Optimal DG Allocations in the Distribution Networks using an Improved PSO Algorithm

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Abstract- This paper discusses how to improve the particle swarm algorithm (PSO) to determine the optimum size and placement of Distributed Generation units (DGs). We aim to decrease active and reactive power loss, minimize voltage deviation, and keep the voltage profile and electrical current within the restrictions. It also addresses complexity, precision, and premature convergence to a local optimum. This strategy increases the number of possible solutions to look for and maintain good solution groups in each generation. Using the IEEE 33-bus radial distribution network to test the algorithm proves that it works well. The results are compared to the classic PSO and other current research.

Keywords- Distribution generation, optimal site and size, power loss optimization, voltage deviation minimization, Improved PSO.

1. Introduction

In 2022, the Russian-Ukrainian war will give rise to a significant increase in energy costs (gas and oil). Besides, electricity demand has risen considerably due to modern industrialization and new technologies such as Industry 4.0 and smart factories that use AI. As a result, voltage deviation and network power loss have increased. Electric companies are expected to investigate other solutions to tackle the energy crisis, such as the orientation toward the insertion of the DG units. This solution is effective in the framework of achieving carbon emissions reduction targets in 2030. Also, to avoid any electrical shut down due to energy stock exhausted.

A literature review should be conducted to determine the benefits and drawbacks of DG's penetration. Several studies have focused on using DG units to provide electricity to faraway consumers rather than building new power lines, which are, in reality, highly expensive. Furthermore, this injection approach helps provide backup and supplemental power for continuous and permanent service with prompt response, even in emergency cases [1].

DG units can be injected into the network or run independently (stand-alone). The load flow and voltage limits may be affected by this insertion approach. Depending on the network topology and DG unit characteristics, these effects can be positive or negative [2]. Table 1 presents the advantages and inconveniences of DG unit insertion.

Table 1. Advantages and disadvantages of DG unit insertion

Advantages [3], [4], and [5]	Disadvantages
• Loss decreases depending on the location. • Improve the performance of the electrical network. • Support the voltage and improve the power flow.	• The literature proves that the power loss depends on the network's location, size, and topology. Consequently, DG unit insertion can increase or decrease the power loss [6] . It also depends on the DG insertion rate [7].

• Due to the DG unit injection, there is no need to construct new electrical infrastructure. • It helps reduce transmission costs by eliminating the long distances needed to transmit power energy to the farthest consumers. • It significantly contributes to environmental protection when using renewable energy.	• The DG unit injection can give abnormal voltage or oscillation of the current. As a result, it can destabilize the system [8]. • It can generate an electrical current error compared with the standard case (a network without any DG units) [9].

Distributed generation is a technique that allows users to generate power close to or at their consumption locations [10]. The DG injection has a vital role in decreasing network transmission and distribution power losses [11]. This strategy tries to respond to consumer needs by minimizing the amount of electricity generated by a central plant. Furthermore, it reduces the environmental effects of the conventional resources used in centralized power generation [12].

The authors of [13] calculated electrical predictions from the targeted quantity to minimize total production costs. The authors of [14] proposed the Model Predictive Control to achieve optimal control. Furthermore, the authors of [15] defined the importance of smart grids in maintaining supply and demand balance.

While the researchers [16] determined that inserting DG units in inappropriate locations or with the wrong sizes results in significant power loss. The recent studies are oriented toward the whale optimization method [17], [18], the harmony search algorithm [19], [20], the improved crow search algorithm [21], the adjusted cuckoo search approach [22], to solve the DG insertion problem.

To enhance the PSO algorithm, we based on [23], who found that the chaotic inertia weight approach is the most precise method for calculating the inertia weight parameter. Then, we propose to enhance the chaotic PSO technique by employing the cosine of the chaos variable described in reference [24]. This improved PSO (IPSO) can provide a new search space with more possible solutions.

There are two parts to determine the best injection: the first one utilizes an optimization method. While, the second uses the power flow to determine the fitness values and meet the restrictions. Several studies [25], [26], and [27], used a hybrid of the classical PSO and Newton-Raphson approach. While, our research used the Backward / Forward Sweep (BFS) technique described in reference [28], with a modified PSO algorithm. The purpose is to support the particles to find more possible solutions as quickly as possible.

Only the active power loss and voltage profile are minimized in the literature [29], [30] [31], [32], [33], [34], [35], [36], among others. In contrast, this research also attempts to reduce reactive power loss and voltage deviation.

The authors of [37] use the Atom Search Optimization (ASO) in conjunction with a Unified Power Flow Controller (UPQC). to minimize PQ concerns such as voltage/current sag, swell, and Total Harmonic Distortions. In contrast, the authors of [38] compared two approaches Lorenz Curves, with the addition of Gini coefficients and a clustering approach. They concluded that these methods assist in distinguishing between centralized and distributed energy generation and give insights for policy decisions related to renewable energy and smart grids. The authors of [39] proposed an advanced approach based on a combination of the adaptive technique and the fuzzy logic theory was applied to ensure an advanced control of the SAPF, to enhance the power grid quality.

We started our research by considering how to use the PSO approach to reconfigure distribution networks without the existence of DG [40]. Secondly, the same PSO method to reconfigure electrical systems with the presence of DG units [41] is used. Thirdly, we oriented toward the DG insertion issue. We started by considering the active power loss minimization [42], and [43].

The contributions of our approach are:

- Provided power loss reduction and voltage deviation minimization.

- Used the backward /forward sweep to check the constraints.

- Generates a new search space with more possible solutions close to the global optimum.

- Insert DG units that generates both active and reactive power.

- We used the IEEE 33-bus network to test the performance of IPSO.

- The performance of the IPSO beats PSO and other recent methods proposed.

The obtained results of real power loss applying our approach are more reduced than those obtained using previous methodologies PSO [34], NLP- PLS [33], IA-LSF [32], BA [35], MOBA [35], IA [36].

The rest of the paper is organized as follows: The following part describes the DG optimization model; on another side, it presents the proposed IPSO. In section 3, we discuss the results. In the end, we close our study with a conclusion.

2. Problem Formulation

This study hopes to reduce real and reactive power loss and Total Voltage Deviation (TVD). To achieve these objectives, we solve the DG insertion problem.

2.1. Objective Function

We use equations 1.a, 1.b, and 1.c to calculate our objective functions:

Min F = $\alpha\times P_{loss} + \beta\times Q_{loss} + \mu\times TVD$ (1)

Where: α, β, $\mu \in [0,1]$, and $\alpha+\beta+\mu = 1$

$\mathbf{P_{loss}}$ = Min $\sum_{l=1}^{l=N} \mathbf{P_{loss,l}}$ = Min $\sum_{l=1}^{l=N} \mathbf{R_l} * \mathbf{I_l^2}$;for $l \in [1,2,\ldots,N]$ (1.a)

$\mathbf{Q_{loss}}$= Min $\sum_{l=1}^{l=N} \mathbf{Q_{loss,l}}$ = Min $\sum_{l=1}^{l=N} \mathbf{X_l} * \mathbf{I_l^2}$; for $l \in [1,2,\ldots,N]$ (1.b)

TVD = Min $\sum_{j=1}^{j=M} \left|\mathbf{V_{nominal}} - \mathbf{V_j}\right|$;for $j\in[1,2,\ldots,M]$ (1.c)

Where :

$P_{loss,l}$: The branch l's active power loss.

R_l : The line's resistance (l).

I_l : Branch's current (l).

$Q_{loss,l}$: The branch l's reactive power loss.

X_l : The line l's reactance.

V_j : The magnitude of the voltage on load bus j.

$V_{nominal}$: The reference voltage, which is set at 1.0 p.u.

N: The network's total number of branches.

M: The network's total number of nodes.

There are several methods for determining real and reactive power loss. We use branch currents in equations (1.a) and (1.b) to simplify computations.

2.2. System Constraints

This optimization problem is subject to the following restrictions.

a. Voltage constraint.

The voltage of each bus should be within certain limits. We use inequality (2) to represent this constraint. We assume that the voltage upper and lower limits are 1.05 p.u and 0.95 p.u, respectively:

$V_{min} \leq V_j \leq V_{max}$; $i\in[1,2,\ldots,M]$ (2)

Where :

V_{min} : The voltage's lowest limit.

V_{max} : The voltage's maximum value.

V_j : The voltage of the j-th node.

M: The network's total number of nodes.

b. Electrical current constraint.

Each edge should have electrical currents more minor than the conductor's maximum allowable value. The inequality (3) represents this constraint. We assume that the electrical current should not exceed 300 A:

$I_l \leq I_{max}$; for $l \in [1,2,\ldots,N]$ (3)

Where :

I_l : The line l's electrical current.

I_{max} : The maximum amount of electrical current that can circulate.

c. DG unit Restrictions.

To prevent reverse power flow, we use inequality (4):

$\mathbf{0} \leq \sum_{i=1}^{i=M} P_{DG,i} \leq \sum_{i=1}^{i=M} P_{Load,i}$; for $i \in [1,2,\ldots,M]$ (4)

Where :

$P_{DG,i}$: The quantity of active power injected into node i.

$P_{Load,i}$: The load on node i.

M: The network's total number of nodes.

Besides, the active and reactive power injected must be subject to inequality (5) and (6).

$P_{DG,min} \leq P_{DG,i} \leq P_{DG,max}$; $i \in [1,2,\ldots,M]$ (5)

$Q_{DG,min} \leq Q_{DG,i} \leq Q_{DG,max}$; $i \in [1,2,\ldots,M]$ (6)

Where:

$P_{DG,min}$, $Q_{DG,min}$: The lowest active and reactive power injection level at node i, respectively.

$P_{DG,i}$, $Q_{DG,i}$: The amount of active and reactive power injected into node i, respectively.

$P_{DG,max}$, $Q_{DG,max}$: The maximum amount of active and reactive power that can be injected into node i, respectively.

M : The network's total number of nodes.

d. Power balance equation.

The electrical network stability requires that the sum of the substation's active power and the active power of all injected DG units equal the sum of the entire load connected to all buses and the total active power loss in the network. Equation 7 illustrates this constraint. The same criteria apply to the reactive power of the network, as seen in equation (8):

$P_{sub} + \sum P_{DG} = P_{load} + \sum P_{loss}$ (7)

$Q_{sub} + \sum Q_{DG} = Q_{load} + \sum Q_{loss}$ (8)

Where:

P_{sub} : The substation's active power.

$\sum P_{DG}$: The total active power of all dispersed generation units.

P_{load}: The total active load connected.

$\sum P_{loss}$: The overall active power loss of the network.

Q_{sub} : The substation's reactive power.

$\sum Q_{DG}$: Total reactive power injected by all dispersed generation units.

Q_{load}: The associated total reactive load.

$\sum Q_{loss}$: The network's total reactive power loss.

2.3. Methodologies

a. PSO algorithm:

PSO is an evolutionary computation approach invented by the authors of [44]. Individual collaboration is one of its properties, which contributes to the success of this optimization tool.

Furthermore, this method is chosen due to its characteristics, which allow particles to move fast through the search space of solutions while assisting them in achieving the global minimum.

This approach finds out the solution by updating the velocity and position of particles:

At iteration t+1, we apply equation (9) to update particle i's velocity:

$$Ve_{i,d}^{t+1} = \omega \times Ve_{i,d}^{t} + C_1 \times r_1 \times (pbest_{i,d}^{t} - X_{i,d}^{t}) + C_2 \times r_2 \times (gbest_{d}^{t} - X_{i,d}^{t}) \quad (9)$$

At iteration t+1, we use equation (10) to get the new position of particle i :

$$X_{i,d}^{t+1} = X_{i,d}^{t} + Ve_{i,d}^{t+1} \quad (10)$$

Where :

ω is the inertia weight.
r_1 and r_2 are random numbers inside [0,1].
C_1 and C_2 are the coefficients of acceleration.
$C_1 \times r_1 \times (pbest_{i,d}^{t} - X_{i,d}^{t})$ is individual cognition that assists particles in moving to the best possible location.
$C_2 \times r_2 \times (gbest_{d}^{t} - X_{i,d}^{t})$ is a social cognition to describe how particles can be directed to the best location that the group can detect.

Then, the inequalities (11) and (12) are used to check velocity and position restrictions to avoid the violations of particles:

$$Ve_{min} \leq Ve_{i,d}^{t+1} \leq Ve_{max} \quad (11)$$

$$Xmin \leq X_{i,d}^{t+1} \leq Xmax \quad (12)$$

Where :

- Ve_{min}: The velocity's lower bound.
- Ve_{max}: Velocity's maximum limit.
- $Ve_{i,d}^{t+1}$: Particle i's velocity at iteration t+1.
- Xmin: The position's lowest bound.
- Xmax: The position's upper limit.
- $X_{i,d}^{t+1}$: Particle i's location at iteration t+1.

b. Modified chaotic PSO:

The author of [24] used the cosine function in equation (13) to enhance the standard chaotic mapping by dispersing the particles in the whole interval [0,1]. This new equation is characterized by inherent ergodicity and randomness, allowing particles to cover all cases within a given area. They have presented chaos into the global best value equation to define the whole close-up possible solution.

$$Z_{t+1} = gbest_t + R \times cos(\mu Z_t(1 - Z_t)); Z_{iter} \epsilon [0,1] \quad (13)$$

Where :

Z: The chaos variable
R: It is the search radius used to supervise the area of chaotic local search for efficient optimization R ϵ [0.1 , 0.4].
The authors of [24] have also proposed new cognitive and social parameters. Compared to a constant value, the Arc Tangent coefficient can balance the entire search along the past period and local convergence in the future state. Equations (14) and (15) were used to define C_1 and C_2, respectively.

$$C_1 = \beta \times tan^{-1}((\frac{iter_j}{iter_{max}}) \times \sigma) + \rho_1 \quad (14)$$

$$C_2 = -\beta \times tan^{-1}((\frac{iter_j}{iter_{max}}) \times \sigma) + \rho_2 \quad (15)$$

Where, β = 1.5, σ = 4, ρ_1 = 2.5, and ρ_2= 0.5, to find C_1 and C_2 range from 2.5 to 0.5 and 0.5 to 2.5, respectively.

The authors of [24] provided the cosine function presented in equation (16). We used this equation to calculate the inertia weight, which simplifies the PSO algorithm's application due to its early global research and later local convergence.

$$\omega = \alpha \times cos((\frac{iter_j}{iter_{max}}) \times \pi) + \varphi \quad (16)$$

Where φ= 0.6, and α =1/3 to find ω range from 0.9333 and 0.2667.

c. Test Case:

To verify the method's performance, we use the IEEE 33-bus network. The characteristics of this network are presented in this reference [45]. This electrical system's network consists of 33 buses and 37 branches. 33,34,35,36,37 are the five switches open on the network, as shown in figure 1.

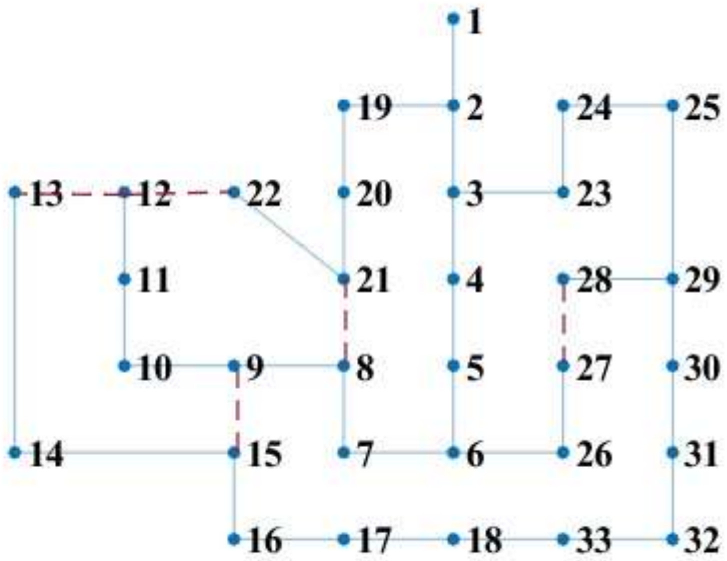

Fig. 1. IEEE 33-bus distribution system

d. Flowchart of the proposed algorithm:

This study uses the combination of the modified PSO and the BFS techniques to solve this problem. Figure 2 depicts the suggested method.

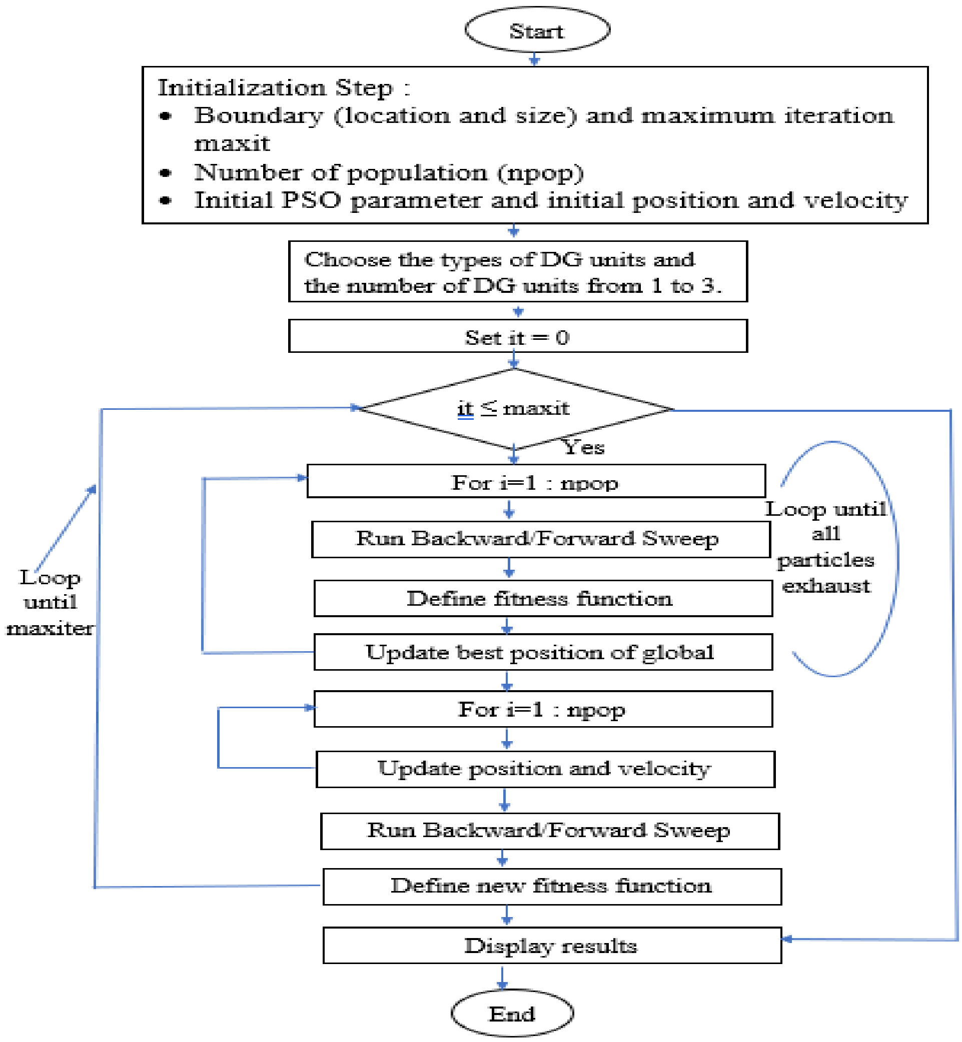

Fig. 2. Our proposed algorithm's flowchart

3. Simulation Results and Discussion

This study injects one to three DG units into the IEEE 33-node network. The following sections will present the outcomes of our method.

The aim is to enhance the obtained outcomes by focusing on the swarm size, the number of iterations, acceleration and inertia coefficients, upper and lower limits of voltage, electric current, rapidity, and position of particles.

Figure 3.a presents the voltage deviation for the various levels of insertions. In contrast, figure 3.b shows the real power loss for the different injections. These results prove that the power loss and the voltage deviation reduce when we insert another DG unit.

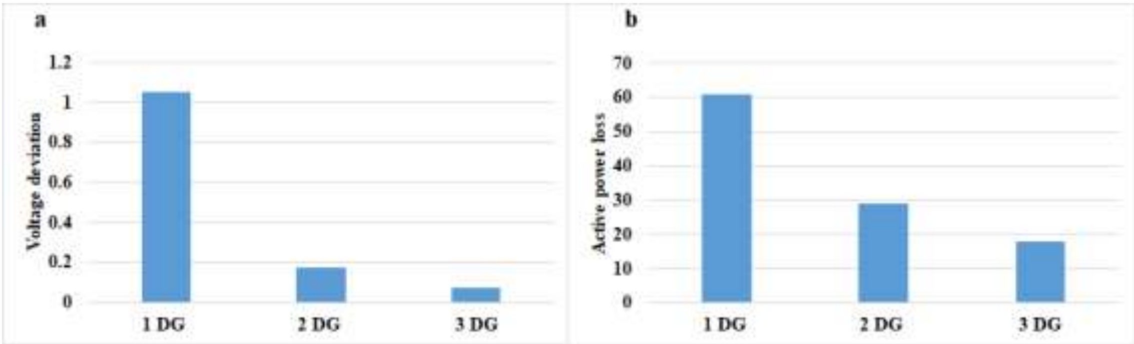

Fig. 3. Various insertion levels: a. Voltage Deviation for IEEE 33-bus network. b. Power loss for IEEE 33-bus network.

3.1. Discussion

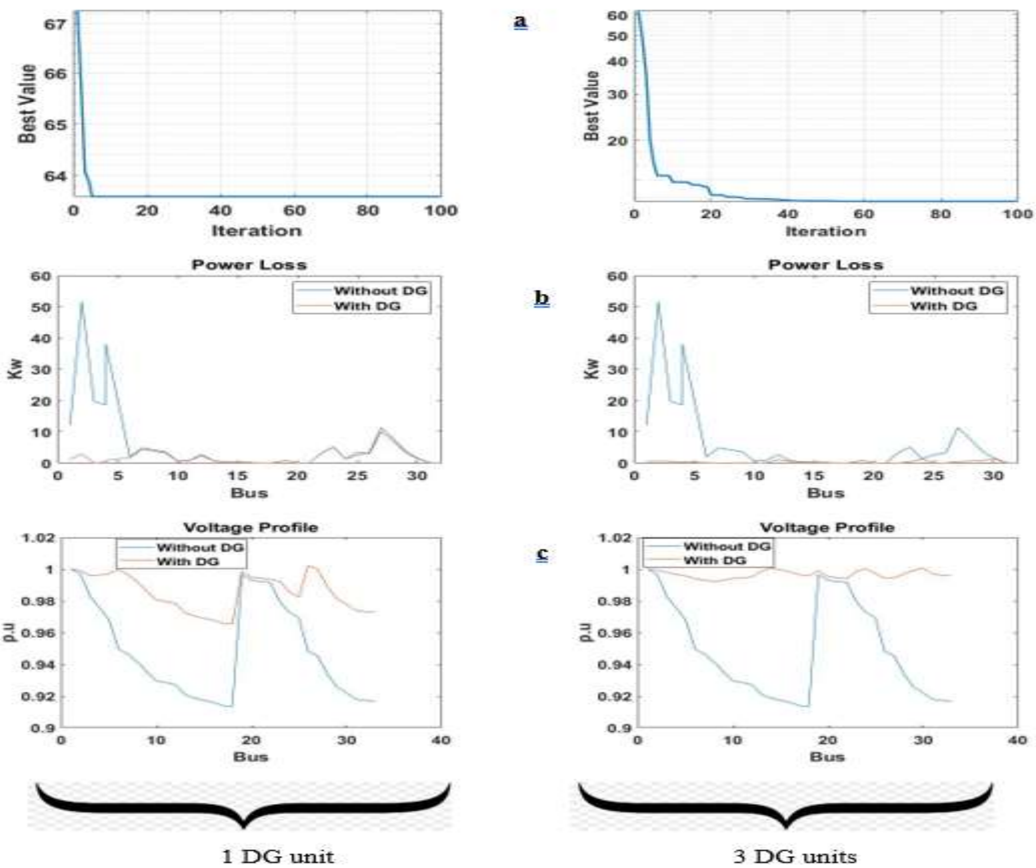

Fig. 4. Different insertion levels for IEEE 33-bus network: a. best power loss value at various iterations. b. power loss at various buses. C. voltage profile at various buses.

Figure 4.b shows the power loss at each bus for networks with and without DG units. While, figure 4.c presents the voltage profiles of the network in two scenarios: before and after DG unit insertion. We observe that introducing a DG unit reduces power loss and improves voltage profile. Table 2 summarizes the outcomes of injecting one to three DG units:

Table 2. simulation results of 33 bus

N° DG	DG Scale (kW)	DG Scale (Kvar)	DG site	Ploss (kW)	Qloss (kVAR)	TVD (%)
1	2583	1770	6	61	48	1.0538
2	969 1093	456 1039	12 30	29	10	0.17157
3	724 999 1655	337 994 803	14 30 3	18	15	0.073489

As an analysis that:

- We determined that the injection of (2583 kW, 1770 kvar) at node 6 is the optimal solution for a single DG unit. In this scenario, the total active power loss is 61 kW, reactive power loss is 48 kvar, and voltage deviation is 1.0538 %. After 0.309229 s, this solution is achieved. The minimum voltage, for this case, is equal to 0.970 p.u.

- We found that the injection of (969 kW, 456 kvar) and (1093 kW, 1039 kvar), respectively, at nodes (12 30) is the optimal solution for two DG units. In this case, the total active power loss is 29 kW, reactive power loss is 10 kvar, and voltage deviation is 0.17157 %. This solution is obtained after 0.017734 s. The minimum voltage, for this case, is equal to 0.988 p.u.

- We obtained the ideal injection for three DG units are (724 kW, 337 kvar), (999 kW, 994 kvar), and (1655 kW, 803 kvar), respectively, at buses (14 30 3). In this case, the total active power loss is 18 kW, while the total reactive power loss is 15 kvar and the voltage deviation is 0.073489 %. After 0.067293 s, this solution is found. The minimum voltage, for this case, is equal to 0.987 p.u.

3.2. Comparative Study

Other articles reduced active power loss and improved the voltage profile. While this research attempts to minimize active, reactive power losses, and voltage deviation, it also enhances voltage profile. Table 3 presents the outcomes of this work and other recent works to demonstrate the performance of the recommended technique.

Table 3. Optimal solutions for the IEEE 33 bus system

Method	DG size (kW)	DG size (kvar)	DG location (node)	ΔP (kW)	Loss reduction (kW)	Loss reduction %
initial	-		-	202.6863	-	-
IPSO	2583	1770	6	141.6863	61	69.90
PSO **[34]**	2550	1761	6	134.8163	67.87	66.51
NLP- PLS **[33]**	2533.26	1749.361	6	134.8863	67.8	66.54
IA-LSF **[32]**	2292.5	0	30	135.2863	67.40	66.74
BA **[35]**	3099	2612.7669	6	134.8863	67.87	66.54
MOBA **[35]**	3619	3315.7278	7	127.1263	75.56	62.72
IA **[36]**	3107	2547.74	7	134.7863	67.90	66.49

For this kind of DG unit, most studies inject a single DG unit; for this reason, we compare just this case. The active power loss using our method is equal to 61 kW. While is equal to 67.87 kW for the authors of [34], 67.8 kW for the authors of [33], 67.40 kW for the authors of [32], 67.90 kW for the authors of [36], 67.87 kW for the authors [35] when they used BA method and 75.56 kW where they used MOBA method.

The lower voltage value obtained using our method is 0.968 p.u instead of 0.9131 p.u for the initial case and 0.9535 p.u for the authors of [32]. Figure 5 presents the power loss defined by different approaches. As observed, the suggested method gives a lower value of power loss.

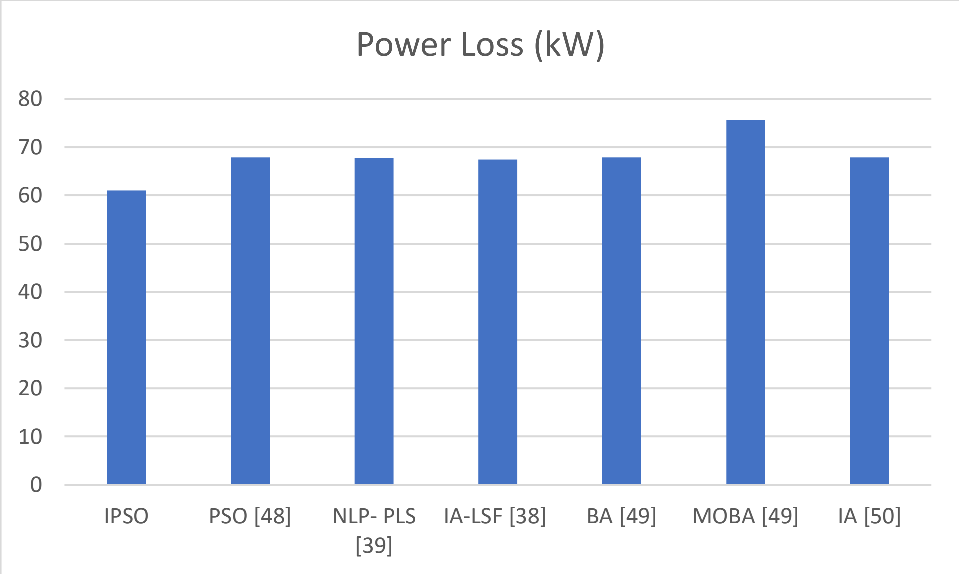

Fig. 5. Power loss for different recent studies

In addition, Compared to results found by the recent approaches PSO [34], NLP- PLS [33], IA-LSF [32], BA [35], MOBA [35], IA [36] , power loss minimization noticed by the proposed approaches is 3.39%, 3.36%, 3.16%, 3.36%, 7.18%, and 3.41 % higher than that of the IPSO.

Table 4. Compared results between IPSO and PSO for DG insertion issue

	Fit min	Fit max	Fit mean	STD
IPSO– 3 DG	11.6896	18.1078	14.89	2.044884
PSO- 3DG	12.8678	19.3697	16.1187	2.345821

Both algorithms were implemented in 50 independent runs. The attained indicators, including maximum fitness (Fit max), minimum fitness (Fit min), mean fitness (fit mean), and Standard Deviation of fitness function (STD), are applied to compare the performance of IPSO and PSO.

The noticed results are shown in Table 4. From the table, the Fit max, Fit min, Fit mean, and STD indicators detected by IPSO are better than those of PSO. Or, these indicators of IPSO are 1.1782, 1.261894, 1.2287, and 0.300937 lower than those of PSO, respectively.

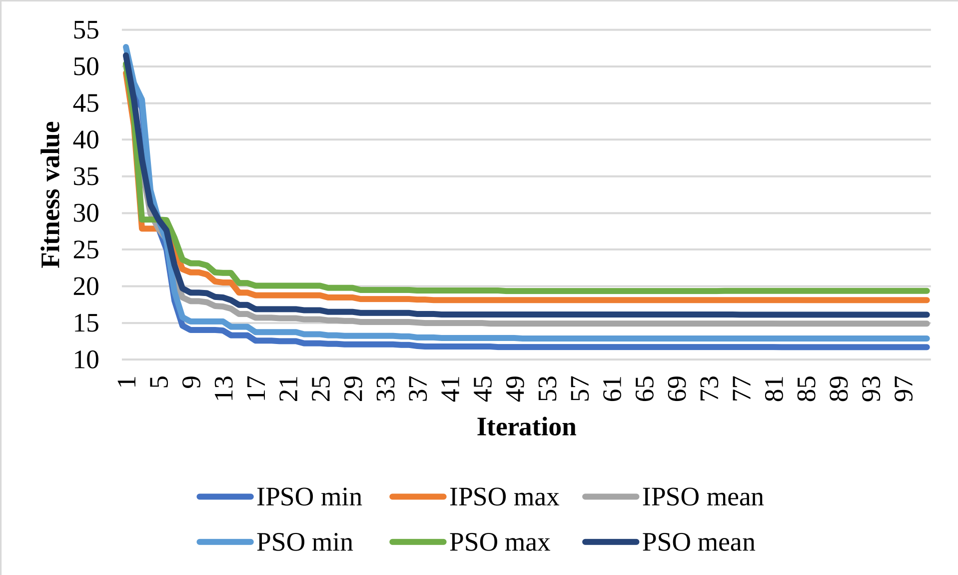

Fig. 6. The convergence curves for the best run in 50 runs

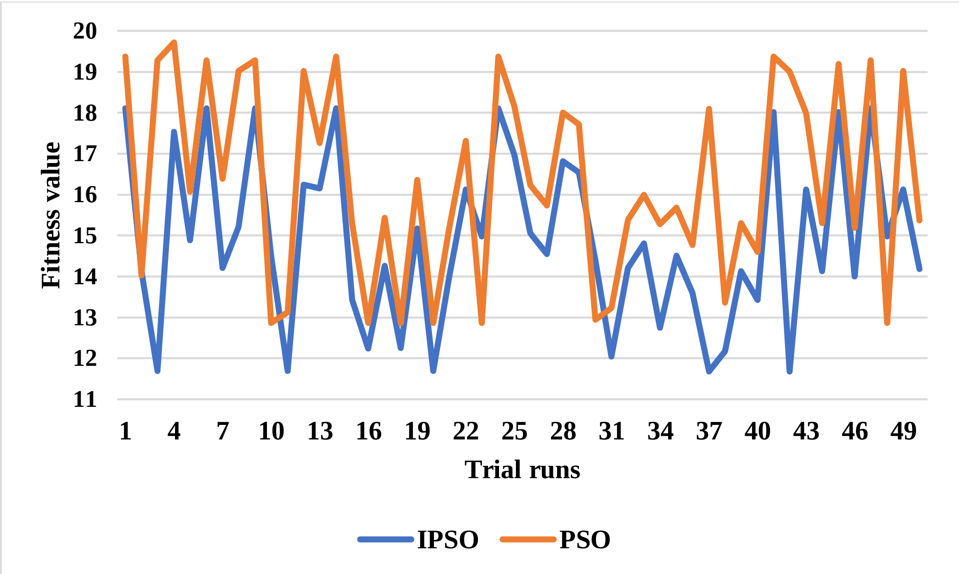

Fig. 7. The fitness function of 50 trial runs

Figure 6 shows the maximum, mean, and minimum convergence curves of IPSO and PSO in 50 runs. IPSO's curves are all lower than PSO's curves. This study demonstrates that IPSO's improvements outperformed PSO on the DG insertion problem. Furthermore, the best fitness value observed in each run, as shown in figure 7, demonstrates IPSO's superior performance to PSO. In 45 of the 50 runs, IPSO discovered the best fitness value, but PSO only found the best fitness value in 5 of the 50 runs.

4. Conclusion

This work presents an enhanced PSO technique to inject DG units ideally into electrical distribution networks. For this reason, we used chaotic cosine mapping and the acceleration arctangent coefficient. Then, we combined this improved PSO with the Backward/Forward Sweep to achieve the restrictions. This research's purpose is to reduce active and reactive power losses and voltage deviation. We consider the IEEE networks of 33 buses to inject DG units that generate active and reactive power simultaneously.

The next step was to compare our findings to those of other recent studies from the literature. Consequently, our algorithm shows that active power loss is better minimized, and the voltage profile is much improved than those of other up-to-date papers.

Adding to that, the chosen parameters prove their ability to reduce computational time and improve the algorithm's performance indices. The proposed method provides the system's voltage improvement, reduces voltage deviation, and minimizes active and reactive power loss. For future research, we recommend using this modified method to insert different kinds of DG units by considering the convergence rate of the solution.

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