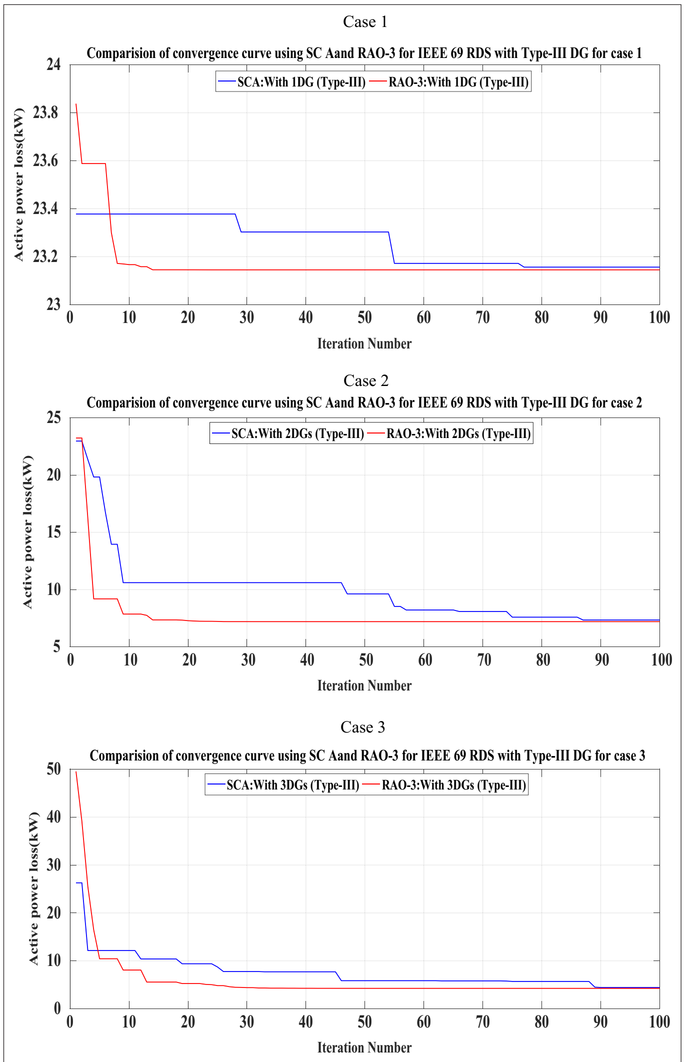


**Fig. 9.** Comparison of convergence curve using SCA and RAO-3 algorithms with Type-III DG in IEEE-69 RDS for different cases 1–3.

**TABLE IX.** COMPARISON OF SCA AND RAO-3 FOR IEEE-69 BUS RDS BASED ON STATISTICAL INFERENCE FOR TYPE-III DG.

| Type of DG | Cases | Statistical Inference for 20 Runs (kW) | Optimization Methods | |
|---|---|---|---|---|
| | | | SCA | RAO-3 |
| Type-III | 1 | M | 23.1538 | 23.1448 |
| | | B | 23.1452 | 23.1448 |
| | | W | 23.1964 | 23.1448 |
| | | SD | 0.00241 | 0 |
| | 2 | M | 7.5846 | 7.1995 |
| | | B | 7.2544 | 7.1995 |
| | | W | 8.1573 | 7.1995 |
| | | SD | 0.04572 | 0 |
| | 3 | M | 5.2714 | 4.265 |
| | | B | 4.4481 | 4.265 |
| | | W | 6.6904 | 4.265 |
| | | SD | 0.1103 | 0 |

SCA, sine cosine algorithm; RDS, radial distribution system; DG, distributed generation.

Figure 8 shows improvement in voltage profile at critical buses while integrating three DGs of Type-III using SCA and RAO-3 concerning the base case.

**TABLE X.** COMPARISON OF CONVERGENCE TIME (SECOND) REQUIRED FOR SCA AND RAO-3 FOR BOTH TEST SYSTEMS

| Test system | DG Type | Cases | Convergence Time (Second) | |
|---|---|---|---|---|
| | | | SCA | RAO-3 |
| IEEE-33 | Type-I | 1 | 26.5398 | 12.9603 |
| | | 2 | 17.2226 | 12.5722 |
| | | 3 | 19.1344 | 12.2222 |
| | Type-III | 1 | 18.8929 | 17.7640 |
| | | 2 | 18.2082 | 17.0691 |
| | | 3 | 18.031 | 16.6616 |
| IEEE-69 | Type-I | 1 | 28.9571 | 19.9986 |
| | | 2 | 33.588 | 22.1266 |
| | | 3 | 32.8327 | 21.3581 |
| | Type-III | 1 | 23.4303 | 20.7536 |
| | | 2 | 22.1854 | 17.8939 |
| | | 3 | 22.1378 | 20.0297 |

SCA, sine cosine algorithm; RDS, radial distribution system; DG, distributed generation.

Figure 9 illustrates the comparison of the convergence curve for TPL for cases 1–3 with Type-III DGs for IEEE-69 bus RDS with SCA and RAO-3 techniques. It is observed that the convergence rate of RAO-3 is higher as compared to SCA.

Table IX represents a comparison of the performance of the SCA and RAO-3 method for IEEE-69 bus RDS based on statistical inference for Type-III DG for cases 1, 2, and 3. RAO-3 method yields the same optimal solutions without any deviation for multiple runs.

Table X summarizes a comparison of convergence time (second) required for SCA and RAO-3 algorithms for cases 1–3 with the integration of Type-I or Type-III DGs for both standard RDS. It is observed that the RAO-3 method required less convergence time as compared to that of SCA for all cases.

## VI. CONCLUSION

This work presents a metaphor-less RAO-3 method and SCA algorithm for optimal sizing of DGs to minimize total active power loss in standard RDS. Loss sensitivity factor, normalized voltage magnitude, and load at each bus are used to identify the optimal location for DGs. These algorithms are tested on IEEE-33 and -69 bus RDS with the integration of Type-I or Type-III DG. It is notified that the percentage reduction in active power loss achieved by the RAO-3 and SCA method while integrating one DG of either Type-I or Type-III on both test systems for case 1 is nearly in close agreement with other existing methods but it is better for case 2. The results show remarkable active power loss reduction using the RAO-3 method for case 3, that is, while integrating three DGs of either Type-I or Type-III on both test systems as compared to SCA and other methods. It was observed that the RAO-3 method provides the best result and converges early as compared to SCA. Samples of real power loss for 20 runs are obtained in each case with different types of DGs for statistical analysis. It was observed that the standard deviation is minimum with the RAO-3 method as compared to SCA.

In addition, the voltage profile at critical buses is observed and more improvement is observed while integrating three DGs (Case 3) of Type-I or Type-III on two standard test systems.

**Peer-review:** Externally peer-reviewed.

**Author Contributions:** Concept – S.S.H., R.A., A.K.; Design – S.S.H.; Supervision – R.A., A.K.; Materials – S.S.H.; Data Collection and/or Processing – S.S.H., R.A., A.K.; Analysis and/or Interpretation – S.S.H., R.A., A.K.; Literature Review – S:S.H.; Writing – S.S.H.; Critical Review – S.S.H., R.A., A.K.

**Declaration of Interests:** The authors have no conflicts of interest to declare.

**Funding:** The authors declared that this study has received no financial support.

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