Optimal Distributed Generations Placement in Radial Distribution Network Using Whale Optimization Algorithm

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ABSTRACT

Due to recent high demand of electricity, the usage of distributed generations (DG) in distribution system has been increasing significantly. Distributed generations (DG) are promising solution to conventional energy issues as they are capable of giving many benefits to the efficiency of radial distribution feeders. However, improper placement of DGs will impact the technical aspects of distribution system in term of system voltage instability and power losses. Hence, optimal DGs placement in radial distribution network is very crucial for power loss reduction and voltage performance enhancement. The selection of optimized DGs location in a radial distribution network involves complex optimization problem. Whale Optimization Algorithm (WOA) is proposed to optimize the location of DG units, subjected to the system constraints. First, the system power loss and bus voltage level without DG placement are calculated using power flow analysis based on 'backward-forward' technique. After that, WOA was implemented to determine the optimal placement of DGs on IEEE 28-bus, 33-bus and 69-bus system. The results are then analyzed and compared with other algorithm based on the consistency and convergence characteristics. The power loss reduction and voltage profile improvement within acceptable range has been achieved after placing DG units at optimized location. Also, WOA is reliable optimization technique with high consistency and fast convergence.

Key words: Active power loss, distributed generations, optimal placement, whale optimization.

1. INTRODUCTION

The utility companies in Malaysia are now facing new challenges where electricity generation needs to be more efficient while also having the characteristics of sustainability and reliability to meet the ever-rising demand for electricity in the future. According to Figure 1, it shows that electricity demand in Peninsular Malaysia is expected to increase by year 2035. However, the increased electricity generation contributes to the high power loss factor in power system. Commercial and industrial consumers in particular will see a significant increase in their electricity bills. Therefore, more electricity needs to be generated to compensate for the increase in consumer load and to reduce the impact of power loss.

Distribution system is more prone to high power loss because it has a higher R / X ratio and radial nature of the system [1]. To address this issue, there are various methods that have been introduced by utility companies. One of the most common solution to minimize power loss is the placement of distributed generations (DG) in the radial distribution system. Distributed generation (DG) uses smaller power generating units to produce electricity near the receiving loads of utility thereby avoiding the need for power to be delivered from distant central power stations, suffering losses during transmission. DG can be installed near residential areas, businesses or critical facilities that require high power supply. The capacity of DG are typically between 25 kW to 100 MW [2].

Solar photovoltaic was chosen as the renewable energy source for DG in this study. The selection factors are based on the availability of photovoltaic cell technology and the climate of Malaysia as Malaysia has a strategic position near the equator [3]. In addition, the total cost of photovoltaic installations is decreasing rapidly, with costs expected to drop even lower towards year 2050 [4]. Distributed generation (DG) is crucial in minimizing power loss, improving grid reliability, providing better voltage profile and improving power quality [5],[6]. DG provides more flexibility and scalability to users as they are easily connected or disconnected from the main power grid.

Although DG provides many potential benefits to its users, there are still challenges faced by DG during its installation. The main challenge is the improper installation of DG which might leads to the increasing power loss, operating costs and unstable system performance [1],[7]. Therefore, this factor also affects the quality and reliability of power distributed to consumers.

Researchers have studied the use of metaheuristic algorithms to overcome this optimization problem. Oppose to traditional method such as trial and error, the use of metaheuristic optimization algorithms can solve optimization problem in short time with high convergence rate and diversity of solutions [8].

Some metaheuristic optimization methods such as Bacterial Foraging Optimization [9], Lion-Ant Optimization Technique [10], Invasive Weed Optimization [11], Cuckoo Search Algorithm [1] and Flower Pollination Algorithm [12] have been utilized to determine the optimal DG placement in the radial distribution system. In addition, Genetic Algorithm (GA) based on natural evolution can also optimize the location of DG units to minimize power loss [13]. Particle Swarm Optimization (PSO) is another population-based algorithm that has been implemented as the optimization solution to find the placement of multiple DGs in the distribution system [14].

In this paper, the optimization algorithm proposed to obtain the optimal placement of DG in radial distribution network is the newly developed Whale Optimization Algorithm (WOA). This technique is a type of metaheuristics algorithm that tries to be faster and more efficient in solving optimization problems by balancing between local and global search [15]. To the knowledge of author, the consistency and convergence characteristics of this algorithm has yet been validated in solving improper DG placement in power system.

2. METHODOLOGY

The methodology of this paper involves three different stages. First, the original power losses and bus voltage level are calculated using 'backward-forward sweep' method. Then, WOA was implemented to optimize the placement of DGs for total active power loss reduction in radial distribution network. Lastly, the result of WOA is compared with PSO to validate the algorithm's performance. Three different case studies based on IEEE 28-bus, 33-bus and 69-bus network are tested with MATLAB software.

2.1 Objective Function and Constraint

Given system operating conditions, a single objective function to minimize active power loss has been formulated as

shown in (1).

$$OF_{min} = P_{Loss} = \sum_{k=1}^{N_s} Loss_k \tag{1}$$

where OF_{min} is the objective function, P_{Loss} is the total active power loss, $Loss_k$ is the power loss at section k, and N_s is the number of section.

The power loss in the system is expressed using (2)-(4).

$$P_{Loss} = \sum_{i=1}^{N} \sum_{j=1}^{N} X_{ij}(P_iP_j + Q_iQ_j) + Y_{ij}(Q_iP_j + P_iQ_j) \tag{2}$$

$$X_{ij} = \frac{RL_{ij}\cos(\delta_i - \delta_j)}{v_iv_j} \tag{3}$$

$$Y_{ij} = \frac{RL_{ij}\sin(\delta_i - \delta_j)}{v_iv_j} \tag{4}$$

where P_i is the active power supplied at bus i, Q_i is the reactive power supplied at bus i, RL_{ij} is the line resistance between buses, V_i is the voltage at bus i and δ_i is the angle at bus i.

Power balance, voltage and current limit constraints are given by (5)-(7) as follows:

$$\sum_{i=1}^{N} P_{DGi} = \sum_{i=1}^{N} P_{Ri} + P_{Loss} \tag{5}$$

$$\sum_{i=1}^{N} P_{DGi} = \sum_{i=1}^{N} P_{Ri} + P_{Loss} \tag{6}$$

$$|I_{ij}| \leq |I_{ij}|^{max} \tag{7}$$

where P_{DGi} is the active power generated by DG at bus i, P_{Ri} is the power request at bus i, $|V_i|^{min}$ is 0.95 per unit and $|V_i|^{max}$ is 1.05 per unit. According to (8), the total active power generated by DGs were set to a fixed value. Equation (9) is expressed to obtain the active power generation by each DG. Therefore, the DG capacity will change with the number of DGs.

$$\sum_{i=1}^{N} P_{DG_i} = 2.36 \, MW \tag{8}$$

$$P_{DG_i} = \frac{\sum_{i=1}^{N} P_{DG_i}}{Number \; of \; DG} \tag{9}$$

2.2 Whale Optimization Algorithm

Whale Optimization Algorithm (WOA) is modeled mathematically according to the unique hunting behavior of humpback whales, namely bubble-net hunting method as shown in Figure 1 [15],[16].
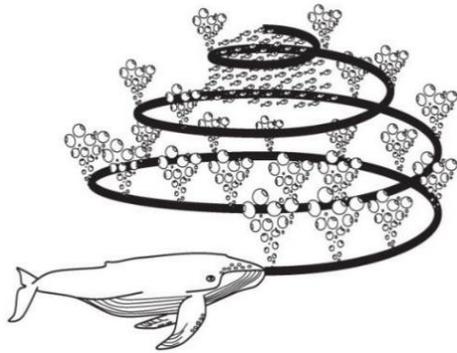
Figure 1: Illustration of whale's hunting behaviour [17]

Figure 2: Illustration of shrinking encircling prey approach [14]

2.2.1 Encircling Prey

The humpback whales encircle around their prey after locating them. In this case, the target prey represents the best solution. After that, the other search agents keep updating their positions towards the best search agent to search for better solution. The equations based on this behaviour are shown below:

$$\vec{X}(t+1) = \vec{X}^*(t) - \vec{A} \cdot \vec{D} \tag{10}$$

$$\vec{D} = \left| \vec{C} \cdot \vec{X}^*(t) - \vec{X}(t) \right| \tag{11}$$

where $\vec{X}$ is position vector of search agent, $\vec{D}$ is distance vector between search agent and best solution, $\vec{X}^*(t)$ is position vector of the best solution and t is current iteration. Both coefficient $\vec{A}$ and $\vec{C}$ are computed from (12) and (13) as follows:

$$\vec{A} = 2 \cdot \vec{a} \cdot \vec{r} - \vec{a} \tag{12}$$

$$\vec{C} = 2 \cdot \vec{r} \tag{13}$$

2.2.2 Shrinking Encircling Prey

To mimic the shrinking encircling prey behavior mathematically, $\vec{A}$ is decreased by linearly reducing the value of $\vec{a}$ from 2 to 0 in (12). Figure 2 shows the possible position of better solution between random search (X,Y) and the current best solution at (X^*,Y^*).

2.2.3 Spirally Position Updating

In Figure 3, the spirally position updating mechanism first compute the distance between the locations of the whale and prey at (X,Y) and (X^*,Y^*) respectively. Then, the helix-shaped movement of the whale is formulated as shown by (14) and (15).

$$\vec{X}(t+1) = \vec{D}' \cdot e^{bl} \cdot \cos(2\pi l) + \vec{X}^*(t) \tag{14}$$

$$\vec{D}' = \left| \vec{X}^*(t) - \vec{X}(t) \right| \tag{15}$$

where $\vec{D}'$ is distance between search agent and best solution, b is constant describing the helix-shape and l is random number between [-1,1].

However, in real life, the whale swims around its victim in a shrinking circle and spirally along the '9' shape at the same time. This mathematical model is expressed mathematically in (16), where assuming there is 50% probability when choosing whether the mechanism is shrinking encircling or spirally position updating during optimization.

$$X(t+1) = \begin{cases} \vec{X}^*(t) - \vec{A} \cdot \vec{D} & \text{if } p < 0.5 \\ \vec{D}' \cdot e^{bl} \cdot \cos(2\pi l) + \vec{X}^*(t) & \text{if } p \geq 0.5 \end{cases} \tag{16}$$

where p is a random number in interval [0,1].
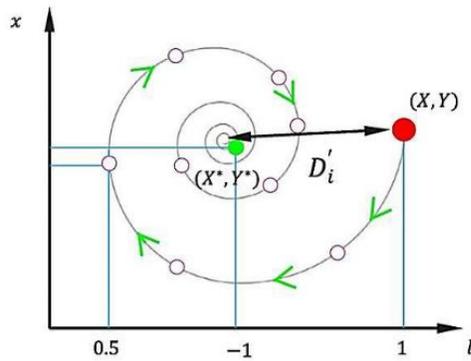
Figure 3: Illustration of spirally position updating approach [16]

2.2.4 Searching Prey

To achieve global optimization, the search agent positions are updated by randomly selecting search agent as the prey rather than the best solution. WOA uses the variations of vector $\vec{A}$ to control the search agent to search for solution globally. Equations (17) and (18) show that $\overrightarrow{X_{rand}}$ has replaced $\vec{X}^*$, where $\overrightarrow{X_{rand}}$ is the position of random search agent.

$$\vec{D} = \left| \vec{C} \cdot \overrightarrow{X_{rand}} - \vec{X} \right| \qquad (17)$$

$$\vec{X}(t+1) = \overrightarrow{X_{rand}} - \vec{A} \cdot \vec{D} \qquad (18)$$

2.2 Implementation of Whale Optimization Algorithm

The procedure to implement WOA to install DGs optimally in radial distribution network for active power losses minimization are explained below:

Step 1 : Initialize bus data, line data, number of DGs, population and iteration.

Step 2 : Calculate power loss and bus voltage magnitude before installing DGs using 'backward-forward sweep' technique.

Step 3 : Generate initial search agent with random position (location of DG units).

Step 4 : Using (4), determine the fitness function for each search agent.

Step 5 : Vector coefficients $\vec{A}$ dan $\vec{C}$ are updated for each search agent using (12) and (13).

Step 6 : If $p < 0.5$, proceed to Step 7. If not, update the current search agent's position using (14).

Step 7 : If $\vec{A} < 1$, update the current search agent's position using (10).

Step 8 : If $\vec{A} \geq 1$, update the position of new search agent using (18).

Step 9 : When $t >$ maximum number of iterations, display the results. Otherwise, return to Step 4.

3. RESULTS AND DISCUSSION

This section presents the results obtained after successfully implementing WOA on IEEE 28-bus, 33-bus and 69-bus network using MATLAB.

3.1 Total Active Power Loss

When one DG unit with 2.36 MW size is installed in the IEEE 28-bus network, it is placed optimally at bus 1. This action didn't impact the original active power loss because the DG capacity is too large. However, installation of two DGs and three DGs in this test system reduced the loss from 68.8192 kW to 48.9097 kW and 43.8066 kW respectively.

When the capacity of DG is higher than load bus, the excess power will be transfer to other users instead. This action will compromise the power quality and the system stability as power injection into the distribution network are limited. Therefore, DG size that are not optimized will increase power losses during transmission and distribution.

The increase of number of DG placements from more than three units will instead increase back the total active power loss to a much higher value. This situation is shown when the total loss increased to 46.9955 kW with the installation of four DG units. Hence, it is proven that the most optimized DGs placement for IEEE 28-bus system is at bus 1, 2, and 6 with the size of 0.787 MW for each three DG units as presented in Table 1.

Active power loss without placing any DGs in IEEE 33-bus system is 203.0812 kW. After installation of one DG at bus 6, the power loss is decreased to 104.8058 kW with 48.39% power loss reduction. The gradual increment to the number of DGs has reduced power losses by significant amount. From Table 2, the minimum real power loss is 69.7410 kW by installing six DG units with the capacity of 0.393 MW at bus 7, 10, 16, 25, 30 and 32.

The result indicates that active power loss reduction percentage increases as the number of DGs increases until seven DG units for IEEE 69-bus system. The placement of seven DGs at bus 12, 21, 60, 61, 62, 63 and 64 with the size of 0.337 MW has achieved the most minimum total real power loss, which is 73.5558 kW as shown in Table 3.

3.2 Voltage Profile

For IEEE 28-bus network with DG installed, the average voltage magnitude is 0.93 per unit. The average voltage level for one DG unit placement remains the same as average voltage level without DG. However, the average voltage level for connection of two DG units and three DG units are increased to 0.9731 per unit and 0.9828 per unit respectively as illustrated in Figure 4.

Figure 5: Voltage profile for IEEE 33-bus network
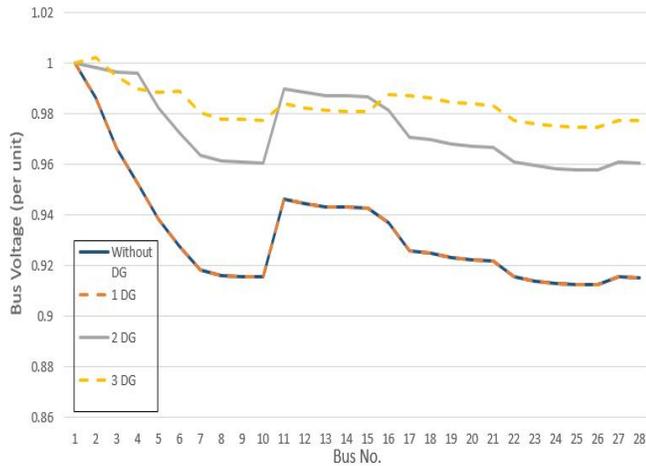
Figure 4: Voltage profile for IEEE 28-bus network

Table 1: Optimal DG location for IEEE 28-bus network

Number of DGs	Total active power loss (kW)	Power loss reduction rate	Size for each DG (MW)	Optimal DG placement (Bus)
0	68.8192	-	-	-
1	68.8192	0.00%	2.360	1
2	48.9087	28.93%	1.180	1
				4
3	43.8066	36.35%	0.787	1
				2
				6
4	46.9955	31.71%	0.590	1
				2
				3
				7

Table 2: Optimal DG location for IEEE 33-bus network

Number of DGs	Total active power loss (kW)	Power loss reduction rate	Size for each DG (MW)	Optimal DG placement (Bus)
0	203.0812	-	-	-
1	104.8058	48.39%	2.360	6
2	87.8012	56.77%	1.180	10
				30
3	75.3344	62.90%	0.787	13
				25
				31
4	71.6261	64.73%	0.590	7

				14
				25
				31
5	70.1381	65.46%	0.472	8
				15
				25
				29
				32
6	69.7410	65.66%	0.393	7
				10
				16
				25
				30
				32

Table 3: Optimal DG location for IEEE 69-bus network

Number of DG	Total active power loss (kW)	Power loss reduction rate	Size for each DG (MW)	Optimal DG placement (Bus)
0	238.6731	-	-	-
1	95.6066	59.94%	2.360	61
2	88.0188	63.12%	1.180	11
				61
3	77.1413	67.68%	0.787	12
				61
				62
4	75.5769	68.33%	0.590	17
				60
				61
				62
5	75.0342	68.56%	0.472	18
				59
				61
				62
				64
6	74.4722	68.80%	0.393	18
				60
				61
				62
				64
				66
7	73.5558	69.18%	0.337	12
				21
				60
				61
				62
				63
				64
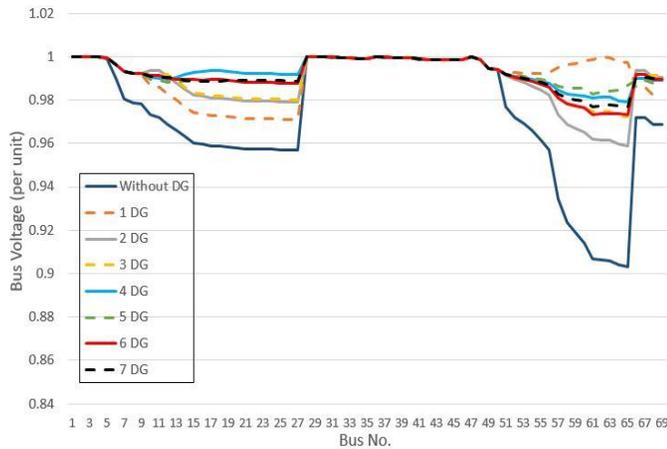
Figure 6: Voltage profile for IEEE 69-bus network

In Figure 5, the voltage profile for optimized placement of one DG until six DGs in IEEE 33-bus network are presented. When no DG units are installed, the average bus voltage is 0.9484 per unit and lowest voltage magnitude is 0.9129 per unit at bus 18.

After installation of one DG, the average bus voltage increased to 0.9727 per unit while minimum bus voltage also increased to 0.9479 per unit at bus 18. When the number of DG increases, the average voltage level is increased to 0.9836 per unit (two DGs), 0.9781 per unit (three DGs), 0.9782 per unit (four DGs), 0.97913 per unit (five DGs) and 0.9800 per unit (six DGs).

According to Figure 6, the average bus voltage before installing DG in IEEE 69-bus network is 0.9725 per unit. The optimal placement of seven DG units increased the average voltage magnitude to 0.9922 per unit. Therefore, the results of all three case studies shown that installing DGs at optimized location enhanced the system voltage performance.

3.3 Validation of Algorithm Performance

The performance of WOA based on consistency, convergence characteristics and optimal DG placement are verified by comparing the simulation results with Particle Swarm Optimization (PSO). The consistency and convergence characteristics tests are conducted with simulation parameter in Table 4.

Table 4: Simulation parameter for consistency and convergence characteristics test

Parameter	Value
Number of search agents	20
Nuber of iterations	100
Number of DGs	3
Number of runs	20

3.3.1 Consistency

Figure 7 shows that WOA gives consistent results at lowest fitness value which is 43.8066 kW for every run compared to PSO which gives 15 out of 20 consistent results for the same fitness value.
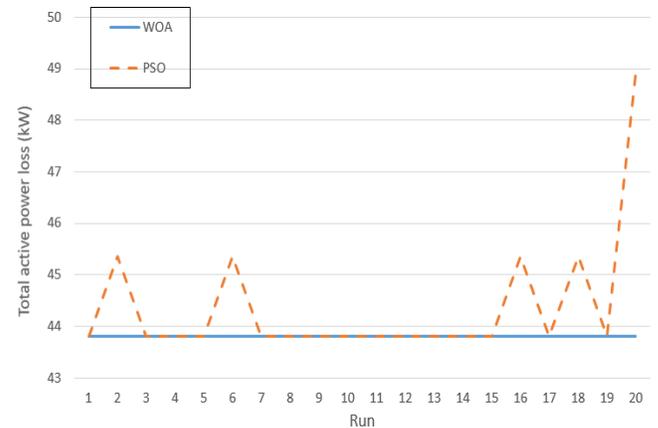
Figure 7: Consistency of WOA and PSO for IEEE 28-bus network
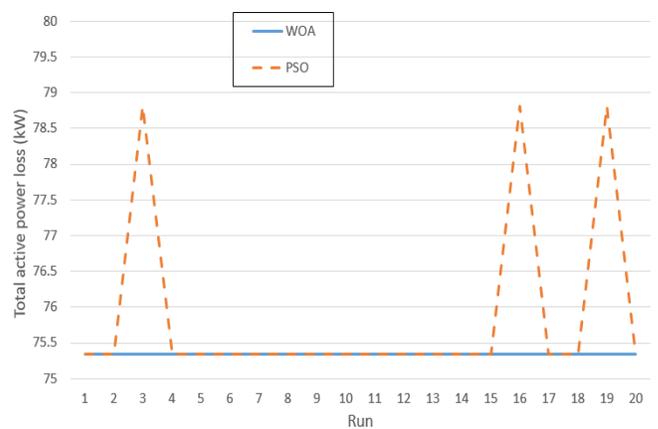
Figure 8: Consistency of WOA and PSO for IEEE 33-bus network
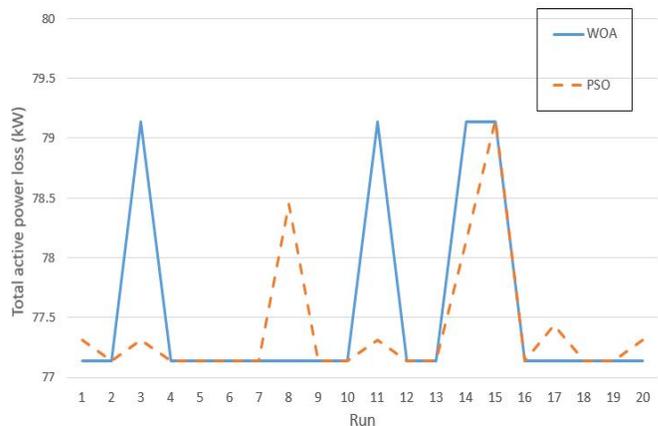
Figure 9: Consistency of WOA and PSO for IEEE 69-bus network

From Figure 8, the lowest fitness value is 75.3344 kW for optimized three DGs placement in 33-bus system. WOA gives 19 out of 20 consistent results at lowest fitness value as

compared to PSO which gives 17 out of 20 consistent results. In Figure 9, WOA gives the minimum active power loss of 77.1413 kW for 16 out of 20 runs. However, PSO gives the same consistent results for 12 out of 20 runs. Hence, overall results shown that WOA produced more consistent results than PSO for all three radial distribution network.

3.3.2 Convergence Characteristics

In Figure 10, WOA reaches minimum total real power loss at 5th iteration while PSO reaches at 26th iteration for IEEE 28-bus network. For IEEE 33-bus system, WOA reaches minimum real power losses at 10th iteration while PSO reaches at 25th iteration as presented in Figure 11.

Meanwhile in Figure 12, WOA reaches minimum total active power loss at 14th iteration while PSO reaches at 21st iteration for IEEE 69-bus system. Therefore, WOA has demonstrated faster convergence rate than PSO.
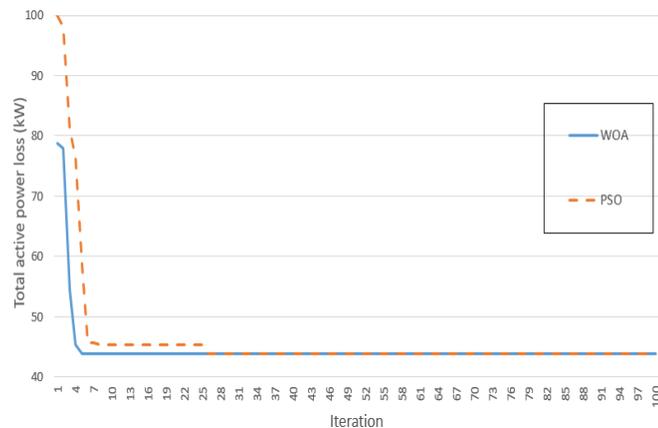
Figure 10: Convergence characteristics of WOA and PSO for IEEE 28-bus network
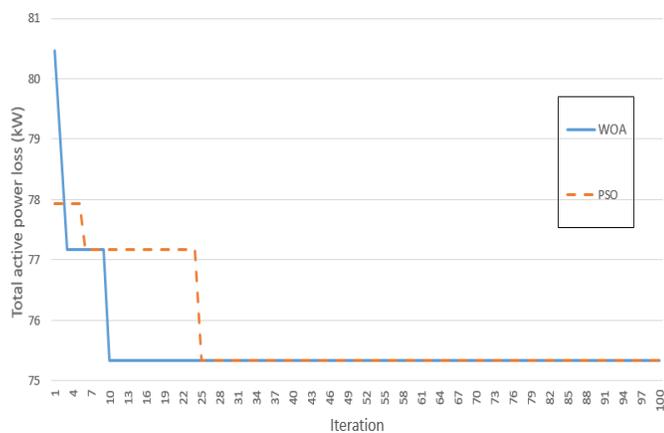
Figure 11: Convergence characteristics of WOA and PSO for IEEE 33-bus network
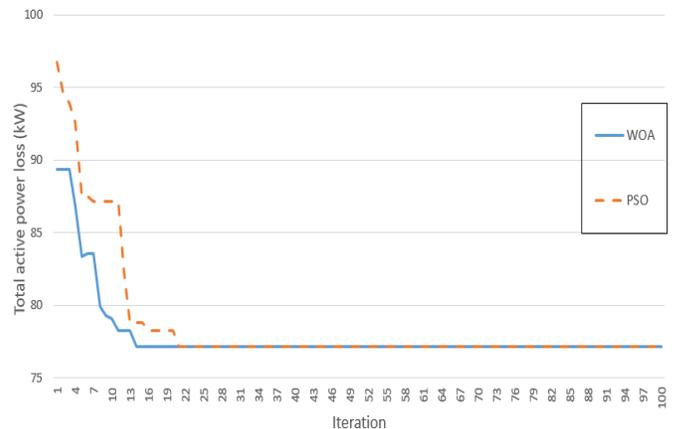
Figure 12: Convergence characteristics of WOA and PSO for IEEE 69-bus network

3.3.3 Optimal Distributed Generations' Placement

Table 5 shows the total active power loss corresponds to DGs location obtained by both algorithms are the same for 28-bus network.

WOA compute that installation of six DGs at bus 7, 10, 16, 25, 30 and 32 which reduces 65.66% from the original active power loss is the most optimized solution for IEEE 33-bus network. On the other hand, PSO acquired optimal DG locations at bus 7, 11, 16, 25, 30 and 32 which reduces 65.54% of the original active power loss as shown in Table 6.

Referring to Table 7, the most optimized solution obtained by WOA for IEEE 69-bus radial distribution is optimal placement of seven DGs which decreases the total active power loss to 73.5558 kW. This value is lesser when compared with the most optimized solution obtained by PSO.

Hence, the results proved that WOA is capable of giving optimization solution that is better than PSO as the radial distribution network configuration becomes larger. Besides that, the computational time taken by WOA is shorter than PSO for all 3 study cases. Therefore, WOA is a fast and capable algorithm in solving optimization problem.

Table 5: Comparison of optimal DG location between WOA and PSO for IEEE 28-bus network

Algorithm	Total active power loss (kW)	Power loss reduction rate	Size for each DG (MW)	Number of DGs	Optimal DG location (Bus no.)	Computational time (seconds)
WOA	43.8066	36.35%	0.787	3	1 2 6	15.58935
PSO	43.8066	36.35%	0.787	3	1 2 6	16.17732

Table 6: Comparison of optimal DG location between WOA and PSO for IEEE 33-bus network

Algorithm	Total active power loss (kW)	Power loss reduction rate	Size for each DG (MW)	Number of DGs	Optimal DG location (Bus no.)	Computational time (seconds)
WOA	69.741	65.66%	0.3933	6	7 10 16 25 30 32	16.33415
PSO	69.7747	65.64%	0.3933	6	7 11 16 25 30 32	16.639735

Table 7: Comparison of optimal DG location between WOA and PSO for IEEE 69-bus network

Algorithm	Total active power loss (kW)	Power loss reduction rate	Size for each DG (MW)	Number of DGs	Optimal DG location (Bus no.)	Computational time (seconds)
WOA	73.5558	69.18%	0.3377	7	12 21 60 61 62 63 64	26.952965
PSO	75.1789	68.50%	0.3933	6	18 60 61 63 64 69	26.989885

4. CONCLUSION

In conclusion, the power loss reduction and voltage profile improvement within acceptable range has been achieved after DG units are installed at optimized location for IEEE 28-bus, 33-bus and 69-bus system using Whale Optimization Algorithm. Besides that, WOA demonstrated high consistency and fast convergence characteristics of in obtaining better solution for optimal placement of DGs in radial distribution network.

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