Whale Optimization Algorithm-Based DG Allotment for Loss Minimization of Distribution Networks

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ABSTRACT

For optimum placement of distributed generation (DG) units in balanced radial distribution network for loss minimization, implementation of whale optimization algorithm (WOA), a state-of-the-art meta-heuristic optimization algorithm is proposed in this paper. Encouraged by bubble-net hunting strategy of whales, WOA mimes the collective practice of humpback whales. For validating performance in solving the mentioned problem, the suggested technique is implemented on IEEE 33-bus and IEEE 69-bus balanced radial distribution test networks. The obtained results demonstrate that feasible and effective solutions are obtained using the proposed approach and can be used as a propitious substitute in practical power systems to overcome the optimum DG siting and sizing issue. Also, to the best knowledge of the authors, it is the first report on the application of WOA in solving optimum DG siting and sizing issue.

KEYWORDS

Distribution Generation Units, Evolutionary Programming, Loss Minimization, Loss Saving, Optimal Siting, Optimal Sizing, Whale Optimization Algorithm

1 INTRODUCTION

In distribution networks the R/X ratio is much higher than in transmission systems. Therefore, throughout the distribution feeders there is a greater loss of power and hence a gradual electrical energy loss (Bansal et al, 2010; Baran & Wu, 1998; Chis et al, 1997; Haque, 199; Haque, 1996). Therefore, minimization of loss has become one of the greater problems for many utilities all over the world that needs to be adhered to. Capacitors placement and network reconfiguration are two extensive well known frequently used techniques minimization of loss in distribution networks (Baran & Wu, 1998; Chis et al, 1997; Haque, 199; Haque, 1996; Narasimham et al, 2013). Lately, because of aspects such as power electronics, restructuring of electricity market and environmental concerns etc. distribution generators (DG) have gained cogent importance (Narasimham et al, 2013; Ackermann et al, 2001). Ranging from some kWs to some MWs, DGs may be considered to be electrical power generating sources linked precisely to distribution networks (Khatod & Viral, 2001). Therefore, in this paper, the idea of minimizing losses via DGs allocations is analyzed.

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2012). In recent times, numerous technologies related to DGs have come up covering conventional to non-conventional sources (Ackermann et al, 2001; Khatod & Viral, 2012). Even though energy injection is the primary objective of DG units, however, if arranged and regulated strategically DGs are capable of serving numerous economic and technical utilities to consumers (Khatod et al, 2013). Voltage and loadability improvement, real power loss reduction, increased energy efficiency, upgraded system reliability and security are some results of such benefits (Ackermann et al, 2001; Khatod & Viral, 2012). Some financial benefits include saving of transmission and distribution cost along with reduction in whole sale electricity price, enhanced productivity, reduced fuel costs and saving of world fuel (Hung & Mithulananthan, 2013; Bansal et al, 2013). As far as current power industry deregulation along with the electricity market security is concerned, DGs observe a crucial function in spinning reserve, frequency control, etc. (Al Abri et al, 2013). However, improper operation and poor planning of DG exhibits a few contrary properties in distribution system functioning. Based on size and location, DGs can cause voltage rise, harmonic distortion, reverse power flows, etc. (Al Abri et al, 2013; Esmaili, 2013). Thus reduction in power loss is a crucial factor which is to be adhered to by proper DG operation.

Optimum DG sizing as well as siting for derogation of loss in distribution systems has lately gained substantial diligence of broad class of scientists and researchers. (Khatod & Viral, 2012; Khatod et al 2013; Hung & Mithulananthan, 2013). In many of the prevailing works on appropriation as well as sizing of DGs, researchers have acknowledged various concerns such as stability of system and voltage profile enhancement (Esmaili, 2013), harmonic pollution reduction (Harrison & Ochoa, 2011), profit maximization (Bhattacharya et al, 2004; Celli et al, 2005) and loading margin (Lee & Park, 2009) in either separate or collective-objective issue formation.

Analytical approach (Acharya et al, 2006; Nehrir & Wang, 2004; Gozel & Hocaoglu, 2009), harmony search algorithm (HSA) (Narasimham et al, 2013), evolutionary algorithms (EA) technique (Khatod et al, 2013), particle swarm optimization (PSO) (Harrison & Ochoa, 2011), genetic algorithm (GA) technique (Celli et al, 2005; Ab Kadir et al, 2011), metaheuristic approaches (Bhattacharya et al, 2004), are a few elaborated approaches used to adhere the DG sizing and siting issue. A few research has also been carried out in DG siting and sizing using WOA. (Prakash and Lakshminarayana, 2018) proposes the application of WOA with the aim of finding optimal placement and size of DGs for multi-objectives, including power loss minimization, voltage profile improvement and operating cost minimization. Proposed method has been demonstrated on 33-bus and 69-bus radial distribution test systems with each test system being considered for two different cases: case 1: placing Type I DGs (only real power injection) and case2: placing Type 2 DGs (both real and reactive power injection). However much improved results are obtained by placement of Type III DG for both the systems. (Morshidi et al, 2018) has demonstrated the installation of DGs by the application of WOA in transmission lines. Here the authors have used fast voltage stability index (FVSI) to decide the size of the DGs. Thereby in the present article the authors have implemented WOA for both sizing and siting of DGs in distributed systems. (Ang and Leeton, 2018) have implemented WOA for both siting and sizing of DGs in distribution systems. The authors have also implement Type I, Type II and Type III DGs for small and medium distribution systems. Therefore, in the present research work, the authors have also tested the approach for a comparatively bigger systems. (Reddy et al, 2017) has implemented WOA and has also used both Type I and Type III DGs. The authors have demonstrated the optimal sizing of the DGs and has shown that the algorithm is able to provide improved results as compared to some other algorithms. Thus, in the present article, the authors have implemented the mentioned approach in distribution systems and have also tested the approach on small and large systems. (Gnanambal et al, 2017) has used WOA for obtaining improved voltage profile and power loss reduction by using only type III DG. However, the number of iterations and population size is varying. Further more stress has been put on siting of DGs. DGs have been treated as purely active power source in most of the research cited above. However the capability of DGs of absorbing or injecting reactive power within its limits depends on its type (Esmaili, 2013). In addition, for DG
siting and sizing most of the common analytical approaches is mostly dependent on exact calculation of loss which requires Jacobian matrix computation. This evaluation of the Jacobian matrix increases the computation time. Therefore application of new metaheuristic approaches providing optimal solution draws further attention.

In order to make some remedial action to mitigate the aforesaid drawback, in this article application of a new and cinch meta-heuristic optimization mechanism is suggested. WOA is a recent meta-heuristic optimization algorithm mimicking the hunting behavior of humpback whales and has been able to provide successful results when applied for solving the OPF (Bhesdadiya et al, 2016) and ELD (Touma, 2016) problems. To the best of the authors’ acquaintance, there is no prior report in the optimization literature on the application of WOA in solving optimal DG allocation and sizing issue. The authors in present paper have tried to develop a general purpose algorithm using WOA approach that is reliable and robust and uncomplicated implementation to critical power system is feasible.

Remaining article is formed accordingly as: Section 2 illustrates the mathematical interpretation of the DG allocation and siting issue. The whale optimization algorithm (WOA) along with Biogeography based Optimization (BBO) is presented in Section 3. Application of suggested approach to optimum allocation and rating of single and collective DGs for loss minimization has been illustrated in Section 4. Simulation and numerical results obtained on applying the WOA to two IEEE test systems are discussed in Section 5. Non-parametric analysis of WOA and BBO approaches in presented in Section 6. Finally the article sums up with the conclusion in Section 7.

2. MATHEMATICAL INTERPRETATION OF DG ALLOCATION AND SITING

While satisfying certain operating constraints, optimal DG siting in a radial distribution system requires obtaining proper locations in a radial network where a DG can be placed thereby minimizing the power loss. The operating constraints are provided below. By computing and summing up individual losses linked with every branch the total active power loss of the system is calculated. The real and reactive power flow is calculated as:

\[ P_{i+1} = P_i - R_{z_{i+1}} \cdot \frac{(P_i^2 + Q_i^2)}{|V_i|^2} \]  
\[ Q_{i+1} = Q_i - X_{z_{i+1}} \cdot \frac{(P_i^2 + Q_i^2)}{|V_i|^2} \]  

Real power loss in the line can be calculated as:

\[ P_{z_{i+1}} = R_{z_{i+1}} \cdot \frac{(P_i^2 + Q_i^2)}{|V_i|^2} \]  

Therefore, the loss minimization of total loss can be considered as the objective function and can be represented as:
\[ f = \min(P_{loss}) \]  
\[ P_{loss} = \sum_{i=2}^{N} \left( p_{g_i} - p_{d_i} - V_i V_k Y_{ik} \cos \left( \delta_i - \delta_k \right) \right) \]  
\[ \text{Equality Constraint} \]  
\[ \sum_{i=2}^{N} \left( p_{g_i} - p_{d_i} - V_i V_k Y_{ik} \cos \left( \delta_i - \delta_k \right) \right) \leq 0 \]  
\[ \sum_{i=2}^{N} \left( q_{g_i} - q_{d_i} - V_i V_k Y_{ik} \sin \left( \delta_i - \delta_k \right) \right) \leq 0 \]  
\[ \text{Voltage limits} \]  
\[ V_i^{\text{min}} \leq V_i \leq V_i^{\text{max}} \]  
\[ \text{Thermal limits} \]  
\[ |S_i| \leq |S_i^{\text{max}}| \]  
\[ \text{DG Capacity Constraint} \]  
\[ p_{d_i}^{\text{min}} \leq p_{d_i} \leq p_{d_i}^{\text{max}} \]  
\[ \text{Loss Sensitivity Factor} \]  
To detect most susceptible node for allocation of distribution generator, the LSF is computed.  
\[ LSF = \frac{2Q_{k,eff} * R_{ik}}{(V_{ik})^2} \]  
In the above equations the notations denote the following parameters:
\( P_i \): Real power flow at ith bus; \( Q_i \): Reactive power flow at ith bus; \( P_{i+1} \): Real power flow at (i+1)th bus; \( Q_{i+1} \): Reactive power flow at (i+1)th bus; \( P_{\text{Loss}} \): Total active power loss; \( N \): Number of bus; \( k \): receiving end bus; \( i \): sending end bus; \( p_{gi} \): Active power generation at bus \( i \); \( q_{gi} \): Reactive power supplied from \( i \)th bus; \( p_{di} \): Active power demand at bus \( i \); \( q_{di} \): Reactive power demand at \( i \)th bus; \( V_i \): Voltage at bus \( i \); \( V_k \): Voltage at bus \( k \); \( Y_{ik} \): Admittance between \( i \)th and \( k \)th bus; \( \delta_{ik} \): Load angle between \( i \)th and \( k \)th bus; \( V_i^{\text{min}} \): Minimum allowable working voltage at \( i \)th bus; \( V_i^{\text{max}} \): Maximum allowable working voltage at \( i \)th bus; \( S_i \): Apparent power at \( i \)th bus; \( S_i^{\text{max}} \): Maximum apparent power at \( i \)th bus; \( R_{ik} \): Resistance between \( i \)th and \( k \)th bus; \( Q_{k,\text{eff}} \): Effective reactive power load connected at \( k \)th bus.

### 3. APPLIED METHODOLOGY

#### Whale Optimization Algorithm

Recently, WOA introduced by (Mirjalili, 2016) which is an efficient optimization approach, has been applied for solving non-linear optimization problems. Whales are supposedly the largest mammals in this world. They can extend up to 30 m in length and 180 ton in weight. Humpback, right, killer, Minke, Sei, dolphin, and blue are 7 different species of whale. The humpback species have a special and interesting hunting technique, where they choose hunting a group of tiny fish nighing to the surface.

While satisfying certain operating constraints, optimal DG siting in a radial distribution system requires obtaining proper locations in a radial network where a DG can be placed thereby minimizing the power loss.

Mathematically, WOA can be structured in following three sections:

#### 3.1 Encircling of Prey

This resembles how Humpback whales encircle their prey after recognizing the location of the prey. As best position in search space is unrecognized initially, WOA approach recognizes the immediate best candidate as target victim or is nearest possible optimal value. As soon as the finest search agent gets specified, remaining search agents amend their respective locations in the direction of this search agent, the characteristic of which may be defined as:

\[
\ddot{z} = k \ddot{y}(t) - \ddot{y}(t) 
\]

\[
\ddot{y}(t+1) = \ddot{y}(t) - \ddot{c}.\ddot{z} 
\]

In equations (9) and (10) the present iteration is given by \( t \), the coefficient vectors are \( c \) and \( k \), the position vector of the of the desired current finest solution is given by \( y' \), \( || \) is the absolute value and \( \ddot{y} \) gives the position vector. For obtaining better solution, it is desirable to highlight that \( y' \) must be revised every iteration (Touma, 2013). Vectors \( c \) and \( k \) is computed from the equations given below:
\[ c = 2\bar{p}.\bar{d} - \bar{p} \]  

(14)

\[ k = 2\bar{d} \]  

(15)

The search agent position given by \( (y, w) \), can be amended in accordance with the current best record position given by \( (x', w') \). By altering the values of \( c \) and \( k \) vectors, the various locations surrounding the specified finest agent corresponding to the immediate location, can be achieved. Also it is very much feasible to reach any desired position surrounding the key-points in search space by simply defining the random vector \( \bar{d} \) defined in \([0,1]\) in both exploration and exploitation phases and with increase in number of iterations \( \bar{p} \) is varied linearly from 2 to 0 and \( \bar{v} \) is a random vector in \([0,1]\). Also over the course of iterations \( \bar{c} \) is linearly varied from 2 to 0 in both exploration and exploitation phases.

### 3.2 Bubble Net Hunting Mechanism

Humpback whales’ bubble-net behavior can be mathematically designed by following processes:

**A] Shrinking Encircling Prey**

By appropriately minimizing the value of \( \bar{p} \) in Eq. (10), the *Shrinking encircling prey* behaviour is achieved. \( \bar{c} \) is an arbitrary value within the interval \([-p, p]\), where, through the following iterations, \( \bar{c} \) is minimized from 2 to 0. The updated amended location of a search agent between the location of present finest agent and original location of the agent, at any point, can be determined by giving random values for \( \bar{a} \) in \([-1,1]\).

**B] Spiral Position Updating**

Here, initially the distance is calculated at the intervals where the prey is at \( (y', w') \) and whale is positioned at \( (y, w) \). Since humpback whales follow a helix-shaped movement, an equation (spiral) is formulated amidst the prey location and whale location in order to parrot the helix-shaped advancement. This can be represented as follows:

\[ \bar{y}(t+1) = z^T e^{pl \cdot \cos(2\pi t)} + \bar{y}' \]  

(16)

Whales continue to swim around its prey while hunting, following the two paths mentioned above. In order to amend the locations of whales, 50% probability is assumed for above mentioned two methods. This is represented as:

\[ \bar{y}(t+1) = \bar{y}'(t) - \bar{c} \bar{z} \text{ if } q < 0.5 \]  

(17)

And \( \bar{y}(t+1) = z^T e^{pl \cdot \cos(2\pi t)} + \bar{y}' \) if \( q \geq 0.5 \)  

(18)
Where $\vec{d}^* = \vec{y}'(t) - \vec{y}(t)$

Eq. (19) describes the radii of whale location and victim location (most appropriate solution). $l$ lies between $[-1,1]$, $q$ is random number uniformly distributed between $[0,1]$.

### 3.3 Search For Prey

The updating is achieved by arbitrarily selected search agents rather than the best agent for attaining global optimal values. This is characterized by:

$$\vec{d} = \bar{c}.x_{rand} - \bar{x}$$

(20)

$$\bar{x}(t + 1) = x_{rand} - \bar{a} \vec{d}$$

(21)

In equations (20) and (21) $x_{rand}$ provides the arbitrary number of whales for the present iteration. The symbol $\parallel$ denotes the absolute values.

A structural diagram of WOA is represented in Fig. 1.

### 4. PROPOSED WOA ALGORITHM IMPLEMENTATION TO DG ALLOCATION PROBLEM

WOA based approach for DG allocation takes the sequential steps as mentioned below:

**Step 1:** Test system values are interpreted.

**Step 2:** An arbitrary set of values for is initialized; $X_i = [Y_{ij}]$ for $i = 1N_p; j \in N_{pq}$

**Step 3:** Set maximum iterations, maximum search agents, maximum generation, and minimum and maximum boundary limit of control variables.

**Step 4:** The control variables are randomly initialized within some effective maximum and minimum control variable bounds. NR power flow is run for at least five iterations and the reactive and active powers are obtained.

**Step 5:** Iteration count is set at one (Itr = 1).

**Step 6:** Using (6) the objective function is calculated.

**Step 7:** Depending on the objectivefunction value, the population is sorted and elite solutions are recognized. Here, the term elite has been used to highlight the solution sets, which provides best objectivefunction values. Best solution sets are kept unaltered after individual iteration without applying further modification to it.

**Step 8:** Tuning operation is applied probabilistically to the control variables of non-elite solutions, to modify the load of the load buses using the behavior of Bubble net hunting approach, Encircling prey, and Search for prey activity as detailed in section 5.

**Step 9:** After each controlled variables is tuned, its usefulness as a problem solution should be established. All feasible solutions are separated from those that are infeasible. This approach coevolves the population of infeasible solutions until they become feasible.

**Step 10:** If maximum specified number of iterations reaches, show results; otherwise return to step 4.
5. RESULT ANALYSIS

WOA have been implemented for solving the allocation as well as sizing of DGs and the results have been compared with BBO. Considering a flat start and providing a convergence tolerance value of 0.0001, the algorithms have been applied on IEEE-33 bus radial test system and IEEE-69 bus radial distribution test networks. The authors have kept the population size and the number of iterations fixed for the sake of generalization. Even though for a small system (IEEE 33 bus), the convergence takes place well before 100 iterations, however for larger systems even if the population size is increased to more than 50 and the number of iterations are increased to more than 100, there is negligible change in the fitness value while the computation time increases. The computation tool used is MATLAB in the Pentium Dual core, 1800 MHz system. An approximation of number of DG allocation in the network has been presumed. It is also assumed that there is a constant power generation by the DG units. The performances of the approaches have been observed for four instances and for each instance the outcomes are enumerated depending on the outputs of 50 trial observations.
5.1 IEEE 33-Bus System

Required data have been availed from (Abdelaziz, 2017). A single-line diagrammatic representation of IEEE 33-bus radial distribution network is provided in Fig. 2. Respective values under base-case condition are provided in Table 1. Here the population size has been fixed to 50 and the number of iterations has been taken as 100.

Figure 2.

5.1.1 Instance 1: Allocation of Single DG

Single DG type I or type III allocation has been considered for this instance. Base-case results i.e in the absence of a DG, are also computed. After type I DG unit inclusion in the network operating at unity power factor (UPF), a type III DG at combined load power factor (CPF) and a type III DG at effective load power factor (ePF), the real power loss is computed.

As noted from table 2, for DG operation at unity pf for type I DG, the system real power loss about 66.84 kW whereas for CPF and ePF mode operation for a type III DG there is a 44.02 kW and 40.29 kW loss reduction in comparison to the base case values. For validating the results obtained using WOA methodology, a comparative research is carried out with BBO by siting a single DG for calculating DG size and corresponding power loss. The convergence plot at UPF operation for Type I DG and at CPF and ePF operation for Type III DG can be observed from Fig.3. Comparison of the reduction in loss obtained for the proposed approach and BBO is provided in Table 3. It is well realized from the results that in comparison to BBO approach, the suggested WOA approach more preferable as it is able to provide improved DG size and reduced power loss. Also a comparative analysis for single DG placement at the three operating conditions is provided in fig. 4. Voltage performance at each bus is provided in fig. 5 and real power loss at the three working modes i.e UPF, CPF and ePF is presented in fig. 6.

5.1. Instance 2: Allocation of Two-DG Units

Placement of two identical DG units at suitable locations has been considered in this instance. The total power loss attained after applying WOA for the three different operation modes along with the most appropriate siting positions for the two DGs to be connected and also the consequent sizes of
the two DGs providing a much decreased power loss in the network are computed. From Table 4, the maximum and minimum voltages at the ith bus location along with the total reduction in power loss can be observed. Comparative analysis of active power loss along with percentage loss minimization attained applying WOA and BBO is provided in Table 5 from which it may be validated that suggested WOA is capable of providing improved power loss reduction and can be considered as a robust alternative approach to most of the methodologies discussed in the literature.

Table 1. IEEE 33 bus radial distribution test network base-case values

| IEEE 33 bus network | Values          |
|---------------------|-----------------|
| Real Power Demand   | 3720 kW         |
| Reactive Power Demand| 2300 kVAr       |
| Working Voltage     | 12.66 kV        |
| Bus Number/Maximum Voltage | 1/1.00       |
| Bus Number/Minimum Voltage | 18/0.9038   |
| Active Power Loss   | 210.987 kW      |
| Reactive Power Loss | 143.1284 kVAr  |
| Absolute Power Loss | 254.9538 kVA   |

Figure 3.
Figure 4.

Figure 5.
Table 2. Results for IEEE 33-bus distribution network for single DG allocation

| Parameters                     | Single DG unit | Type I (UPF) | Type III (CPF) | Type III (ePF) |
|--------------------------------|----------------|--------------|----------------|----------------|
| Bus for DG allocation         | 6              | 6            | 9              |
| Size of DG                    | 1968.2         | 2103.2       | 2105.3         |
| Power factor                  | 1              | 0.85         | 0.81           |
| Bus/Min. voltage              | 25/0.9685      | 3/0.9786     | 8/0.9931       |
| Bus/Max. voltage              | 26/1.004       | 1/1.005      | 6/1.0051       |
| Active Power Loss             | 66.84          | 44.02        | 40.29          |
| Reactive Power Loss           | 43.09          | 28.40        | 26.00          |
| Absolute Power Loss           | 79.53          | 52.39        | 47.95          |
| Total reduction in loss (%)   | 68.80          | 79.45        | 81.19          |

Table 3. Correlation of Active Power loss minimization with WOA and BBO

| Methods          | Real Power loss | Loss Reduction |
|------------------|-----------------|----------------|
| WOA              |                 |                |
| Type I           | 66.84           | 68.32%         |
| Type III         | 44.02           | 79.14%         |
| Type III         | 40.29           | 80.90%         |
| BBO[25]          |                 |                |
| Type I           | 137.85          | 34.66%         |
| Type III         | 87.61           | 67.69%         |
| Type III         | 87.365          | 67.79%         |
5.2 IEEE 69-Bus System

The suggested approach is applied on IEEE 69-bus radial distribution network for validating the applicability in case of a bigger network. Required information for the mentioned network have been availed from (Aruldoss & Ravindran, 2018). Base-case values are tabulated in Table 6. A single line schematic representation of the network is presented in fig. 7. Also for this system, the population size has been fixed to 50 and the number of iterations has been taken as 100.

5.2.1 Instance 1: Single DG Placement

A type I or type III single DG unit is infused in the network. Table 6 consists of the results attained under base-case condition. The parametric outcomes attained by application of WOA are provided in Table 7. Reduction in active power loss because of insertion of a DG of type I is approximately 72.4% of base value. By insertion of a type III DG at bus 61 a further reduction in loss by 87.539% (CPF mode) and 88.658% (ePF mode) is obtained in comparison to the base loss. Values attained by application of WOA have been collated with BBO and is given in Table 8. Also a comparative analysis of the mentioned cases is provided in Fig. 8.
Table 6. Initial values of IEEE 69-bus system

| Parameters                          | IEEE 69- Bus network       |
|-------------------------------------|-----------------------------|
| Power Demand (Real)                 | 3800 kW                    |
| Power Demand (Reactive)             | 2690 kVAR                  |
| Working Voltage                     | 12.66 kV                   |
| Bus Number /Maximum Voltage         | 1/1.00                     |
| Bus Number /Minimum Voltage         | 65/0.9092                  |
| Active Power Loss                   | 225.461 kW                 |
| Reactive Power Loss                 | 102.3663 kVAR              |
| Absolute Loss                       | 247.6116 kVA               |

Table 7. Values obtained for IEEE 69-bus network: single DG siting

| Parameters                          | Single DG unit              |
|-------------------------------------|-----------------------------|
|                                    | Type I (UPF)               |
| DG capacity                         | 1567.47                     |
| Bus/ Min. voltage                   | 27/0.9717                  |
| Active Power Loss                   | 62.232 kW                  |
| Reactive Power Loss                 | 30.572 kVAR                |
| Absolute Power Loss                 | 69.3359 kVA                |
| Total loss reduction (%)            | 71.9981                    |
|                                    | Type III (CPF)             |
| DG placement                        | 62nd bus                   |
| DG capacity                         | 1822.118                   |
| Bus/ Min. voltage                   | 50/0.9950                  |
| Active Power Loss                   | 17.489 kW                  |
| Reactive Power Loss                 | 10.372 kVAR                |
| Absolute Power Loss                 | 20.333 kVA                 |
| Total loss reduction (%)            | 91.7883                    |
|                                    | Type III (ePF)             |
| DG placement                        | 60th bus                   |
| DG capacity                         | 1821.116                   |
| Bus/ Min. voltage                   | 50/0.9948                  |
| Active Power Loss                   | 17.3884 kW                 |
| Reactive Power Loss                 | 10.2847 kVAR               |
| Absolute Power Loss                 | 20.2023 kVA                |
| Total loss reduction (%)            | 91.8411                    |

Table 8. Comparison of reduction in power loss of WOA with BBO

| Methods   | Real Power loss | Loss Reduction |
|-----------|-----------------|----------------|
| WOA       | Type I          | 62.232         | 72.397%        |
|           | Type III        | 17.489         | 92.243%        |
|           | Type III        | 17.388         | 92.287%        |
| BBO[25]   | Type I          | 93.503         | 58.528%        |
|           | Type III        | 28.094         | 87.539%        |
|           | Type III        | 27.572         | 88.658%        |
Table 9. Results of IEEE 69-bus network for two DG placement

| Parameters                  | Single DG unit | Type I (CPF) | Type III (ePF) |
|-----------------------------|----------------|--------------|----------------|
| DG placement                | 61st bus, 17th bus | 61st bus, 17th bus |
| DG capacity                 | 1780.3959,532.9859 | 2133.6876,633.9703 |
| Power factor                | 1              | 60/0.9967    |
| Bus/Min. voltage            | 50/0.9951      | 5/1.0042     |
| Bus/Max. voltage            | 1/1.005        | 6.0324 kVAR  |
| Active Power Loss           | 59.2176 kW     | 8.3769 kVA   |
| Reactive Power Loss         | 28.3361 kVAR   | 6.0324 kVAR  |
| Absolute Power Loss         | 65.6480 kVA    | 96.616       |
| Total loss reduction (%)    | 73.487         |              |

Table 10. Comparison of reduction in power loss of WOA with BBO

| Methods       | Real Power loss | Loss Reduction |
|---------------|-----------------|----------------|
| WOA           | Type I          | 59.2176        | 73.734%        |
|               | Type III        | 5.8123         | 97.422%        |
| BBO[25]       | Type I          | 72.1174        | 68.013%        |
|               | Type III        | 7.2211         | 96.797%        |

Figure 9.
Figure 10.

Figure 11.
5.2.2 Instance 2: Placement of Two DG

For validation of WOA based approach for IEEE 69-bus radial DS two identical DG units are positioned at appropriate positions as placement of two DG units concurrently into the network provides more benefit as compared to insertion of a single DG unit. Post computation it was observed that better results are availed if the two DGs are placed at bus numbers 61 and 17. Thus bus number 61 and 17 represents the most appropriate location sequence for the two forms of DG units (Aruldoss & Ravindran, 2018). For Type I DG when operated in UPF mode, 73.73% reduction in loss was attained by implementation of suggested WOA approach in as compared to base case. Insertion of Type III DG units provides a better loss reduction of 97.42% of the base case, representing larger saving of energy. Results are provided in Table 9. The comparison of results for BBO and WOA approaches corresponding to loss reduction is provided in Table 10.

Table 11. Statistical description for IEEE-33 bus system

| Methods | Fitness value (Estimated Error) | Computational Time (sec) |
|---------|--------------------------------|--------------------------|
|         | Minimum | Maximum | Mean | Median | Standard Deviation |                      |
| BBO     | 1.1221  | 1.2013  | 1.1617 | 1.1615 | 0.2441           | 0.31 |
| WOA     | 0.0678  | 0.0679  | 0.0678 | 0.0651 | 0.0131           | 0.23 |

Table 12. Statistical description for IEEE-69 bus system

| Methods | Fitness value (Estimated Error) | Computational Time (sec) |
|---------|--------------------------------|--------------------------|
|         | Minimum | Maximum | Mean   | Median | Standard Deviation |                      |
| BBO     | 0.9778  | 1.0821  | 1.0299 | 1.0294 | 0.2139           | 0.36 |
| WOA     | 0.3468  | 0.3859  | 0.3663 | 0.3662 | 0.0761           | 0.26 |

Table 13. p-values of Wilcoxon test for the different bus systems on comparison of WOA algorithm with BBO algorithm

| Number of Buses | N_{SR} | Z     | P(1-tail) |
|-----------------|--------|-------|-----------|
| 33              | 10     | -2.36 | 0.0088    |
| 69              | 10     | -2.75 | 0.0026    |

Table 14. p-values of Friedman test for the different bus systems on comparison of WOA algorithm with BBO algorithm

| Number of buses | Significance Level | p-value |
|-----------------|-------------------|---------|
| 33              | 0.05              | 0.02534 |
| 69              | 0.05              | 0.02528 |
The convergence plot obtained for two-DG placement using WOA for loss minimization is presented in fig. 9. The power loss at the three different operation modes can be observed from fig. 10. Also voltages at the various buses at UPF, CPF and ePF operation modes are represented in fig. 11.

6. NON-PARAMETRIC STATISTICS

From Table 11 and Table 12, the statistical description for 33 bus system and 69 bus system respectively, can be observed. The mean (average) value obtained in case of WOA is much lower to that as compared with BBO. Also the measure of variability (standard deviation) reduces significantly with the application of WOA as compared to BBO. The effects can be observed for small and large systems with a reduction of almost 50% in both the values as compared to the values obtained by the application of BBO. To further the superiority of WOA over BBO has also been validated by conducting Friedman test and Wilcoxon rank sum test on the two algorithms. Both the tests are non-parametric statistical tests and are carried at 5% level of significance. The null hypothesis is as follows.

H0: The proposed Algorithm (WOA) is statistically better than BBO algorithm.

The respective detailed results (p-value) for the two tests is presented in Table 13 and and Table 14.

7. CONCLUSION

Distributed generators have become important peripherals for power factor compensation as well as power generation because of recent advancements in renewable energy systems. Reduction of system power losses, reduction in operating cost and analysis in improvement in voltage profile are the multi objectives taken in this article and is carried out using a more recent algorithm called Whale Optimization Algorithm. Directed by a probability rule WOA can refurbish the habitat fitness values using extensive information. Proposed methodology is tested on 33-bus and 69-bus test systems for two cases: - case-1: single DG placement and case-2: 2 DG placement. The results obtained from the suggested algorithm are compared with other well-known optimization algorithms like BBO and found to be effective for multi objectives and multi constraints. Better results have been achieved with WOA as observed from the simulation results. The results indicates that the overall impact of the DG units on voltage profile is positive and proportionate reduction in power losses is achieved. It can be resolved that best results can be achieved with type III DG, because it generates both real power and reactive power. The results show that the WOA is efficient and robust.
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