Multi Objective Allocation of Distribution Generation in Distribution System Using Whale Optimization Algorithm

[1]Ramavath Gnanendar [2]Dr. M. Sushama

[1]*Research Scholar, Department of EEE, JNTU Hyderabad, Telangana, India*

[2] *Professor, Department of EEE, JNTUHUCEST Hyderabad, Telangana, India*

Abstract: *Distributed generation (DG) units are decentralized small-scale power generation systems, they enhance the benefits of distribution networks, such as minimizing power losses, enhancing voltage profiles, and improving the system reliability. However, in order to achieve these benefits, DG units should be optimally sited and sized within the network. The outline in this paper is the use of Whale Optimization Algorithm (WOA) which is an innovative and robust metaheuristics technique based on the hunting behavior of hump-back whales, to address the issue of multi-objective optimization in the placement of distributed generation. The method proposed in this work identifies the best location and size to apply DG devices in a radial distribution network, thereby reducing power losses and improving voltage stability. The performance of the algorithm avails itself using the IEEE 33-bus radial distribution test system. Different types of DGS as well as other optimization algorithms are used as treatment groups in the comparative analyses. Type-III DG, which operated at the 0.9 p.f showed the best performance in terms of loss minimization and voltage improvement and thus confirming the effectiveness and efficiency of the WOA*

Keywords: **Whale Optimization Algorithm, Distributed Generation, Radial Distribution System, Voltage Profile Improvement, Loss Reduction**

1. INTRODUCTION

The modern electric power system comprises three primary components: generation, transmission, and distribution. Among these, the distribution system plays a crucial role in delivering electricity to end-users by connecting loads to the transmission network through substations. However, it is also the most vulnerable segment, accounting for nearly 70% of total power losses, while the remaining 30% occur at the transmission level. Consequently, improving the efficiency and performance of distribution systems has become a pressing issue, with targeted loss reductions set at approximately 7.5%.

Deploying distributed generation (DG) units at strategically selected locations within the distribution network can significantly reduce losses and improve system performance. Renewable energy sources such as photovoltaic (PV) systems and wind turbines are widely used as DG units, typically situated in remote areas. These systems require seamless integration into both transmission and distribution networks to enhance reliability, minimize costs, and lower greenhouse gas emissions. DG units offer several advantages, including reduced power losses, improved voltage profiles, enhanced system reliability, and lower fuel costs due to increased efficiency.

Optimizing the placement and sizing of DG units is essential to fully leverage their potential benefits. Research shows that improper selection of DG locations and sizes can exacerbate losses and further degrade voltage profiles. Utilities already grappling with high power losses and poor voltage stability must adopt strategic methods to integrate DG units effectively. Earlier studies have proposed various methodologies, such as analytical approaches by Acharya et al. (2006) and Duong Quoc et al. (2010), which did not consider voltage constraints, and probabilistic approaches to account for uncertainties in load variations and network configurations (Su, 2010). Over the years, several optimization techniques have been employed for DG allocation and sizing. Abu-Mouti and El Hawary (2010) used Artificial Bee Colony (ABC) algorithms, while Zangiabadi et al. (2011) addressed DG uncertainties. Moradi MH (2011) introduced a hybrid Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) approach. Evolutionary algorithms for DG placement were proposed by Alonso et al. (2012), Hosseini et al. (2013), and Doagou-Mojarrad et al. (2013). Simultaneous capacitor and DG placement based on sensitivity analysis was explored by Naik et al. (2013). Harmony Search

Algorithm (Nekooei et al., 2013) and Symbiotic Organism Search (Das et al., 2016) were also utilized for multi-objective DG placement.Dynamic load conditions and time-varying load models have been incorporated into studies by Qian et al. (2011) and Murty and Kumar (2014). More recently, El-Fergany (2015) employed the Backtracking Search Optimization Algorithm (BSOA) for DG planning, addressing multiple DG types under different scenarios. Probabilistic approaches for DG penetration and voltage stability improvements were discussed by Kolenc et al. (2015), Aman et al. (2012), and Singh and Parida (2016). Whale Optimization Algorithm (WOA) was introduced by Prakash and Lakshmi naraya (2016) for capacitor sizing but has yet to be extensively explored for DG placement. However, Whale Optimization Algorithm (Mirjalili, 2016) has demonstrated promising performance across diverse optimization scenarios. Inspired by the unique hunting behavior of humpback whales, WOA is a nature-inspired metaheuristic optimization technique used to address multi-objective problems effectively. In this study, WOA is employed to optimize DG placement and sizing to minimize power losses and enhance voltage profiles in distribution systems.

This paper investigates the application of WOA to optimize DG size and placement in IEEE 33-bus test systems under different scenarios and power factors. DG units are categorized as follows (Reddy et al., 2016):

Type I: Injects real power at unity power factor (e.g., PV cells, microturbines, fuel cells).

Type II: Injects reactive power (e.g., synchronous compensators, capacitors, kVAR compensators).

Type III: Injects both real and reactive power (e.g., biomass plants with synchronous generator).

Type IV: Consumes reactive power while injecting real power (e.g., wind).

2. PROBLEM FORMULATION

Electrical distribution systems, responsible for the final delivery of power to end-users, are inherently more susceptible to energy losses compared to high-voltage transmission networks. A primary contributor to these inefficiencies is the real power loss (Ploss) occurring in the distribution lines due to their resistance (R_i) and the current (I_i) flowing through them. For a distribution system with n buses, the total real power loss is mathematically expressed as the sum of losses in each branch:

$$P_{loss} = \sum_{i}^{n} I_i^2 R_i \tag{1}$$

Minimizing these losses is crucial for enhancing the economic efficiency and sustainability of power delivery. Simultaneously, maintaining an acceptable voltage profile across all buses is essential for ensuring the proper operation of connected loads and upholding power quality standards. Significant voltage deviations from the nominal voltage ($V_{nominal}$) can lead to equipment malfunction and system instability. Therefore, the strategic integration of Distributed Generation (DG) must simultaneously address the reduction of real power losses and the improvement of the voltage profile.

$$VD_{RMS}{}^2 = \frac{1}{n} \sum_{i=1}^{n} (V_i - V_{nominal})^2 \tag{2}$$

2.1 Multi-Objective Function

To achieve a balanced optimization of both real power loss reduction and voltage profile improvement, this research employs a multi-objective function. This function combines normalized measures of both objectives, allowing for a comprehensive evaluation of potential DG allocations:

$$\text{Minimize } F = w_1 \times f_1 + w_2 \times f_2 \tag{3}$$

where:

f_1-represents the total real power loss

f_2 -represents the Voltage deviation

w_1 and w_2 are non-negative weighting factors such that $w_1+w_2=1$. These weights allow for the assignment of relative importance to minimizing real power losses and improving the voltage profile, respectively. The selection of these weights is crucial as it defines the trade-off between the two objectives, reflecting the priorities of the system operator.

The minimization of this rigorously defined multi-objective function will guide the Whale Optimization Algorithm to identify the optimal locations and sizes for various DG types, leading to distribution systems with enhanced energy efficiency and improved voltage stability and quality.

2.2 Operational Constraints

The practical implementation of DG units necessitates adherence to several operational constraints to ensure the safe and reliable functioning of the distribution network:

Voltage Constraints: The voltage magnitude (V_i) at each bus i in the system must remain within the permissible operational limits:

$$0.95 \leq V_i \leq 1.05 \tag{4}$$

Power Balance Constraints: At each iteration of the optimization, the total active power generated within the system must be equal to the sum of the total active power demand and the total real power losses within the network:

$$P + \sum_{k=1}^{N} P_{DG} = P_d + P_{loss} \tag{5}$$

Distributed Generation Capacity Limits: The active and reactive power injection (or consumption) capabilities of each DG unit (j) are subject to technical and economic constraints, defined by minimum and maximum limits:

$$60 \leq P_{DG} \leq 3000 \tag{6}$$

where the limits are in kW, kVAR and kVA for type I, II and III DG, respectively.

3. METHODOLOGY

3.1 Whale Optimization Algorithm

Recently a new optimization algorithm called whale optimization algorithm (Mirjalili 2016) has been introduced to metaheuristic algorithm by Mirjalili and lewis. The whales are considered to be as highly intelligent animals with motion. The WOA is inspired by the unique hunting behavior of humpback whales. Usually, the humpback whales prefer to hunt krill's or small fishes which are close to the surface of sea. Humpback whales use a special unique hunting method called bubble net feeding method. In this method they swim around the prey and create a distinctive bubble along a circle or 9-shaped path.

The mathematical model of WOA is described in the following sections:

- Encircling prey
- Bubble net hunting method
- Search the prey

3.1.1 Encircling prey

WOA expects that the present best candidate solution is the objective prey. Others try to update their positions toward best search agent. The behavior modelled is as

$$\vec{X}(t+1) = \overrightarrow{X^*} - \vec{A} \cdot \vec{D} \tag{5}$$

$$\vec{D} = |\vec{C} \cdot \overrightarrow{X^*}(t) - \overrightarrow{X^*}| \tag{6}$$

$$\vec{A} = 2 \cdot \vec{a} \cdot \vec{r} - \vec{a} \tag{7}$$

$$\vec{C} = 2 \cdot \vec{r} \tag{8}$$

Where $\overrightarrow{X^*}$, $\vec{X}$ denote the position of best solution and position vector. Current iteration is denoted by t. $\vec{A}$, $\vec{C}$ are coefficient vectors. $\vec{a}$ is directly diminished from 2 to 0. $\vec{r}$ is a random vector [0, 1].

3.1.2 Bubble net hunting method

In this hunting method two approaches are there.

a. Shrinking encircling prey

Here $\vec{A} \in [-a, a]$, where $\vec{A}$ is decreased from 2 to 0. Here $\vec{A}$ position is setting down at random values in between [−1, 1]. The new position of $\vec{A}$ is obtained between original position and position of the current best agent. Figure 1 shows the possible positions from (X, Y) toward (X*, Y*) that can be achieved by $0 \leq A \leq 1$ in a 2D space represented by Eq. 7.

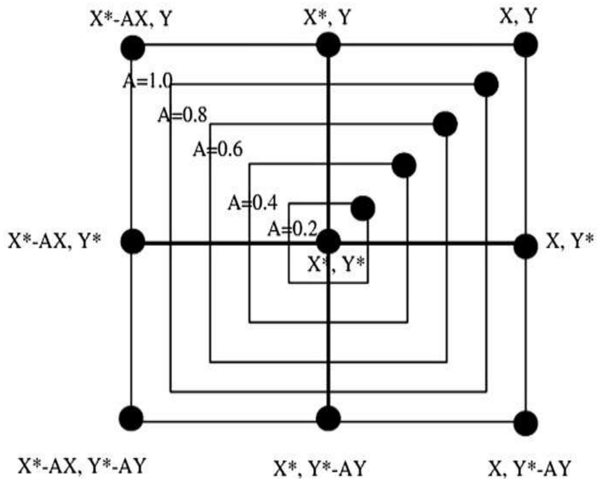

Figure.1 Bubble net search shrinking encircling mechanism

b. Spiral position updating

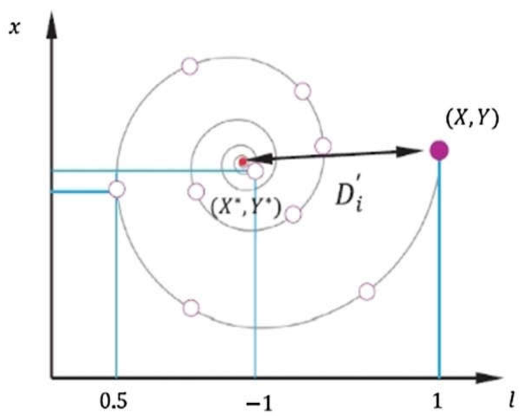

Figure.2 Bubble net search spiral updating position mechanism

To mimic helix-shaped movement spiral equation is used.

$$\vec{X}(t+1) = \overrightarrow{D'} \cdot e^{bl} \cdot cos(2\pi l) + \overrightarrow{X^*} \tag{9}$$

In hunting whales swim around the prey in above two paths simultaneously. To update whale's positions 50% probability is taken for above two methods.

$$\vec{X}(t+1) = \begin{cases} \overrightarrow{X^*}(t) - \vec{A} \cdot \vec{D} & if\ P < 0.5 \\ \overrightarrow{D'} \cdot e^{bl} \cdot cos(2\pi l) + \overrightarrow{X^*} & if\ P \geq 0.5 \end{cases} \tag{10}$$

where D′=$|\overrightarrow{X^*} - \vec{X}(t)|$ represents the distance between whale and the prey (best solution). b is constant, l ∈ [−1, 1]. P is random number [0, 1]. Figure 2 shows the spiral updating position approach represented by Eq. 10.

3.1.3 Search for prey

To get the global optimum values updating has done with randomly chosen search agent rather than the best agent.

$$\vec{D} = |\vec{C} \cdot \overrightarrow{X_{rand}} - \vec{X}| \tag{11}$$

$$\vec{X}(t+1) = \overrightarrow{X_{rand}} - \vec{A} \cdot \vec{D} \tag{12}$$

$\overrightarrow{X_{rand}}$ is the random whale in current iteration. The symbol || denotes the absolute values. Fig3 shows flowchart of the proposed algorithm.

Implementation of WOA

The detailed algorithm is as follows:

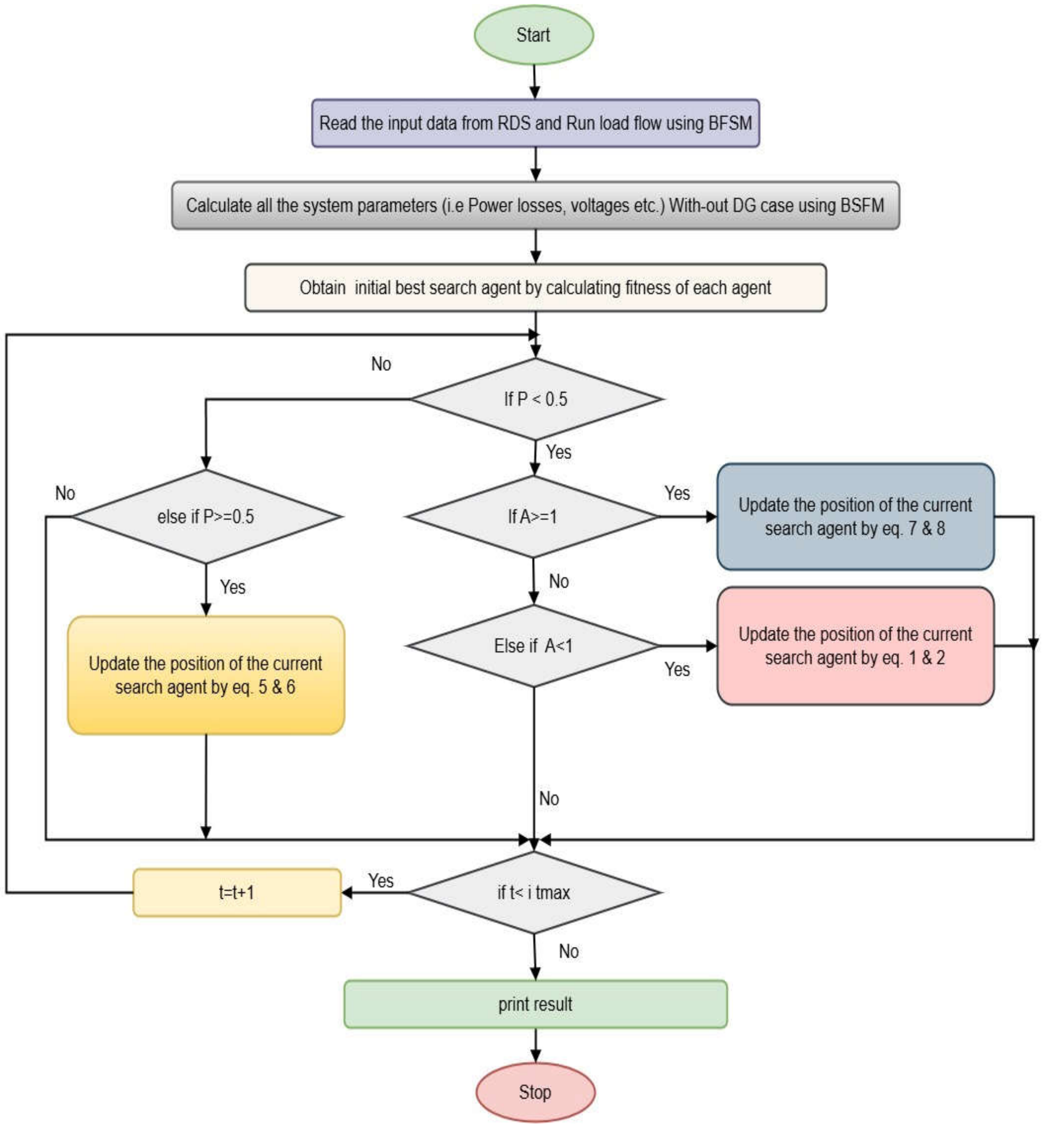

Figure.3 Flowchart of proposed whale optimization algorithm

Step 1 Read line and load data of the system and solve the power flow using backward forward sweep method.

Step 2 Initialize the population/solutions and it_{max} = 50, number of DG locations d = 1 for, dg_{min} = 60, dg_{max} = 3000.

Step 3 Generate the population of DG sizes randomly using equation

$$population = (dg_{max} - dg_{min}) \times rand\ () + dg_{min} \qquad (13)$$

where dg_{min} and dg_{max} are minimum and maximum limits of DG sizes.

Step 4 Find power losses for generated population.

Step 5 Current best solution is DG values with low losses.

Step 6 By using Eqs. 9-12 update the position of whales.

Step 7 For updated population determine losses by performing load flow.

Step 8 If obtained losses are less, then replace current best solution with it or else go back to step 6

Step 9 Print the results if tolerance is <0.00001 or maximum iterations reached.

4 RESULTS AND DISCUSSION

WOA is evaluated in the application of DG planning problem with IEEE 33 bus test system as test case. The WOA is used to obtain the optimal location size of DG. IEEE 33-bus distribution system (Baran and Wu 1989) is shown in Fig. 4.

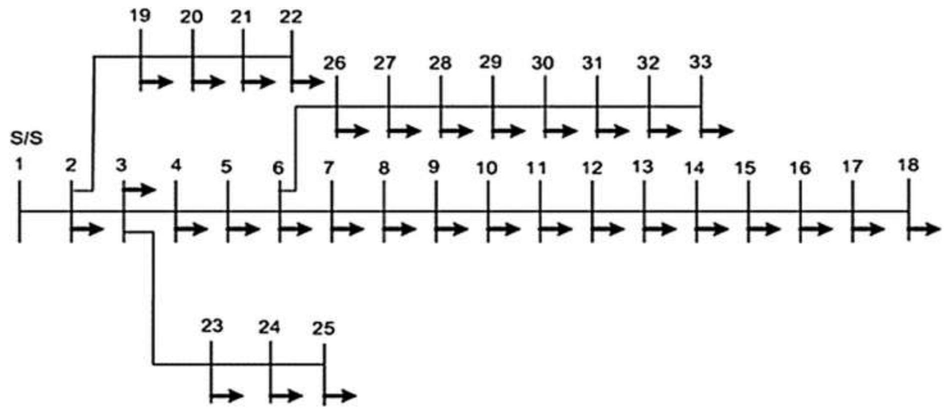

Figure.4 Single-line diagram of 33-bus system

Table 1 Results of 33-bus system

Parameter	**Without DG**	**With Type I DG (kW)**	**With Type II DG (kVAR)**	**With Type III DG (kVA) at 0.9 pf lag**
Location	-	15	15	15
DG Size	-	1061	612.04	1255.89
Total Active Power Loss (kW)	210.99	133.50	183.93	108.40
Total Reactive Power Loss (kVAR)	143.03	90.73	125.61	74.77
Minimum Voltage (V_{min})	0.903	0.930	0.927	0.951

Table 1 shows the real, reactive power losses and minimum voltages after the placement of different types of DGs. The optimal location for 33-bus system is 15. The minimum voltage is more in case of type III DG operating at 0.9 pf. In Table 1 it is inferred that by using DG type III operating at 0.9 pf the losses are reduced more when compared to other types of DGs. It is observed from the results that the DG size obtained is higher at lagging power factor compared to the size obtained at unity power factor; however, the losses are found lower with DGs at lagging power factor rather than DGs at unity power factor. This is due to the reason of reactive power available locally for the loads, thereby decreasing the reactive power available from substation. The voltage profile also improves with DGs at lagging power factor, and it is observed in Figure.5.

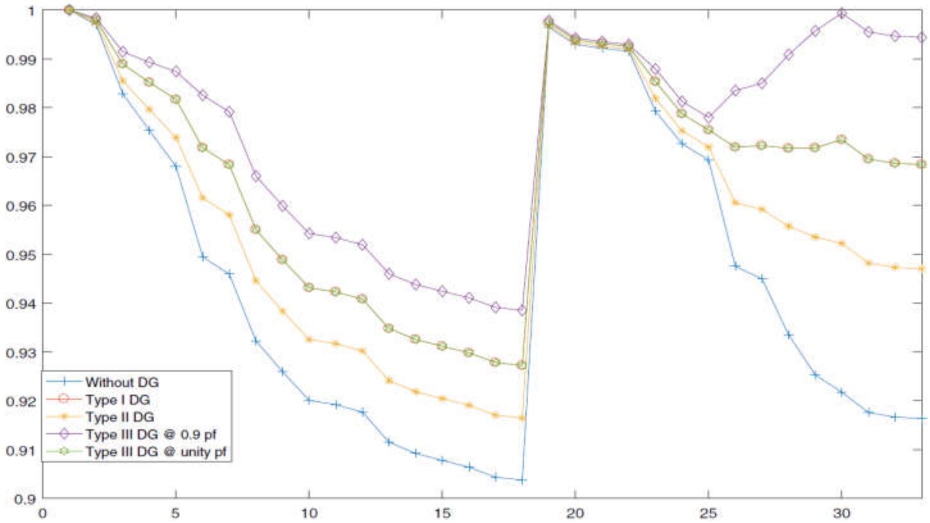

Figure.5. Voltage profile 33-bus system

The minimum voltage obtained for the system is better compared to the voltage obtained with DGs at unity power factor. Thus, it is essential to consider the reactive power available from DGs for its size calculations and its impact on losses reduction and voltage profile improvement. The results obtained with consideration of reactive power are better than the results obtained with DGs at unity power factor.

5. CONCLUSION

Novel nature-inspired whale optimization algorithm is used to determine the optimal DG size in this paper. WOA is modelled based on the unique hunting behavior of humpback whales. Reduction of system power losses and improvement in voltage profile are the objectives taken in this paper. The proposed method has been applied on typical IEEE 33- bus radial distribution systems with different types of DGs. The simulation results indicated that the overall impact of the DG units on voltage profile is positive and proportionate reduction in power losses is achieved. From the test system results, it is concluded that the percentage active and reactive power losses are reduced with type I DG are 36.72 % and 36.56 % respectively., percentage active and reactive power losses are reduced with type II DG are 12.82 % and 12.17% respectively., and the percentage active and reactive power losses are reduce With type III DG (kVA) at 0.9 pf (lag) are 48.62 % and 47.42% respectively., The voltage profile in the case of the type III DG (kVA) at 0.9 pf (lag) is better than other type of DG, Minimum voltage without DG Case is 0.903 (p.u.) at Bus 18, Minimum voltage with type I DG is 0.9327 (p.u.) at Bus 18, Minimum voltage with type II DG is 0.9224 (p.u.) at Bus 18 and Minimum voltage with type III DG (kVA) at 0.9 pf (lag) DG is 0.939 (p.u.) at Bus 18.It can be concluded that best results can be achieved with type III DG operating at 0.9 pf, because it generates both real power and reactive power. The results show that the WOA is efficient and robust.

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