

Analytical Hybrid Particle Swarm Optimization Algorithm for Optimal Siting and Sizing of Distributed Generation in Smart Grid

Syed Muhammad Arif, Akhtar Hussain, Tek Tjing Lie, Syed Muhammad Ahsan,
and Hassan Abbas Khan

Abstract—In this paper, the hybridization of standard particle swarm optimisation (PSO) with the analytical method (2/3rd rule) is proposed, which is called as analytical hybrid PSO (AHPSO) algorithm used for the optimal siting and sizing of distribution generation. The proposed AHPSO algorithm is implemented to cater for uniformly distributed, increasingly distributed, centrally distributed, and randomly distributed loads in conventional power systems. To demonstrate the effectiveness of the proposed algorithm, the convergence speed and optimization performances of standard PSO and the proposed AHPSO algorithms are compared for two cases. In the first case, the performances of both the algorithms are compared for four different load distributions via an IEEE 10-bus system. In the second case, the performances of both the algorithms are compared for IEEE 10-bus, IEEE 33-bus, IEEE 69-bus systems, and a real distribution system of Korea. Simulation results show that the proposed AHPSO algorithm converges significantly faster than the standard PSO. The results of the proposed algorithm are compared with those of an analytical algorithm, and the results of them are similar.

Index Terms—Siting and sizing of distributed generation, distribution system, hybrid algorithm, loss minimization, particle swarm optimization (PSO).

I. INTRODUCTION

THE conventional power grids are radial in nature, and the generation units are typically far away from the loads. In this way, it is inevitable that power will be lost during the transmission and distribution of power to the end consumers. To mitigate these losses, a variety of solutions have been proposed. One possibility is to use superconductor materials for transmission and distribution lines. However, superconductor technology is prohibitively with high

cost. Another option is to install power generation units near the consumers. However, due to environmental pollution and social issues, it is not applicable in most of scenarios. Therefore, more recently, the concept of distributed generation has emerged which reduces line losses and is now technologically viable, environment-friendly, and economical.

Due to the advancements in communication technologies, an optimal allocation of distributed generators (DGs) in smart grids would impact many important parameters of the grid including power/energy losses, voltage profile, power quality, reliability, control and stability. As a result, various heuristic methods have been proposed for optimal siting and sizing of DGs in distribution systems [1]–[3]. Among various heuristic optimization techniques, particle swarm optimization (PSO) is the most widely used for the siting and sizing of DGs [4], [5]. Improper siting and sizing of DG units in power system not only reduce the efficiency but also negatively impact the stability of the entire power system [6]. Therefore, [7], [8] proposed an analytical approach for the siting and sizing of DGs. Subsequently, [9]–[11] evaluated the positive impacts of optimally sited and sized wind power systems on other emerging areas of power systems with the inclusion of future loads such as electric vehicle (EV) charging and discharging. References [12]–[16] discussed the effects of siting and sizing of DGs and random charging of EVs on the voltage profiles and network losses.

In addition to optimizing siting and sizing, PSO was utilized to improve a wide range of technical challenges such as the voltage profile, line loading, active and reactive power losses of the power grid in [17]–[21]. The proposed algorithms generally improved the power system operation, minimizing the above-mentioned technical challenges. Another key work in [22] proposed a PSO methodology for the siting and sizing of DG units in a primary distribution system to increase the loadability of the distribution system by improving the voltage stability while minimizing the reactive power losses of the system.

The other heuristic approach for the siting and sizing of DGs includes genetic algorithms (GAs) [23]–[25] and simulated annealing (SA) [26]. The drawback of these algorithms is its high computation cost. However, PSO has significantly better computation efficiency [19], i.e., its function evaluation. A key issue with PSO is the trapping of particles into

Manuscript received: March 6, 2019; accepted: December 1, 2019. Date of CrossCheck: December 1, 2019. Date of online publication: September 24, 2020.

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DOI: 10.35833/MPCE.2019.000143



local optima, which could consume large amount of time to converge to an optimal solution. Additionally, there is no guarantee that the optimal solution will be a global optima. As a result, a lot of recent research works focused on the hybridization of the standard PSO with analytical approaches or other optimization techniques for achieving better results. For instance, [27], [28] hybridized the analytical method with a heuristic search method to optimize placement of multiple DGs in a distribution network for power loss reduction. Sizing of DGs was performed with an analytical method while siting of DGs was calculated with the PSO-based technique to improve the bus voltage profile and power factor. For optimal reactive power and voltage control of distribution networks, [29] proposed an efficient methodology based on fuzzy adaptive hybrid PSO. The objective of this proposed algorithm was to minimize the power loss and the operation cost of transformers and capacitors while considering constraints like the maximum/minimum reactive power limits of DGs. Further, [30] utilized PSO for optimal allocation of DGs for the multi-phase unbalanced distribution network. This study showed that optimal siting and sizing of DG units could reduce the total power loss and improve the voltage profile in the distribution network.

A critical challenge with the standard heuristic methods is to overcome the local trapping issue. Due to the increasing usage of PSO for optimal siting and sizing of DGs, this paper uses PSO to evaluate the feasibility of the proposed algorithm. With the limitations of PSO, a hybrid standard PSO and the analytical method (2/3rd rule) for siting and sizing of DGs is proposed to reduce the power loss and improve the voltage profile. It is well known that the standard 2/3rd rule is only valid for uniformly distributed loads. However, most of the real loads in power systems are not uniformly distributed. Therefore, in this paper, the standard 2/3rd rule is modified and different rules are devised for specific pattern loads, i.e., uniformly distributed, increasingly distributed, and centrally distributed loads. The 2/3rd rule is extended to randomly distributed loads by placing DG at the bus with 2/3rd of the total load, starting from the source side. Initially, a bus number is determined by using the modified 2/3rd rule. Then, the upper and lower bounds are determined for the search space of the proposed analytical hybrid PSO (AHP SO) algorithm. Thus, instead of searching in the whole area, the search space is limited by using the AHP SO algorithm. Consequently, a fast convergence is achieved without compromising on the siting and sizing aspects from the standard PSO. To demonstrate the effectiveness of the proposed algorithm, different load patterns, i.e., uniformly distributed, increasingly distributed, centrally distributed, and randomly distributed, should be implemented in an IEEE 10-bus system. Then, the performance of the proposed AHP SO algorithm is evaluated for different power systems including a real distribution system of Korea Electric Power Corporation (KEPCO), Korea. The results of the proposed algorithm are compared with those of analytical algorithms. And the results of the proposed AHP SO algorithm are similar to those of analytical algorithms.

II. AHP SO ALGORITHM

A. Load Flow Analysis

The main goal of the proposed algorithm is to minimize the active power loss P_{loss} and improve the voltage profile of the power system. The active power loss [31], which is the objective function of this formulation, can be mathematically expressed as:

$$\begin{cases} P_{loss} = \sum_{i=1}^N \sum_{j=1}^N [\alpha_{ij}(P_i P_j + Q_i Q_j) + \beta_{ij}(Q_i P_j - P_i Q_j)] \\ \alpha_{ij} = \frac{x_{ij}}{v_i v_j} \cos(\delta_i - \delta_j) \\ \beta_{ij} = \frac{x_{ij}}{v_i v_j} \sin(\delta_i - \delta_j) \quad \forall ij = 1, 2, \dots, n \end{cases} \quad (1)$$

where N is the total distance of the feeder; α_{ij}, β_{ij} are the sensitivity factors of exact loss formula; i, j are the numbers of buses; P_i, P_j are the active power at buses i and j , respectively; Q_i, Q_j are the reactive power at buses i and j , respectively; x_{ij} is the reactance of line connecting buses i and j ; v_i, v_j are the voltage magnitudes at buses i and j , respectively; and δ_i, δ_j are the phase angles at buses i and j , respectively.

$$P_i = P_{DG_i} - P_i^{load} \quad (2)$$

$$Q_i = Q_{DG_i} - Q_i^{load} \quad (3)$$

where P_{DG_i}, Q_{DG_i} are the active and reactive power injected by DG units at bus i , respectively; and P_i^{load}, Q_i^{load} are the active and reactive loads at bus i , respectively.

B. Standard PSO Algorithm

The PSO algorithm is a non-linear optimization algorithm [32], [33] while observing the social behavior of animals and birds. The velocity and position equations are proposed for each particle traveling in a group. The prevailing velocity can be calculated by using the previous velocity and the distance between p_{best} and g_{best} . All particles adjust their position according to the personal flying experience called p_{best} (personal best) as well as the flying experience of the other particles in the group called g_{best} (global best). The prevailing velocity is shown in (4).

$$V_i^{k+1} = V_i^k + C_1 r_1 (p_{best}^k - x_i^k) + C_2 r_2 (g_{best}^k - x_i^k) \quad (4)$$

where V_i^k is the velocity of particle i at iteration k ; x_i^k is the position of particle i at iteration k ; C_1, C_2 are the cognitive factor and social factor [0, 1], respectively; r_1, r_2 are the random numbers between [0, 1]; and p_{best}^k, g_{best}^k are the personal best and global best among all in the group at iteration k , respectively.

The current position can be calculated by adding the current velocity in the previous position.

$$x_i^{k+1} = x_i^k + V_i^{k+1} \quad (5)$$

where x_i^{k+1} is the current velocity of particle i at iteration $k+1$.

Reference [32] proposed the acceleration coefficient value $C_1 = C_2 = 2$. On one hand, if C_1 is much greater than C_2 , each particle will remain attracted to its own personal best-causing excessive wandering. Consequently, the particles can-

not find the optimal solution and remain trapped in the local value. On the other hand, if C_2 is much greater than C_1 , the particles will be strongly attracted towards the global best position. This is also undesirable because the particles may move away from the optimal value. The particles in the swarm cooperate by exchanging the information discovered in the places they visited. As shown in Fig. 1, the cooperation between the particles should follow the below three rules [34]. The red triangle represents the particle near to the optimal solution while the gray triangles show the particle around the red triangle, and the transparent triangles represent the other particles in the swarm.

- 1) Rule 1: avoid the collision with neighboring birds.
- 2) Rule 2: match the velocity of neighboring birds.
- 3) Rule 3: stay near neighboring birds.

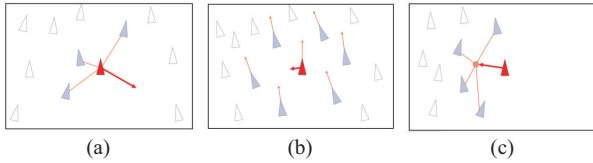


Fig. 1. Swarm cooperation rules. (a) Rule 1. (b) Rule 2. (c) Rule 3.

Equations (4) and (5) represent how the global position and velocity of the particles update at interval k , respectively. Equation (4) consists of three terms. The first term is the current speed of the particle, while the second and third terms show the cognition and social terms, respectively. How the velocity of particle is updated mathematically can be seen in [35] and (4).

C. Application of AHPSO Algorithm

AHPSO is proposed to overcome the problem of particles being trapped into local minima. The modified 2/3rd rule is combined with the standard PSO, and AHPSO algorithm is developed for the siting and sizing of DGs in the smart grid. The search space for searching the optimal location is reduced by using the modified 2/3rd rule, and then PSO is used to search within the specified bounds. The step-by-step process of the proposed AHPSO algorithm is described as follows:

Step 1: input system data. Total number of iterations, line data (resistance, reactance, and susceptance) and bus data (bus-type, voltage magnitude and angle, active and reactive power limits, etc.) are given.

Step 2: calculate the active power loss. Calculate the active power loss of base case by using exact loss formula and voltage and current by using load flow analysis.

Step 3: site and size DG. Determine the search space by using the modified 2/3rd rule based on the load distribution behavior.

Steps 4: calculate the total active power loss. For each DG, calculate the total active power loss by (1) if the bus voltage is within the limits. Otherwise, the particle is infeasible.

Step 5: find the p_{best} and g_{best} . For each DG, objective function P_{loss} is calculated and compared with p_{best} . If this value is lower than p_{best} , set this value as the current p_{best} and record the corresponding particle position. The smallest active power loss among all is the g_{best} .

Step 6: update the velocity and position. Update the veloc-

ity and position using (4) and (5).

Step 7: terminate criteria. If the conditions below are satisfied, then terminate the loop. Otherwise, set iteration index $k = k + 1$ and go back to **Step 4**.

The loop termination conditions are: ① no improvement is found; ② the maximum number of iterations is reached. The best siting and sizing represent the minimum real power loss.

D. Modified 2/3rd Rule

The standard 2/3rd rule states that if a DG is placed at two thirds distance from the feeder, the power losses are minimized [7]. This rule has been widely used for capacitor placement in distribution systems. However, it is valid only when the system load is uniformly distributed. Due to non-uniformity of loads in real power systems, this rule cannot be applied directly. Therefore, by using the analytical method suggested in [32], the standard 2/3rd rule can be modified for specific pattern loads. According to [32], the average power loss in a given time period T can be determined by using (6).

$$\begin{cases} P_{tot,loss}(x_0) = \frac{1}{T} \sum_{i=1}^{N_i} P_{loss}(x_0, T_i) T_i \\ P_{loss}(x_0, T_i) = \int_0^{x_0} \left(\int_0^x I_d(x, T_i) dx \right)^2 R dx + \int_{x_0}^l \left(\int_0^x I_d(x, T_i) dx - I_{DG}(T_i) \right)^2 R dx \\ T = \sum_{i=1}^{N_i} T_i \end{cases} \quad (6)$$

where $P_{tot,loss}(x_0)$ is the total value of power loss at node x_0 ; N_i is the total distance of the feeder at time t ; $I_d(x, T_i)$ is the phasor current density; and $I_{DG}(T_i)$ is the injected current by DG. The goal of the process is to deploy the DG in a location where the average power loss is minimum. Therefore, it can be expressed as $dP_{tot,loss}(x_0)/dx_0 = 0$.

1) If the loads are uniformly distributed as shown in Fig. 2(a), the above formula gives an optimal location of $N/3$ from the opposite side of the feeder. Therefore, the distance from the feeder will be $N - N/3$, which is $2N/3$, and it is the same as 2/3rd rule.

2) If the load is increasingly distributed as shown in Fig. 2(b), the above formula gives an optimal location of $(1 - \sqrt{2}/3)N$. The distance from the feeder will be $N - (1 - \sqrt{2}/3)N$.

3) If the loads are centrally distributed as shown in Fig. 2(c), the above formula gives an optimal location of $N/\sqrt{6}$. This can be transformed into $N - N/\sqrt{6}$ for obtaining the distance from the feeder side.

4) Finally, in the case of random loads, mathematical modeling is not possible. Therefore, the bus ($n \in N$) is searched, where the load is equal to 2/3rd of the total networks load, starting from the feeder side. This node is considered as the optimal location for the placement of DGs.

5) The real loads of power systems do not exactly follow these specific pattern loads. Therefore, each system load is categorized as based on its proximity to one of four load patterns.

6) An uncertainty gap of $\pm 10\%$ is considered for specific pattern, i.e., uniformly distributed, increasingly distributed, and centrally distributed, randomly distributed loads, and $\pm 20\%$ is considered for randomly distributed loads.

7) If a node ($n \in N$) is selected as the optimal node for a given system, the upper and lower bounds of the nodes are selected by using upper node number $\min(n + xN, N)$ and lower node number $\max(n - xN, 2)$. And x will be replaced with 0.1 for specific pattern loads and with 0.2 for random pattern loads. The search space of the proposed PSO will be limited to these upper and lower bounds due to the implementation of the modified 2/3rd rule. Therefore, the search space of the proposed PSO is reduced and the probability of local trapping will also be reduced. Additionally, due to limited search space, the convergence of the proposed PSO will be faster than that of the standard PSO.

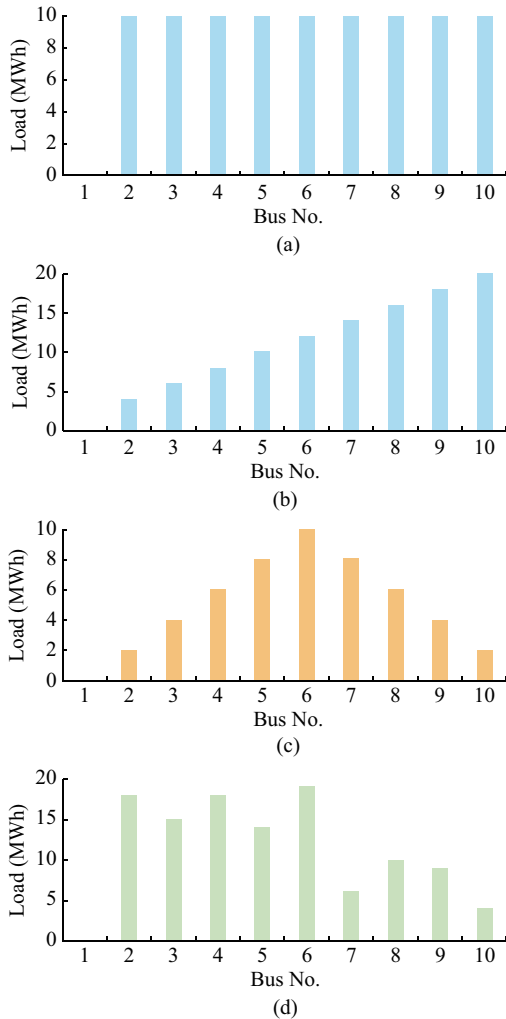


Fig. 2. Different load patterns for IEEE 10-bus system. (a) Uniformly distributed load. (b) Increasingly distributed load. (c) Centrally distributed load. (d) Randomly distributed load.

III. PROBLEM FORMULATION

A. Objective Function

The objective of the proposed PSO is to obtain optimal siting and sizing of DGs, minimizing the following objective

function as expressed in (7). The first term contains the cost for the deployment of a d -type DG. There are various types of distributed energy sources, which are used as DGs, i.e., gas turbines, stirling engines, diesel generators, steam engines, photovoltaic arrays, and fuel cells. The deployment and maintenance costs for each type of energy source are different. Therefore, the DG-type indicator u_d^{DG} is defined and used in this paper. The second term contains the penalty cost for voltage limit violation at each bus of the network. If there is a violation, then $u_i^{viol} = 1$ and the penalty cost will be added. Otherwise, $u_i^{viol} = 0$ and the whole term will be zero. Therefore, no penalty cost will be added to the objective function. The third term contains the cost for active power loss in the network.

$$\min F(C^{DG}, C^{viol}, C^{loss}) = \sum_{d=1}^D C_d^{DG} u_d^{DG} + \sum_{i=1}^N C_i^{viol} v_i + \sum_{i=1}^N \sum_{j=1}^N C_{ij}^{loss} P_{ij}^{loss} \quad (7)$$

$$v_i = \begin{cases} 1 & V_i^{\min} \leq V_i \leq V_i^{\max} \\ 0 & \text{otherwise} \end{cases} \quad \forall i = 1, 2, \dots, N \quad (8)$$

where C^{DG} , C^{viol} , C^{loss} are the costs of DG, violation, and power loss, respectively; C_d^{DG} is the cost for the deployment of a d -type DG; v_i is the voltage at bus i ; C_{ij}^{loss} is the cost of loss at buses i and j ; P_{ij}^{loss} is the power loss at buses i and j ; and V_i^{\min} , V_i^{\max} are the minimum and maximum voltages at bus i , respectively.

The voltage at each bus should not violate and remain in a certain limit, which is specified in (8).

$$v_i^{DG} = \begin{cases} 1 & d\text{-type DG is placed} \\ 0 & \text{otherwise} \end{cases} \quad \forall d = 1, 2, \dots, D \quad (9)$$

Equation (9) shows the category of DG types deployed at bus i .

B. Energy Balancing

The energy balancing of the total network is given by (10), which states that the amount of power injected by the substation and the DG should be balanced with the total load of the network along with network losses.

$$P^{s/s} + \sum_{d=1}^D P_d^{DG} = \sum_{i=1}^N P_i^{load} + \sum_{i=1}^N \sum_{j=1}^N P_{ij}^{loss} \quad (10)$$

where $P^{s/s}$ is the power injected by the substation; and P_d^{DG} is the power generated by the d -type DG.

C. Boundary Conditions

The generation bounds of a selected d -type DG units are given by (11). The angle deviation limits at each bus of the network are given by (12). Finally, the current flowing through each line should be within the rated limits as given by (13).

$$P_{DG}^{\min} \leq P_d^{DG} \leq P_{DG}^{\max} \quad \forall d = 1, 2, \dots, D \quad (11)$$

$$\delta^{\min} \leq \delta_j \leq \delta^{\max} \quad \forall j = 1, 2, \dots, N \quad (12)$$

$$I_i \leq I_i^{\text{rated}} \quad \forall i = 1, 2, \dots, N \quad (13)$$

where P_d^{DG} is the power generated by the d -type; P_{DG}^{\min} , P_{DG}^{\max} are the minimum and maximum power generated by the d -type DG, respectively; δ_j is the angle at node j ; δ^{\min} , δ^{\max} are

the minimum and maximum allowable angles for voltage at bus j , respectively; I_i is the current at node i ; and I_i^{rated} is the rated current at node i .

IV. SIMULATION RESULTS

In order to show the performance of the proposed AHPSO algorithm, three cases are simulated. In the first case, an IEEE 10-bus system is considered and the performance of the modified 2/3rd rule for different load patterns is evaluated. In this case, all the four load patterns, i.e., uniformly distributed, increasingly distributed, centrally distributed, and randomly distributed loads, are considered. In the second case, the convergence speed of the proposed AHPSO for different sizes of networks is evaluated. In addition to IEEE 10-bus, IEEE 33-bus, IEEE 69-bus systems, and a real distribution system in Korea, are also simulated. Finally, we have compared the performance of the proposed AHPSO algorithm with those of an analytical algorithm proposed in [36] for the IEEE 10-bus, IEEE 33-bus, IEEE 69-bus systems, and a real distribution system in Korea. The optimization has been carried out using MATLAB version 2017a on an Intel Core™ i5 PC with 3.20 GHz speed and 16 GB RAM.

A. Validation Through IEEE 10-bus System

In the case of the standard PSO, all 10 nodes are in the search space while the search space has been revised by using the proposed AHPSO algorithm. The iteration numbers vs. power loss for all the four load patterns are shown in Fig. 3. It can be observed from Fig. 3(a) that the standard PSO takes 22 iterations to converge for uniformly distributed loads while the proposed AHPSO algorithm converges for only 10 iterations. Figure 3(b) shows that the standard PSO takes 20 iterations to converge for increasingly distributed loads while the proposed AHPSO algorithm converges in only 9 iterations. Figure 3(c) shows that the standard PSO has converged after 33 iterations for centrally distributed loads while the proposed AHPSO algorithm has converged after 9 iterations. Finally, the standard PSO takes 11 iterations to converge for randomly distributed loads and the proposed AHPSO algorithm takes 5 iterations, as shown in Fig. 3(d).

Table I shows the performance comparison between the standard PSO and the proposed AHPSO algorithms. It can be observed from Table I that the siting and sizing of DGs determined by PSO and the proposed AHPSO algorithms are identical for all four cases. However, the search space has been drastically reduced by the proposed AHPSO algorithm due to the utilization of the modified 2/3rd rule.

Due to this reduced search space, the searching speed of the proposed AHPSO algorithm has been increased by 32% for randomly distributed loads and by about 55% for the remaining three load patterns. The improvement has been determined by using the number of iterations taken by each algorithm (standard PSO as reference) for its convergence.

Since the siting and sizing of DGs determined by standard PSO and the proposed AHPSO algorithms are identical, the voltage load profile of the network has been compared before and after placing the DGs, as shown in Fig. 4.

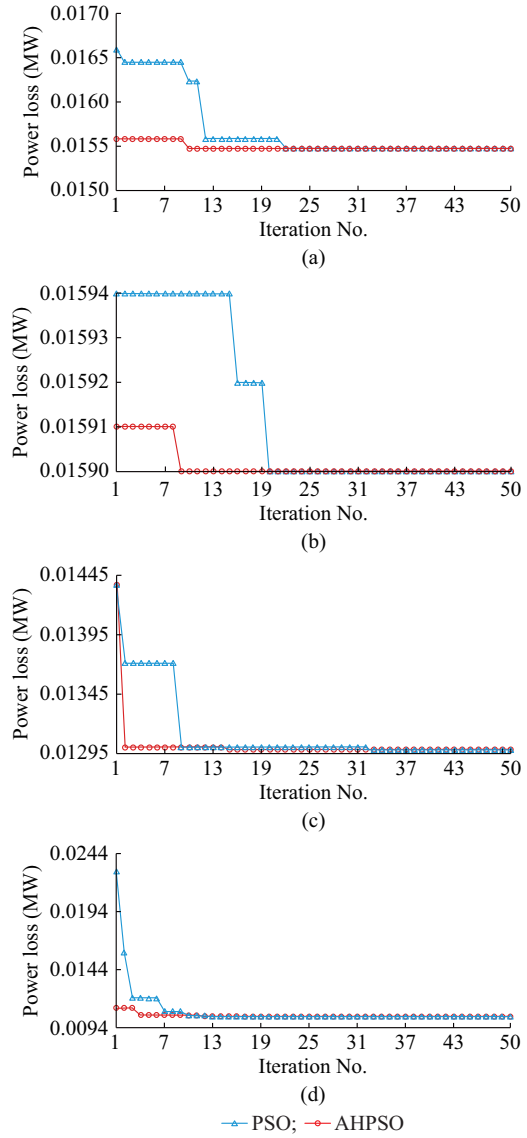


Fig. 3. Convergence of standard PSO and AHPSO for different load patterns in IEEE 10-bus system. (a) Uniformly distributed load. (b) Increasingly distributed load. (c) Centrally distributed load. (d) Randomly distributed load.

TABLE I
PERFORMANCE OF STANDARD PSO AND AHPSO FOR DIFFERENT LOAD PATTERNS IN IEEE 10-BUS SYSTEM

Load distribution	Algorithm	Location	Size (MW)	Bus no.	Improvement (%)
Uniformly distributed	PSO	7	1.8411	2-10	0.00
	HPSO	7	1.8411	6-8	54.55
Increasing distributed	PSO	8	1.7995	2-10	0.00
	HPSO	8	1.7995	7-9	54.55
Centrally distributed	PSO	7	1.7557	2-10	0.00
	HPSO	7	1.7557	5-7	54.55
Randomly distributed	PSO	9	0.4551	2-10	0.00
	HPSO	9	0.4551	6-10	32.00

It can be observed from Fig. 4 that in all four cases, before deploying the DG, the voltage profiles of some of the buses are not in the acceptable bound, i.e., 1 ± 0.05 p.u.. However, after placing the optimal sized DG at the optimal

location determined by the proposed AHPSO algorithm, the voltage profiles of all the buses have shifted to the acceptable range in all cases.

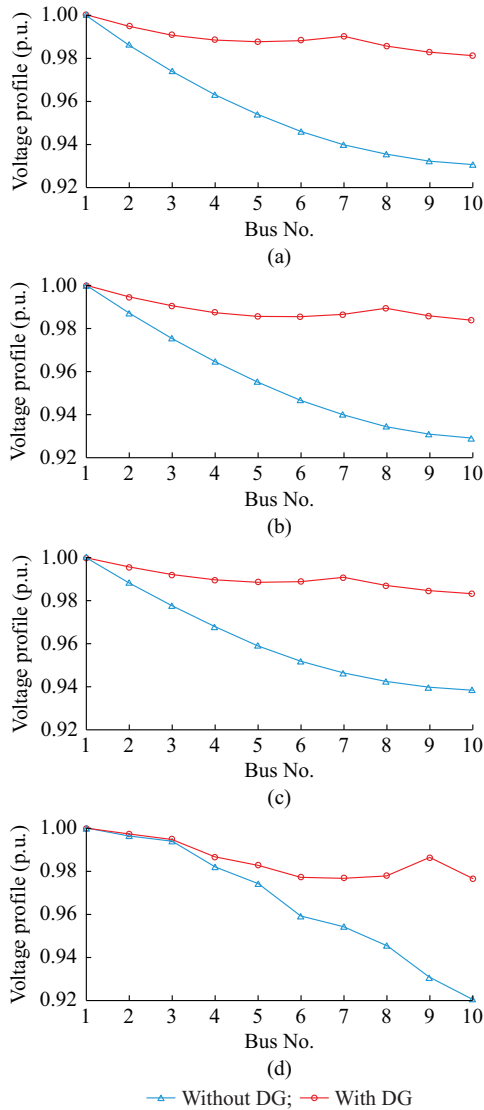


Fig. 4. Voltage profile for different load patterns in IEEE 10-bus system before and after placing DGs. (a) Uniformly distributed load. (b) Increasingly distributed load. (c) Centrally distributed load. (d) Randomly distributed load.

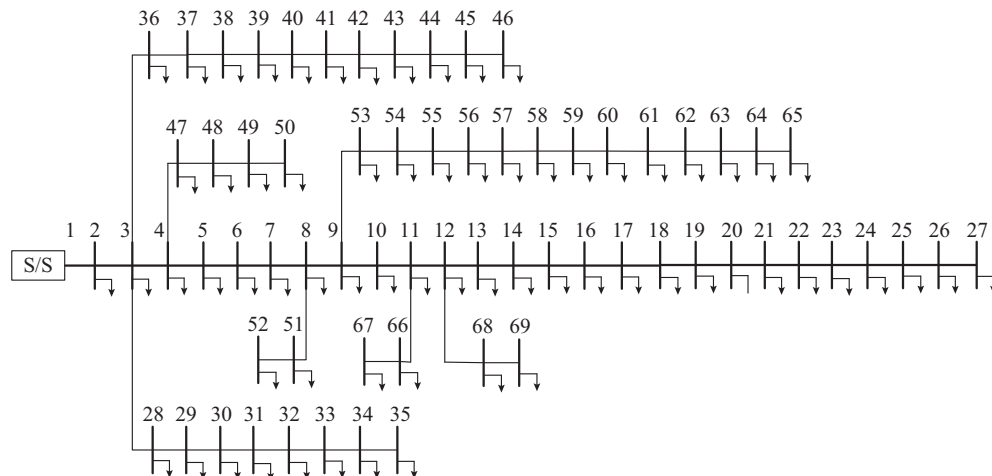


Fig. 7. Single-line diagram of IEEE 69-bus system.

B. Performance Comparison for Different Distribution Systems

In this sub-section, the performances of the proposed AHPSO algorithm and the standard PSO are compared in different distribution systems. IEEE 10-bus [36], [37], IEEE 33-bus [38], [39], IEEE 69-bus [40] systems and one real distribution system in Korea [41] are considered. In all the cases, due to the proximity of loads to the randomly distributed loads, the modified 2/3rd rule for randomly distributed loads is considered. Similar to the previous section, the number of iterations, the improvement in the search space, and the voltage profiles are evaluated.

1) IEEE 10-bus System

The proposed algorithm is firstly tested on IEEE 10-bus, single-feeder, zero-lateral radial distribution system as shown in Fig. 5 [36], [37]. The rated line voltage of this system is 23 kV.

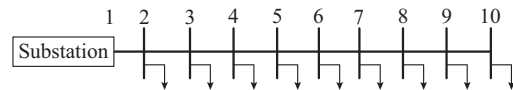


Fig. 5. Single-line diagram of IEEE 10-bus system.

2) IEEE 33-bus System

IEEE 33-bus system is a radial distribution system consisting 32 branches and 33 buses with total load of 3.715 MW and 2.3 Mvar, and the substation voltage is 12.66 kV as shown in Fig. 6.

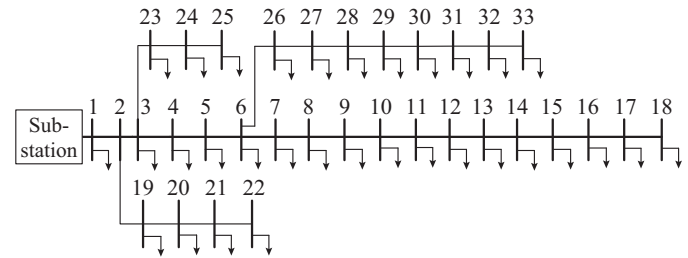


Fig. 6. Single-line diagram of IEEE 33-bus system.

3) IEEE 69-bus System

The IEEE 69-bus system is also a radial distribution system consisting 65 branches, 69 buses, and the total demands of the IEEE 69-bus system are 3802.19 kW and 2694.60 kvar as shown in Fig. 7.

4) KEPCO Distribution System

The KEPCO distribution system is also a radial distribution system consisting of 4 feeders. Figure 8 presents the single-line diagram of KEPCO distribution system. The 1st feeder is taken into consideration, which has the total load of 6.106 MW, 3.011 Mvar.

5) Performance Comparison Through Different Test Systems

The objective is to minimize the active power loss of the network. Therefore, the active power loss after each iteration is shown in Fig. 9. It can be observed from Fig. 9(a) that the number of iterations has been reduced from 20 to 10 for the IEEE 10-bus system by using the AHP SO algorithm. Likewise, the standard PSO has taken 54 iterations to converge for the IEEE 33-bus system as shown in Fig. 9(b). AHP SO algorithm has reduced the iterations to 31 for the same results. In the case of IEEE 69-bus system, the standard PSO takes 55 iterations to converge while AHP SO algorithm converges in only 27 iterations as shown in Fig. 9(c). Finally, in the case of the KEPCO distribution system, the standard PSO takes 18 iterations while AHP SO algorithm

takes 8 iterations to converge as shown in Fig. 9(d).

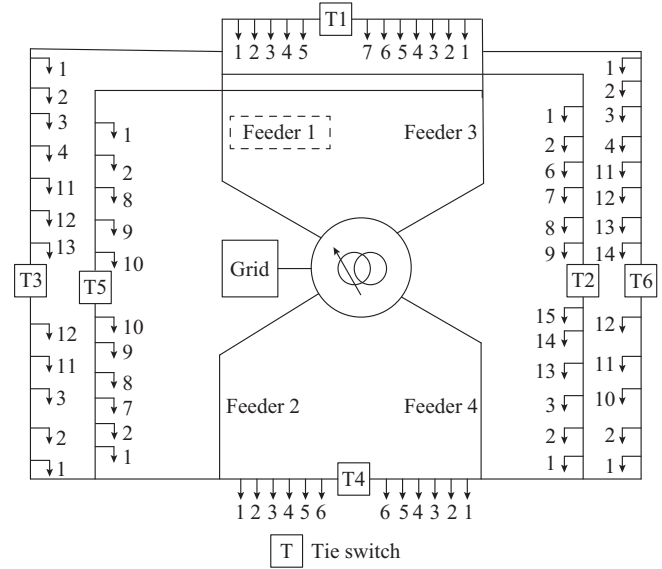


Fig. 8. Single-line diagram of KEPCO distribution system.

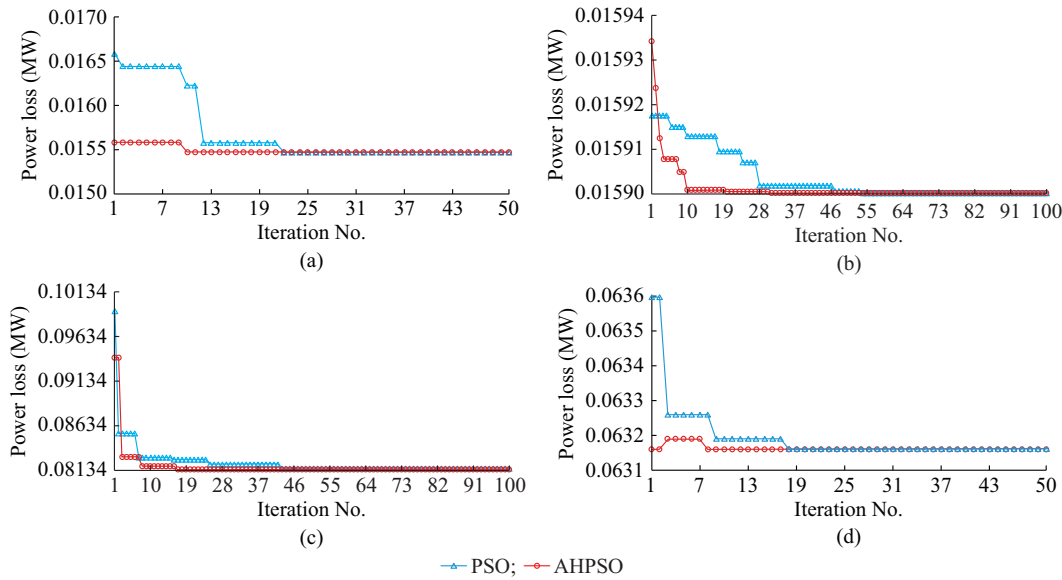


Fig. 9. Convergence of standard PSO and AHP SO for different distribution systems. (a) IEEE 10-bus system. (b) IEEE 33-bus system. (c) IEEE 69-bus system. (d) KEPCO distribution system.

Similar to the previous sections, the siting and sizing of DGs determined by both the standard PSO and AHP SO algorithms are identical for all types of distributions systems, as shown in Table II. The search space has been drastically reduced by the AHP SO algorithm, especially for the large distribution systems. The improvement in the performance of the AHP SO algorithm is increased for all types of distribution systems. The performance of the AHP SO algorithm is getting better for the larger distributions systems, as shown in Table II.

Figure 10 shows the comparison of the voltage profiles for all the four distribution systems before and after placing DGs.

TABLE II
PERFORMANCE OF STANDARD PSO AND AHP SO FOR DIFFERENT DISTRIBUTION SYSTEMS

Test system	Method	Location	Size (MW)	Bus No.	Improvement (%)
IEEE 10-bus system	PSO	9	0.4551	2-10	0.00
	HPSO	9	0.4551	6-10	32.55
IEEE 33-bus system	PSO	7	2.8875	2-33	0.00
	HPSO	7	2.8875	2-13	42.59
IEEE 69-bus system	PSO	61	1.8715	2-69	0.00
	HPSO	61	1.8715	53-69	50.91
KEPCO system	PSO	3	5.7655	2-14	0.00
	HPSO	3	5.7655	2-7	55.56

Before placing the DG, the voltage profiles of some of the buses in all the distribution systems are violating the acceptable bound limits. However, after placing the optimally sized DG at the optimal location determined by AHPSO algorithm, the voltage profile of all the buses in all the systems have moved to the acceptable range.

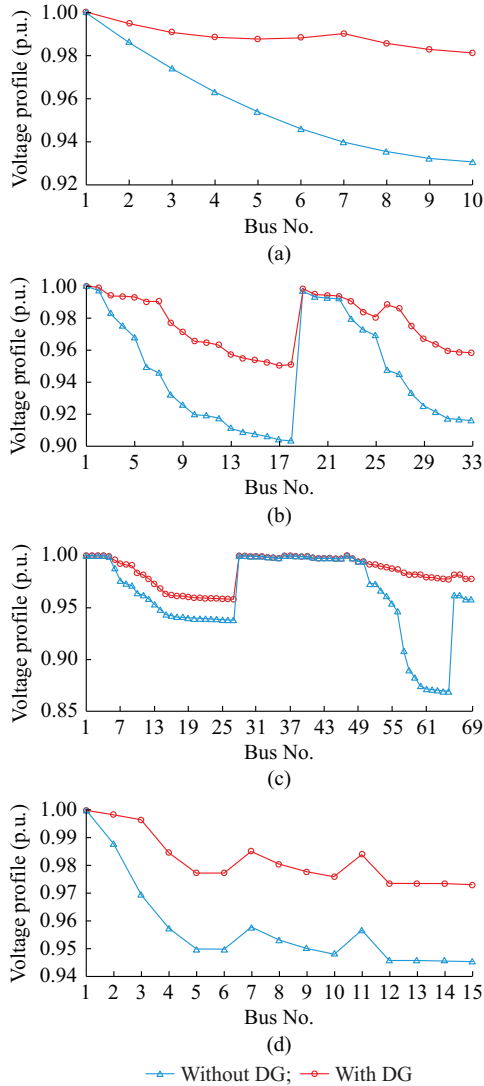


Fig. 10. Voltage profiles for different distribution systems before and after placing DGs. (a) IEEE 10-bus system. (b) IEEE 33-bus system. (c) IEEE 69-bus system. (d) KEPCO distribution system.

C. Performance Comparison of Proposed and Analytical Algorithms

The performance of the proposed algorithm is compared with that of the analytical algorithm proposed in [34] using different test systems. The comparison of the results for both the cases is presented in Table III. It can be observed that the siting and sizing of DGs proposed by both the analytical and the proposed algorithms for IEEE 10-bus system are the same. Note that the siting and sizing of DGs for IEEE 33-bus system are different, which is due to the consideration of voltage violation bounds in the proposed algorithm, i.e., only power loss has been considered in [34]. Although the network loss is lower in the analytical case, the determined

siting and sizing of DGs in [34] result in voltage violation in busses 14, 15, 16, and 17, i.e., below 0.95 p.u.. In the case of IEEE 69-bus system, the proposed and the analytical algorithms show similar results. Voltage limits are not violated in both the cases but power loss has been further reduced by the proposed algorithm. Finally, the performance of both the proposed and the analytical algorithms are similar in the case of the KEPCO test system with reduced power loss by the proposed algorithm.

TABLE III
PERFORMANCE COMPARISON OF PROPOSED AND ANALYTICAL ALGORITHMS FOR DIFFERENT TEST SYSTEMS

Test system	Location	Analytical algorithm [45]		Proposed algorithm	
		Size (MW)	Loss (MW)	Size (MW)	Loss (MW)
IEEE 10-bus	9	0.4551	0.0097	0.4551	0.0097
IEEE 33-bus	6	2.4900	0.1112	2.8875	0.1149
IEEE 69-bus	61	1.8100	0.0814	1.8715	0.0813
KEPCO	3	5.6490	0.0632	5.7655	0.0631

V. CONCLUSION

In this paper, a novel AHPSO algorithm has been proposed to determine the optimal siting of DGs in various load distribution patterns including randomly distributed loads. The modified 2/3rd rule is utilized to narrow down the search space of the searching algorithm. Due to the increasing use of PSO for the optimal siting and sizing of DGs in distribution systems, PSO with the modified 2/3rd rule is utilized in this paper. However, the proposed modified 2/3rd rule can be applied to other heuristic algorithms to limit their search space, and finally to avoid local trapping. The convergence speed to the standard PSO and the proposed AHPSO algorithm are compared for two cases. In the first case, the performance is compared for different load distribution patterns in an IEEE 10-bus system. The convergence speed of AHPSO has improved by about 55% for uniformly distributed, increasingly distributed, and centrally distributed loads and by 32% for randomly distributed loads. In the second case, the convergence speed of both the algorithms is compared for different distribution systems. The convergence performance of AHPSO has improved by 32%, 42.59%, 50.91%, and 55.56% for the IEEE 10-bus, IEEE 33-bus, IEEE 69-bus systems, and KEPCO distribution system, respectively. The final result of the siting and sizing of DG is the same in all the cases for both standard PSO and the proposed AHPSO algorithms. In all the cases, the voltage profiles of all the networks have moved to the acceptable range after placing optimally sized DG at the designated position by the proposed algorithm.

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