International Journal of Applied Mathematics

Volume 38 No. 5s, 2025

ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

MULTI-OBJECTIVE OPTIMIZATION FRAMEWORK FOR SITING AND SIZING OF RENEWABLE DISTRIBUTED GENERATORS IN IEEE-33 BUS RADIAL DISTRIBUTION NETWORKS

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Abstract

Transmission networks may be integrated with renewable dispersed generation (DG), including such as photovoltaic (PV) systems & wind turbines (WT), as a bright and effective response to the rising demand. In addition to enhancing voltage consistency, this study introduces an unique robust and efficient hybrid optimization algorithm that proposes to identify the ideal site with practical size of DG units. There are two stages in applied work. First, the best candidate busses for DG deployment are chosen using the Loss Sensitive Factor (OSFs). The technique is utilized in the next stage to determine the best siting and size of the DG among the selected buses. The suggested approach has been tested on IEEE standards radial distribute systems with 33-bus configurations. The investigated outcomes have been matched with those of other methodologies, including Simulation Annealing Method (SA), Genetic Algorithm (GA), Book merged Genetic Algorithm as well as Particles Swarm Optimization (GA/PSO), but also Bacterial Foraging Optimization Method, to ensure the validity of the suggested approach. The superiority and high efficiency of the suggested method to identify the best options for allocating DG units have been proven by the quantitative finding with use of MATLAB.

Keywords: Optimal Distributed Generation (DG) Sizing, Metaheuristic Optimization, Radial Distribution Systems, Real Power Losses.

Received: August 06, 2025

1. Introduction

In recent years, distributed generation (DG) has been recognized as a cornerstone of modern power distribution due to its role in strengthening system sustainability, operational efficiency, and supply reliability [1,19]. The integration of DG into radial distribution systems requires precise analytical frameworks, where advanced modelling and power flow analysis provide the foundation for evaluating system behaviour [2,7]. Research consistently shows that the location and capacity of DG units have a decisive impact on power loss reduction, voltage regulation, and economic viability, making DG allocation a complex but high-priority task [3,6,10,11]. To address this, researchers have widely adopted metaheuristic optimization techniques, ranging from improved PSO and GEPSO to hybrid bio-inspired algorithms such as bat and artificial rabbits optimization, with the objective of maximizing performance under practical constraints [4,5,8,9,12,14]. The research trend has further expanded to include challenges such as harmonic distortion, stochastic variations, diverse DG technologies, and the integration of microgrid structures [13,16,17]. Hybrid and swarm-based approaches have demonstrated superior performance in multi-objective environments, outperforming classical strategies [15,18,20]. Yet, ensuring reliable outcomes under realistic load variations and system uncertainties remains a persistent research gap, underscoring the demand for robust hybrid optimization frameworks in DG planning.

At the same time, the identified optimization approaches can be used to create combinations capable of surpassing typical approaches, as this research has demonstrated. It was found that optimisation and integration of distributed generations is a growing field with its own different approaches and techniques. Current studies on quantum machine learning and combos of first and second-order optimization point at the necessity of a more elaborate approach to these energy systems. In many situations as the transition to renewable energy moves forward, research will be critical to developing sustainable strategies for distributed generation and tools. By implementing IEEE radial distributing networks with 33-bus the suggested system and methodology have been incorporated and the results derived were comparable to the results derived using other methods.

The QPSOGSA is an optimization method that blends features from the Particle Swarm Optimization (PSO) and the Gravitational Search Algorithm (GSA) using principles from Quantum Physics. The contributions are as follows:

1. Regarding Quantum-Inspired Exploration:
   i. Novelty: The methods used by QPSOGSA are quantum-inspired exploration techniques.
   ii. Quantum Probability Laws: The rules of quantum probability regulation are behind this process and promote finding a unique solution that does not exist at all.
   iii. Global Search Capability: The global exploration is performed based on Quantum-inspired exploration and it helps QPSOGSA to achieved better solutions.
2. Thus, Implementation can lead to Improved Robustness and Performance.
   i. Novelty: Meaning that QPSOGSA shows improvement in its performance as well as the algorithmic model’s resistance to deviations from its ideal form.

Received: August 06, 2025

Volume 38 No. 5s, 2025
ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

ii. Robustness: They are robust and work efficiently within uncertainties or system variation.

3. Enhanced Control Effort: The QPSOGSA scheme is more effective in terms of control effort than any other method because the control effort has a wider operation range for the overall system.

2.1. Creating an energy flow

For energy flow calculations, the Backward/Forward Sweeps (BFS) technique is used. Fig.1. shows an example distribution system where 2 buses "K" and "B" are connected by a line Z.

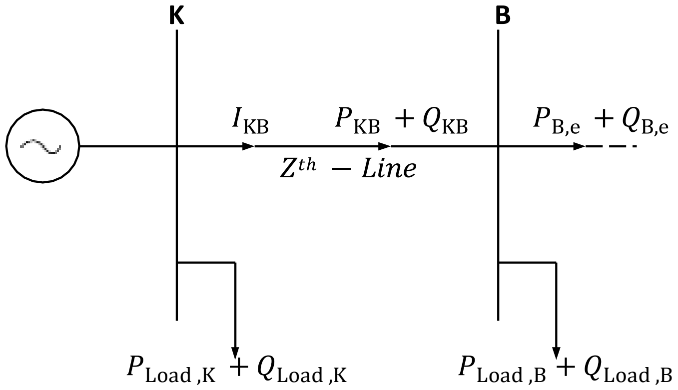

Fig. 1. A representation of transmission line

Kirchhoff's voltages & currents theory is the foundation for the 3 steps that make up the study of the BFS technique (KVL and KCL respectively). Nodal Current, Back-Ward Sweep, and For-Ward Sweep Analyses make up the 3 steps. These actions are dependent on converging successes if the highest voltage difference is lower than the epsilon tolerances "mistake" (in this study, $\varepsilon = 0.000001$ was taken into consideration). After converging, it is simple to assess the active and reactive energy loses for the radial distributing network. The estimated BFS power flow is determined as follows:

In Eq. (1) backward sweeps direction from the final node, the active energy (P_{KB}) and reactive energy (Q_{KB}) that flow through nodes "K" to node "B" via branch "Z" may be deduced as,

$$P_{KB} = P'_B + R_{KB}\frac{P_B'^2 + Q_B'^2}{V_B^2} \quad (1)$$

$$Q_{KB} = Q'_B + X_{KB}\frac{P_B'^2 + Q_B'^2}{V_B^2} \quad (2)$$

Where, $P_{KB} = P_B + P_{YB}$ and $Q_{KB} = Q_B + Q_{YB}$; P_{YB} and Q_{YB} are loads connected at node "B".

The amount and inclination of the voltage at every node are displayed by the directions of the backward sweep in Eq. (2). Assume a voltage at nodes 'K' of $V_K\angle\partial_K$ with a voltage at nodes 'B' of $V_B\angle\partial_B$. The nodal current study at node 'K' going along branches 'Z' with impedance $A_{KB} = R_{KB} + j\,X_{KB}$ is calculated by,

Received: August 06, 2025

ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

$$I_{KB} = \frac{(V_K\angle\partial_K - V_B\angle\partial_B)}{R_{KB} + j\,X_{KB}} \quad (3)$$

$$I_K = \frac{(P_K - j\,Q_K)}{V_K\angle -\partial_K} \quad (4)$$

A voltage on bus "B" may be calculated as follows using Eq. (3) & (4):

$$V_B = \left(V_B^2 - 2 * (P_K R_{KB} + j\,Q_K X_{KB}) + (R_{KB}^2 + X_{KB}^2) * \left(\frac{P_K^2 + Q_K^2}{V_K^2}\right)\right)^{\frac{1}{2}} \quad (5)$$

The voltage & inclination at each node of the radially distribution systems may be determined using the amplitude and phases angle expressions, correspondingly, in a forward sweeps orientation. It is possible to calculate the active & reactive energy losses of line "Z" connecting buses "K" & "B" as follows:

$$P_{L(KB)} = R_{KB} \frac{P_{KB}^2 + Q_{KB}^2}{V_K^2} \quad (6)$$

$$Q_{L(KB)} = X_{KB} \frac{P_{KB}^2 + Q_{KB}^2}{V_K^2} \quad (7)$$

The radial distributing system's overall real energy loss may be calculated as,

$$P_{Total_{loss}} = \sum_{B=1}^{NOBR} P_{loss(KB)} \quad (8)$$

If $K = 1: NOB$, "NOBR" stands for the numbers of branch, while "NOB" stands for the quantity of busses.

2.2 Using DG units to calculate energy losses

The energy loss across a lines section shown Figure 1 may be calculated once DG units have been located in the distribution system as,

$$P_{DG_{loss}}(KB) = R_{KB} \frac{P_{DG(KB)}^2 + Q_{DG(KB)}^2}{V_K^2} \quad (9)$$

The resulting Eq. (10), when applied, yields the total power failure:

$$P_{DG,Total_{loss}} = \sum_{B=1}^{NOBR} P_{DG_{loss}}(KB) \quad (10)$$

2.3 Index of energy loss

According to [20], the powers loss indices $\Delta\, Ploss_{DG}$ are calculated as that of the ratio of the overall energy loss including DG units towards the overall energy losses without DG.

$$\Delta\, Ploss_{DG} = \frac{P_{DG,Total_{loss}}}{P_{Total_{loss}}} \quad (11)$$

2.4 Measure of Voltage Variations

The following equations can be used to measure the voltage variation indices $\Delta\, V_{deviation}$: [20]

$$\Delta\, V_{deviation} = maximum\ \left(\frac{V_1 - V_K}{V_1}\right), for\ K = 1,2,3, \ldots\ldots\ldots, NOB \quad (12)$$

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2.5 Reducing Operating Expenses

One benefit of installing DGs in distribution systems is said to be the reduction of operational costs [20]. There are two parts to the operating cost. The initial one is considered to be the substation's operational active power supply. The other part is for price of the operational power provided by integrated DG devices. The following Eq. (13) may be used to reduce the overall operational cost (ROE):

$$ROE = (CC_1 P_{DG,Total_{loss}} + CC_2 P_{Total,DG}) \quad (13)$$

While CC_1 & CC_2 are the pricing coefficients in $/kW for the overall real energy loss after integrating DG & supplied energy by DG, respectively. The overall operational active power used by the mounted DG units is expressed as $P_{Total,DG}$. The following is a deduction of the net operational cost OE that may be lowered:

$$\Delta\, OE = \frac{ROE}{P^{MAXI}_{Total,DG}} \quad (14)$$

2.6 Fundamental purpose

This study's primary objective functions are a multi-objective service designed to reduce the distributing network's overall operating costs, power failure, and voltages variation. It is produced by the subsequent feature:

$$minimize(OF) = minimum(\gamma_1 \Delta\, Ploss_{DG} + \gamma_2 \Delta\, V_{deviation} + \gamma_3 \Delta\, OE\,) \quad (15)$$

Where

$$\sum_{x=1}^{3} \gamma_x = 1\, for \quad 0 \le \gamma_x \le 1 \quad (16)$$

These γ_x parameters are regarded as the objectives function's weighting variables. Some constraints are used to minimize this objectives function:

- Balancing of Power
$$\sum_{K=2}^{NOB} P_{DG(KB)} = \sum_{K=2}^{NOB} P_K + \sum_{B=1}^{NOBR} P_{loss(KB)} \quad (17)$$
- Limits of Voltage Drop
$$|V_1 - V_B| \le \Delta V^{MAX}_{DROP} \quad (18)$$
- Limits on capacity
$$P^{MINI}_{Total,DG} \le P_{Total,DG} \le P^{MAXI}_{Total,DG} \quad (19)$$

3. Assessment of Sensitivity Factors

To analyse most candidates' buses for DG unit location, the loss sensitivities factor (OSF) has been proposed. According to Fig. 1, the loading is defined as the total efficient active & responsive power delivered across bus "B" that is $P_{B,e} + j\; Q_{B,e}$ The continuous power losses ($P_{Lloss(KB)}$) across lines outside the bus "B" can been shown as

$$P_{Lloss(KB)} = R_{KB} \frac{(P^2_{B,e} + Q^2_{B,e})}{(V_B^2)} \quad (20)$$

Furthermore, the losses sensitivity factors (OSF_{KB}) may be assessed by taking into account the supplied active energy ($P_{B,e}$) in Eq. (20) and the first derivatives of $P_{Lloss(KB)}$ as shown in Eq. 21 [20]:

$$OSF_{KB} = \frac{\partial P_{Lloss(KB)}}{\partial P_{B,e}} = \frac{2 * P_{B,e} * R_{K,B}}{V_B^2} \quad (21)$$

Received: August 06, 2025

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ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

The basic scenario magnitudes of voltage at bus V_B are compared to minimum allowable voltage i.e. 0.95 pu to obtain voltage sensitivity factors (TSF). For each of the lines inside the specified system, the OSF outcomes are arranged in decreasing order. The busses chosen as candidates for DG sites had the highest OSF value & the lowest TSF value ($i.e < 1.01$)

4. Optimization Algorithm

PSOGSA is represented by following equations [20].

$$\upsilon_K^p = w * \upsilon_K^{p-1} + c_{1'} * r_{1'} * ac_K^{p-1} + c_{2'} * r_{2'} * (g^{best} - \chi_k^{p-1}) \quad (22)$$

$$\chi_K^p = \chi_K^{p-1} + \upsilon_K^p \quad (23)$$

Where

$\upsilon_K^p = velocity\ of\ K^{th}\ particle\ at\ p^{th}\ ilteration$;

$\chi_K^p = updated\ position\ of K^{th}\ particle\ at\ p^{th}$
$ilteration$

$ac_K^{p-1} = acclearation\ factor\ for\ best\ current$
$velocity\ of\ K^{th}\ particle\ at\ (p-1)^{th}\ ilteration$

$g^{best} = best\ current\ position\ of\ particle$

$c_{1'}, c_{2'}, r_{1'}, r_{2'}\ \&\ w = factors\ responsible\ for\ weighting$

In quantum application to PSOGSA, every particle is denoted by angle and bit [15]. The meeting criteria of QPSOGSA technique is given by following equation:

$$\rho_{KB}^{p-1} = \Gamma_B^{p-1} * ac_{KB}^{p-1} + (1 - \Gamma_B^{p-1}) * gbest_B^{p-1} \quad (24)$$

Where

$$\rho_{KB}^{p-1} = attraction\ of\ each\ particle\ to\ its\ local\ best\ value$$

$$\Gamma_B^{p-1} = density\ function\ of\ B^{TH} paticle$$

$$\Gamma_B^{p-1} = \frac{c_1{}' * r_1{}'_B}{c_1{}' * r_1{}'_B + c_1{}' * r_2{}'_B} ; \quad (25)$$

$$0 \le \Gamma_B^{p-1} \le 1; \quad (26)$$

$$|\Gamma_B^{p-1}|^2 = 1 \quad (27)$$

Using MC method [15], Eq. (26) – (28) will be followed.

$$\chi_{KB}^p = \rho_{KB}^{p-1} + \varsigma * |\mathcal{H}_B^{p-1} - \chi_{KB}^p| * \log_e {}^1/_\varrho \qquad if\ \beth \ge 0 \quad (28)$$

$$\chi_{KB}^p = \rho_{KB}^{p-1} - \varsigma * |\mathcal{H}_B^{p-1} - \chi_{KB}^p| * \log_e {}^1/_\varrho \qquad if\ \beth \le 0 \quad (29)$$

Where

$\chi_{KB}^p = updated\ position\ of K^{th}\ particle\ towards\ B^{th} particle\ at\ p^{th}\ ilteration$

$\varsigma = convergence\ controller$

$\varsigma, \beth\ \epsilon\ (0,1) = random\ variables$

$\mathcal{H}_B^{p-1} = average\ best\ acclearation\ factor$

Received: August 06, 2025

ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

$$\mathcal{H}_{B}^{p-1} = \frac{1}{NOB} \sum_{K=1}^{NOB} ac_{KB}^{p-1} \tag{30}$$

Equation 24 represents sizes and 28-29 represents allocations of DGS.

5. Outcomes

PSOGSA algorithm-based suggested methodology has been put into practice using the MATLAB software. One 12.66 kV IEEE standards radial distributions systems, 33bus has been used to test the suggested method [20]. The acceptable voltage amplitude limitations for the test equipment are 0.95 to 1.05 pu. The major goal function's weighing factors γ_1, γ_2, & γ_3 are listed as 0.5, 0.4, & 0.1, correspondingly [6]. The expense factors CC_1 & CC_2 inside the ROE equations are set at 4 & 5 dollars per kW, respectively, with CC_2 representing the DG unit installations & servicing expenses. According on TSF values, the candidate's buses from OSF are selected. The buses with TSF values under 1.01 pu at are considered as critical bus for DG location. The best DG size and location from the essential buses are then provided by the QPSOGSA algorithms. The operation of DGs is selected at two distinct power factor 0.866 & unity, which are believed to be 2 types of DGs pursuant to ref. [20], in order to analyse the productivity & effectiveness of the suggested QPSOGSA. While Type-2 at unit power factors can only inject active power (such as a photovoltaic "PV" system), Type-1 at the ideal power factor of 0.866 can inject both active & reacting power. The following paragraph compares the suggested optimization methodology with different optimization techniques & methods.

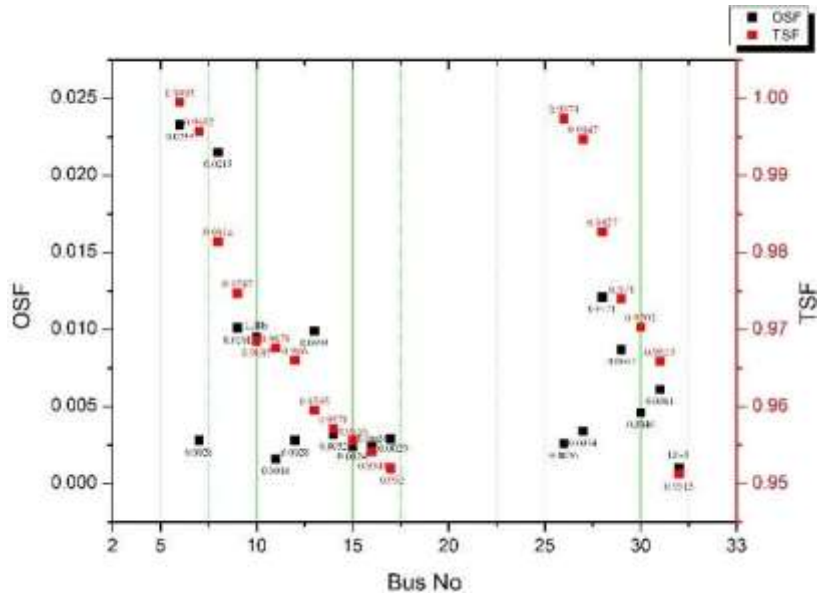

Fig. 2. The Outcomes Of OSF And TSF For Radial Distribution Networks 33-Bus

A IEE-33 bus radially distribution testing framework is conditioned to implement the suggested system [20]. Fig. 2 displays the findings for highest OSF with the smallest TSF value (i.e., $TSF < 1.01$). After running the optimization process on the first eight busses, we select the

Received: August 06, 2025

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Volume 38 No. 5s, 2025

ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

three that are most important and have a significant impact on the system with DGs. They are categorized as buses 8, 13, & 31. We used the optimization technique once more to determine the ideal sizes for the mentioned crucial buses, that are 480, 570, & 860 (kW) respectively for PV system. The power factor is 1. The QPSOGSA ideal size results for three crucial busses are 500, 500, & 900 kW, correspondingly, with a total actual power of 2194.4 (kVA) for WT system with power factor 0.866 PF.

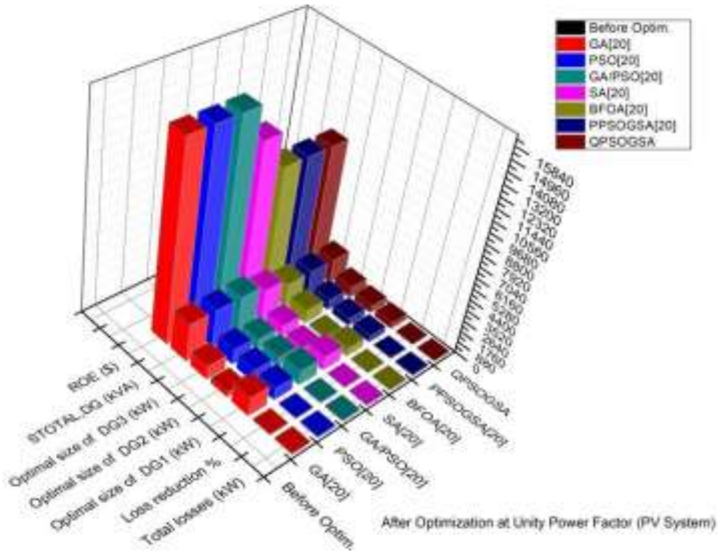

Fig. 3. Various Results for Radial Distribution Networks 33-Bus (PV SYSTEM)

Outcomes from the QPSOGSA are demonstrated in Fig. 3 and Fig. 4, the total size of power output as well as overall actual power for the suggested method are much lower than those of existing systems [21-28] with considerable increases in the % decrease of ROE & power losses.

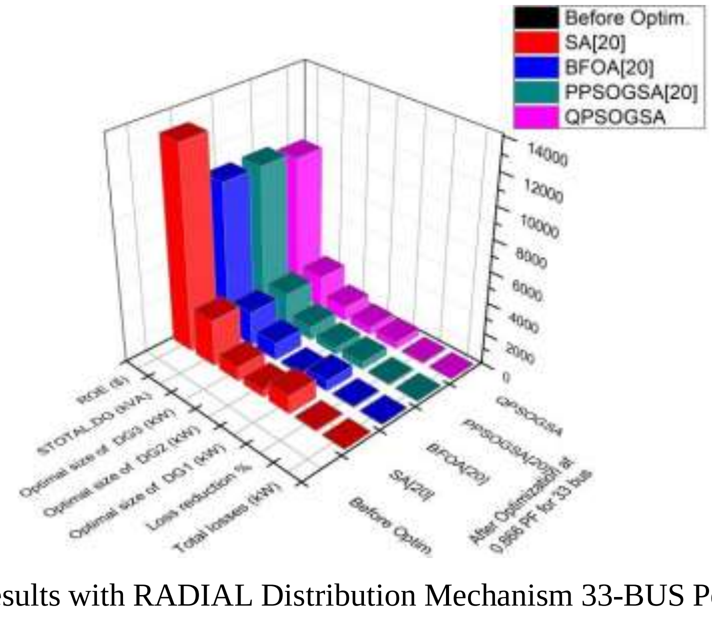

Fig. 4. Various results with RADIAL Distribution Mechanism 33-BUS Performance AT 0.866 PF (Wind Turbine System)

Received: August 06, 2025

ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

The net power loss is decreased to 82.03 kW when using SA technique as well as at uniform PF, with a ROE of 12,666.6 dollars, or 2844.4 dollars more than the QPSOGSA. BFAO likewise has a ROE of 9948.1 dollars, or 125.9dollars more than the QPSOGSA. Using QPSOGSA reduces the ROE to 9345.9 dollars at 0.866 PF, which is smaller than just the ROE of both the SA & BFAO approaches, correspondingly. Also, BFAO's lowest voltage at 0.866 PF is smaller than QPSOGSA is a suggested algorithm. This shows that the suggested method accurately and effectively forecasts the best location and number of DGs for minimizing power failure and running costs while also enhancing voltage profile.

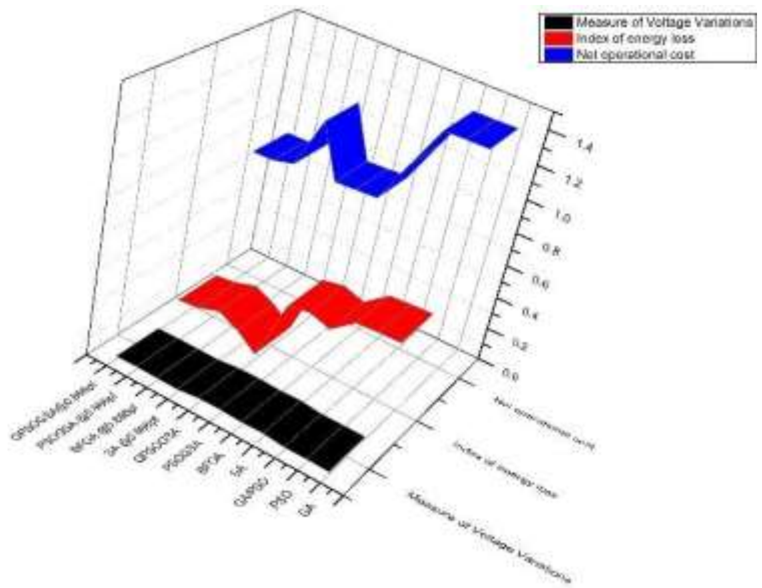

Fig. 5. Analysis of various performances for 33 bus radial distribution network.

The effectiveness of every strategy was shown in Fig. 5 when it came to comparison using QPSOGSA. As shown in Fig. 5, the voltage consistency index is significantly decreased by the GA, PSO, GA/PSO, & BFAO approaches, although their net operating costs (OE) & power loss indices are larger than those of the suggested algorithm. Although the SA method reduced the power losses index, its OE is significantly more than QPSOGSA. In terms of appropriate & superior answers, the effectiveness of QPSOGSA is demonstrated to be superior to other approaches with PV systems and WT as shown in Fig. 3, Fig. 4 and Fig. 5

6. Conclusion

Inside this paper, a novel approach based on a mixed Quantum & PSOGSA algorithms is suggested to determine the best placement and size when DGs are used in radial distribution systems. The sensitivities factors are created by predicting the majority of potential busses for DG unit seating in order to decrease the searching space of the QPSOGSA method. The backward/forward sweeps method is used to determine power transmission. In radial distributing networks with 33-bus capacity, the QPSOGSA proposal has been tested. To ensure

Received: August 06, 2025

Volume 38 No. 5s, 2025
ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

that the suggested algorithm is valid, the findings have been compared to those from alternative approaches. The outcomes show that the suggested strategy offers a high precision & efficiency solution. It was evident that the suggested plan may increase voltage consistency while decreasing the systems losses & overall operational costs for various DG variants with various power factors. Moreover, any radial distributing network with n busses can employ the systems technique.

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Received: August 06, 2025