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Whale optimization algorithm for optimal sizing of renewable resources for loss reduction in distribution systems

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Abstract

Distributed generator (DG) resources are small scale electric power generating plants that can provide power to homes, businesses or industrial facilities in distribution systems. Power loss reductions, voltage profile improvement and increasing reliability are some advantages of DG units. The above benefits can be achieved by optimal placement of DGs. Whale optimization algorithm (WOA), a novel metaheuristic algorithm, is used to determine the optimal DG size. WOA is modeled based on the unique hunting behavior of humpback whales. The WOA is evaluated on IEEE 15, 33, 69 and 85-bus test systems. WOA was compared with different types of DGs and other evolutionary algorithms. When compared with voltage sensitivity index method, WOA and index vector methods gives better results. From the analysis best results have been achieved from type III DG operating at 0.9 pf.

Keywords: Whale optimization algorithm, Index vector method, Distributed generation placement, Radial distribution system, Loss reduction

Background

Distribution system is that part of the electric power system which connects the high-voltage transmission network to the low-voltage consumer service point. It is an important part of an electric power system since the supply of electric power to consumers is ensured by an efficient distribution system. The capital investment in the distribution system constitutes a significant portion of the total amount spent in the entire power system. Due to the recent market deregulations, this portion had become even more important.

Three divisions of an electric power system are generation, transmission and distribution. A distribution system connects loads to the transmission line at substations. Most of the losses about 70% losses are occurring at distribution level which includes primary and secondary distribution system, while 30% losses occurred in transmission level. Therefore distribution systems are main concern nowadays. The losses targeted at distribution level are about 7.5%.

By installing DG units at appropriate positions the losses can be minimized. Photovoltaic (PV) energy, wind turbines and other distributed generation plants are typically situated in remote areas, requiring the operation systems that are fully integrated into transmission and distribution network. The aim of the DG is to integrate all generation plants to reduce the loss, cost and greenhouse gas emission. The main reason for using DG units in power system is technical and economic benefits that have been presented as follows. Some of the major advantages are

- Reduced system losses.
- Voltage profile improvement.
- Frequency improvement.
- Reduced emissions of pollutants.
- Increased overall energy efficiency.
- Enhanced system reliability and security.
- Improved power quality.
- Relieved transmission and distribution congestion.

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Some of the major economic benefits

- Deferred investments for upgrades of facilities.
- Reduced fuel costs due to increased overall efficiency.
- Reduced reserve requirements and the associated costs.
- Increased security for critical loads.

Determining proper capacity and location of DG sources in distribution systems is important for obtaining their maximum potential benefits. Studies have indicated that inappropriate selection of the location and size of DG may lead to greater system losses than losses without DG. Utilities like distribution companies which are already facing the problem of high power losses and poor voltage profiles cannot tolerate any further increase in losses.

Different types of distributed generations and their definitions have been discussed in Ackermann et al. (2001). An analytical approach was proposed by Acharya et al. (2006) and Duong Quoc et al. (2010) without taking voltage constraint. The uncertainties in operation including varying load, network configuration and voltage control devices have been considered in Su (2010).

Abu-Mouti and El-Hawary (2010) proposed ABC for allocation and sizing of DGs. Distributed generation uncertainties (Zangiabadi et al. 2011) have been taken in account for the placement of DG. A novel combined hybrid method GA/PSO is presented in MoradiMH (2011) for DG placement. Alonso et al. (2012), Hosseini et al. (2013) and Doagou-Mojarrad et al. (2013) proposed evolutionary algorithms for the placement of distributed generation. Sensitivity-based simultaneous optimal placement of capacitors and DG was proposed in Naik et al. (2013). In this paper analytical approach is used for sizing. Nekooei et al. (2013) proposed harmony search algorithm with multiobjective placement of DGs. With unappropriated DG placement, it can increase the system losses with lower-voltage profile. With the proper size of DG it gives the positive benefits in the distribution systems. Voltage profile improvement, loss reduction, distribution capacity increase and reliability improvements are some of the benefits of system with DG placement (Ameli et al. 2014).

Doagou-Mojarrad et al. (2013) and Kaur et al. (2014) proposed hybrid evolutionary algorithm for DG placement. Mesh distribution system analysis with time-varying load model was presented in Qian et al. (2011) and Murty and Kumar (2014). The backtracking search optimization algorithm (BSOA) was used in DS planning with multi-type DGs in El-Fergany (2015); BSOA was proposed for DG placement with various load models. Simultaneous placement of DGs and capacitors with reconfiguration was proposed by Golshannavaz (2014) and Esmaeilian and Fadaeinedjad (2015). Dynamic load conditions have been taken in Gampa and Das (2015). Probabilistic approach with DG penetration was discussed in Kolenc et al. (2015). In distribution network voltage profile improvement and voltage stability issues have been taken as objectives in Aman et al. (2012), Sultana et al. (2016) and Singh and Parida (2016). Das et al. (2016) proposed symbiotic organisms search algorithm for DG placement. Zeinalzadeh et al. (2015), Khodabakhshian and Andishgar (2016) and Rahmani-andebili (2016) proposed simultaneous DGs and capacitors placement in distribution networks. Prakash and Lakshminaraya (2016) proposed whale optimization algorithm for sizing of capacitors.

In optimization algorithm literature there is no optimization algorithm that logically proves no-free-lunch (NFL) theorem for solving all optimization problems. But whale optimization algorithm (Mirjalili 2016) proves that it can be used for all optimization problems. A novel nature-inspired metaheuristic optimization algorithm called whale optimization algorithm is used to find the optimal DG size in this paper. To the best knowledge of authors WOA has not been used in literature of DG placement. WOA has been modeled based on the unique hunting behavior of humpback whales. The WOA is used to determine the optimal size of DGs at different power factors to reduce the power losses of the distribution system as much as possible and enhancing the voltage profile of the system. IEEE 15, 33, 69 and 85-bus systems are examined as test cases with different types of DG units for the objective function.

DG types can be characterized (Reddy et al. 2016) as

Type I Injects real power. It operates at unity pf. PV cells, microturbines, fuel cells.
Type II Injects reactive power. Synchronous compensator, capacitors, kVAR compensator etc.
Type III Real and reactive powers injection, e.g., synchronous machines (cogeneration, gas turbine, etc.).
Type IV Consuming reactive power but injecting real power, e.g., induction generators in wind farms.

Problem

Objective

More losses are there due to low voltage compared to transmission system in distribution side. Copper losses are predominant in distribution system; this can be calculated as follows

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

where I_i is current, R_i is resistance, and n is number of buses. Objective taken in this paper is real power loss minimization.

Constraints

The constraints are

- Voltage constraints

$$0.95 \leq V_i \leq 1.05 \tag{2}$$

- Power balance constraints

$$P + \sum_{k=1}^{N} P_{\mathrm{DG}} = P_{\mathrm{d}} + P_{\mathrm{loss}} \tag{3}$$

- Upper and lower limits of DG

$$60 \leq P_{\mathrm{DG}} \leq 3000 \tag{4}$$

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

Index vector method

Optimal locations of DG are obtained by index vector (IV) method (VVSN Murthy 2013). The IV for bus n is given by:

$$\mathrm{index}[n] = \frac{1}{V(n)^2} + \frac{Iq(k)}{Ip(k)} + \frac{\mathrm{Qeff}(n)}{\mathrm{totalQ}} \tag{5}$$

$Ip[k]$, $Iq[k]$ are real and imaginary part of current in kth branch. Qeff[n] and $V[n]$ are effective load, voltage at nth bus. Total reactive load is taken as totalQ.

Algorithm

The algorithm is as follows

Step 1 Solve the feeder-line flow for the system.
Step 2 Calculate the IV of bus n using Eq. (5).
Step 3 Index vector was arranged in descending order.
Step 4 Normalized voltage values by $V(i) = V(i)/0.95$.
Step 5 Buses with <1.01 are suitable locations for DG sizing.

For DG placement the locations are 6, 15, 61 and 55 for 15, 33, 69 and 85-bus test systems, respectively.

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 krills 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 bubbles along a circle or 9-shaped path.

The mathematical model of WOA is described in the following sections

1. Encircling prey.
2. Bubble net hunting method.
3. Search the prey.

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 modeled is as

$$\overrightarrow{X}(t+1) = \overrightarrow{X^*}(t) - \overrightarrow{A} \cdot \overrightarrow{D} \tag{6}$$

$$\overrightarrow{D} = \left| \overrightarrow{C} \cdot \overrightarrow{X^*}(t) - \overrightarrow{X}(t) \right| \tag{7}$$

$$\overrightarrow{A} = 2\overrightarrow{a} \cdot \overrightarrow{r} - \overrightarrow{a} \tag{8}$$

$$\overrightarrow{C} = 2 \cdot \overrightarrow{r} \tag{9}$$

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

Bubble net hunting method

In this hunting method two approaches are there.

Shrinking encircling prey

Here $\overrightarrow{A} \in [-a, a]$, where $\overrightarrow{A}$ is decreased from 2 to 0. Here $\overrightarrow{A}$ position is setting down at random values in between $[-1, 1]$. The new position of $\overrightarrow{A}$ 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. 8.

Spiral position updating

To mimic helix-shaped movement spiral equation is used.

$$\overrightarrow{X}(t+1) = \overrightarrow{D'} \cdot e^{bl} \cdot \cos(2\pi l) + \overrightarrow{X^*} \tag{10}$$

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

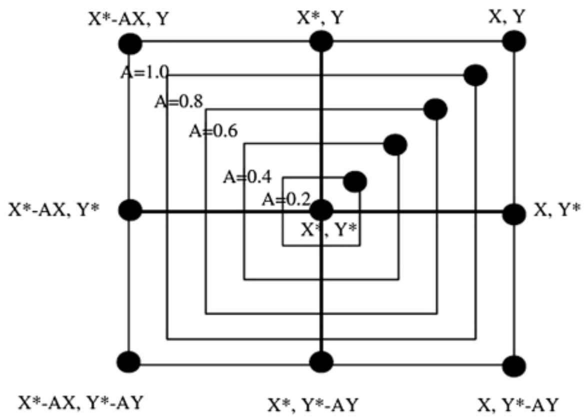

Fig. 1 Bubble net search shrinking encircling mechanism

$$\vec{X}(t+1) = \begin{cases} \vec{X^*}(t) - \vec{A} \cdot \vec{D} & \text{if } p < 0.5 \\ \vec{D'} \cdot e^{bl} \cdot \cos(2\pi l) + \vec{X^*} & \text{if } p \geq 0.5 \end{cases} \quad (11)$$

where $D' = \left|\vec{X^*} - \vec{X}(t)\right|$ represents the distance between whale and the prey (best solution). b is constant, $l \in [-1, 1]$. P is random number [0, 1]. Figure 2 shows the spiral updating position approach represented by Eq. 11.

Search for prey

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

$$\vec{D} = \left|\vec{C} \cdot \overrightarrow{X_{\text{rand}}} - \vec{X}\right| \quad (12)$$

$$\vec{X}(t+1) = \overrightarrow{X_{\text{rand}}} - \vec{A} \cdot \vec{D} \quad (13)$$

$\overrightarrow{X_{\text{rand}}}$ is the random whales in current iteration. The symbol || denotes the absolute values. Figure 3 shows flowchart of the proposed algorithm.

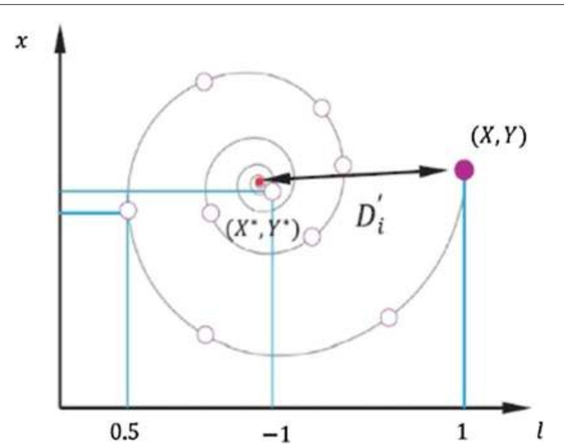

Fig. 2 Bubble net search spiral updating position mechanism

Implementation of WOA

The detailed algorithm is as follows.

Step 1 Read line and load data of the system and solve the feeder-line flow for the system using load flow method. In this paper branch current load flow method is used.
Step 2 Find the best DG locations using the index vector method.
Step 3 Initialize the population/solutions and itmax = 50, number of DG locations $d = 1$ for, $dg_{min} = 60$, $dg_{max} = 3000$.
Step 4 Generate the population of DG sizes randomly using equation
population = $(dg_{max} - dg_{min}) \times \text{rand}() + dg_{min}$
where dg_{min} and dg_{max} are minimum and maximum limits of DG sizes.
Step 5 Find power losses for generated population.
Step 6 Current best solution is DG values with low losses.
Step 7 By using Eqs. 10–13 update the position of whales.
Step 8 For updated population determine losses by performing load flow.
Step 9 If obtained losses are less, then replace current best solution with it or else go back to step 7
Step 10 Print the results if tolerance is <0.00001 or maximum iterations reached.

Simulation results

WOA is evaluated in the application of DG planning problem with IEEE 15, 33, 69 and 85-bus test systems as test cases. The WOA is used to obtain the optimal size of DG.

IEEE 15-bus system

IEEE 15-bus test system (Baran and Wu 1989) is shown in Fig. 4.

Table 1 shows the real, reactive power losses and minimum voltages after the placement of different types of DGs. The optimal location for 15-bus test system is 6. The minimum voltage is more in case of type III DG operating at 0.9 pf. The losses are also lower with DG type III operating at 0.9 pf when compared to other types of DGs which is shown in Table 1. 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.

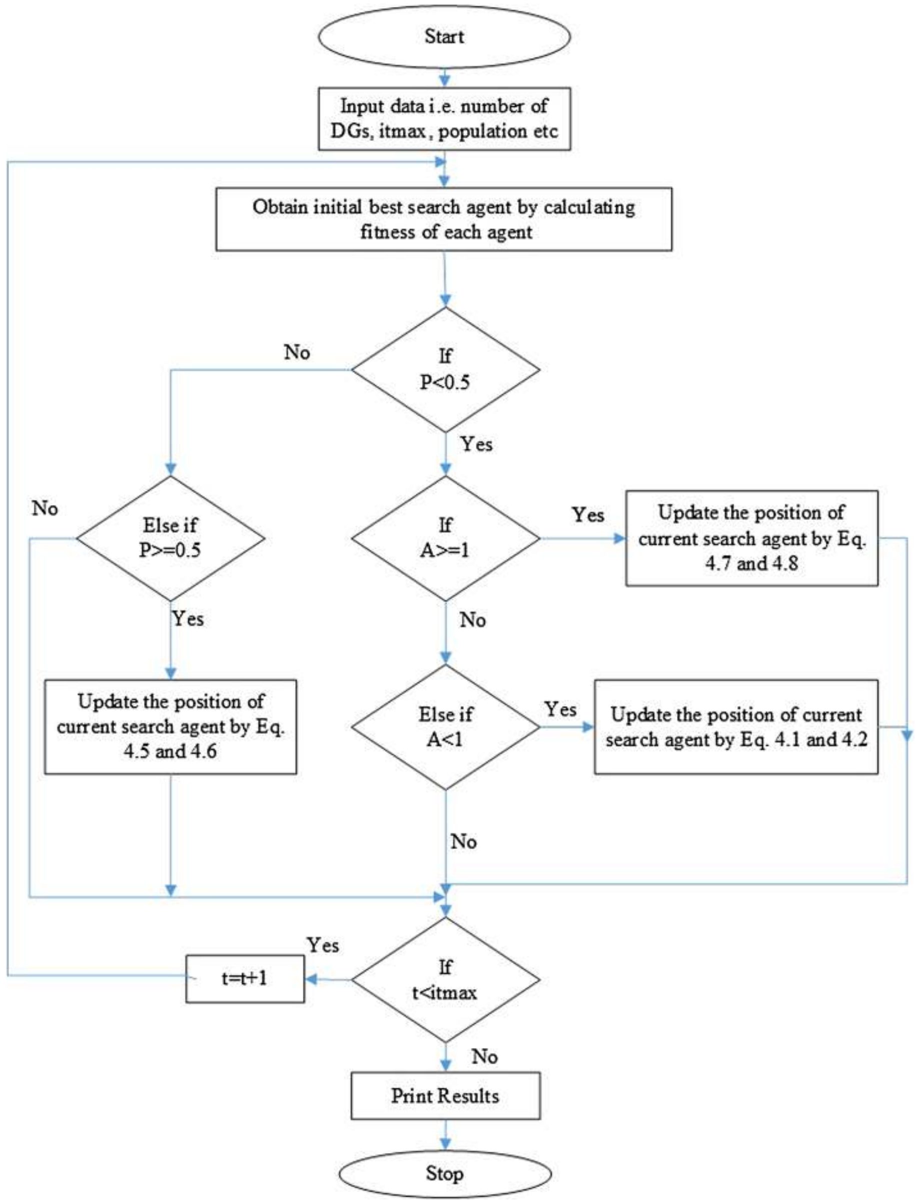

Fig. 3 Flowchart of proposed whale optimization algorithm

The voltage profile also improves with DGs at lagging power factor, and it is observed in Fig. 5. The minimum voltage obtained with lagging power factor is better compared with DGs at unity power factor. Thus, for losses reduction and voltage profile improvement it is essential to consider the reactive power available from DGs. The results obtained with consideration of reactive power are better than the results obtained with DGs at unity power factor.

IEEE 33-bus system

IEEE 33-bus distribution system (Baran and Wu 1989) is shown in Fig. 6.

Table 2 shows the real, reactive power losses and minimum voltages after the placement of different types of DGs. Tables 3 and 4 show comparison of results with type III DG operating at 0.9 pf and unity pf, respectively. 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.

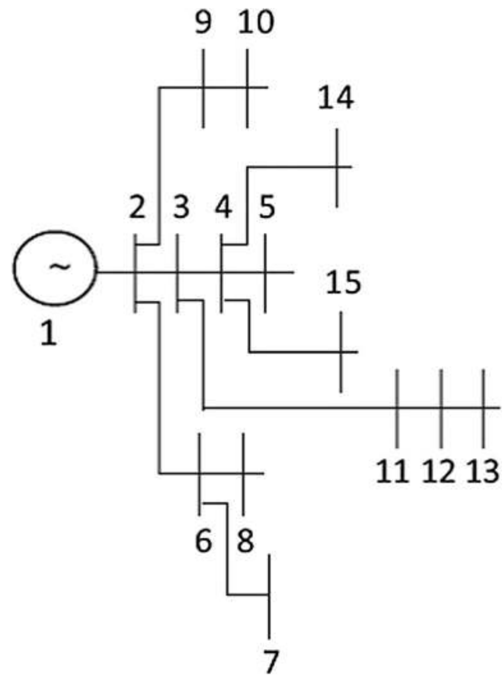

Fig. 4 Single-line diagram of 15-bus system

In Table 2 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 Fig. 7. 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. When comparing (VVSN Murthy 2013) voltage sensitivity index (VSI) method, proposed method gives better results as shown in Tables 3 and 4.

IEEE 69-bus system

The IEEE 69-bus distribution system (Baran and Wu 1989) is shown in Fig. 8.

Table 5 shows the real, reactive power losses and minimum voltages after the placement of different types of DGs. The optimal location for 69-bus system is 61. The minimum voltage is more in case of type III DG operating at 0.9 pf. In Table 5 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.

From the results it is observed that the DG size 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 because 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 Fig. 9.

The minimum voltage that is 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. When comparing (VVSN Murthy 2013) voltage sensitivity index (VSI) method, proposed method gives better results as shown in Tables 6 and 7.

IEEE 85-bus system

The IEEE 85-bus distribution system (Baran and Wu 1989) is shown in Fig. 10.

Table 8 shows the real, reactive power losses and minimum voltages after the placement of different types of DGs. The optimal location for 85-bus test system is 55. The minimum voltage is more in case of type III DG

Table 1 Results of 15-bus system

	Without DG	With type I DG (kW)	With type II DG (kVAR)	With type III DG (kVA) at 0.9 pf lag	With type III DG (kVA) at upf pf
Location	–	6	6	6	6
DG size	–	675.248	682.344	907.785	675.248
TLP (kW)	61.7933	45.8035	45.3228	33.385	45.8035
TLQ (kVAR)	57.2969	41.8809	41.4261	29.8915	41.8809
Vmin	0.9445	0.9527	0.9526	0.9590	0.9527

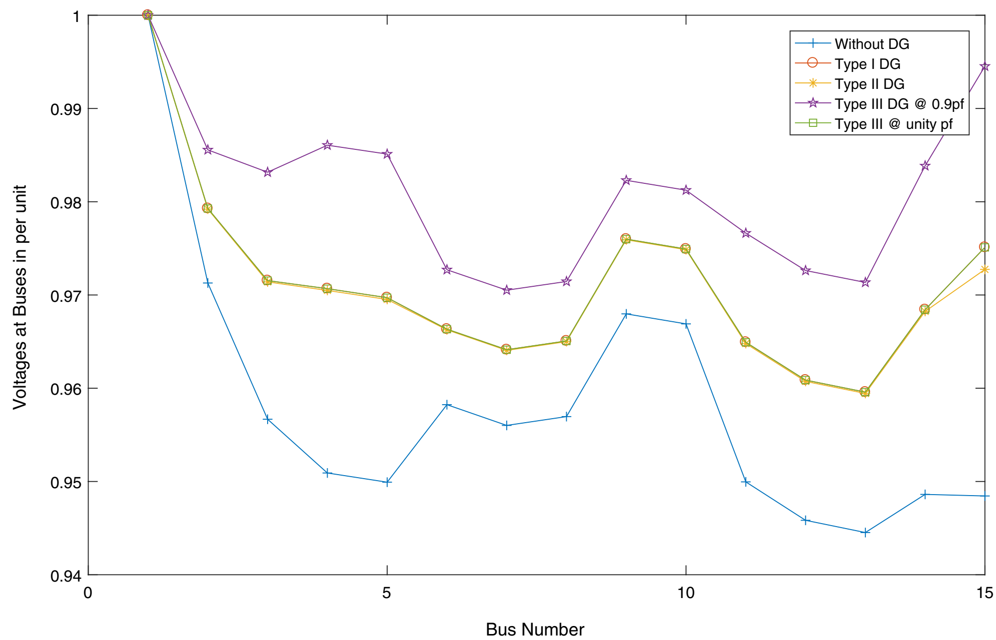

Fig. 5 Voltage profile of 15-bus system

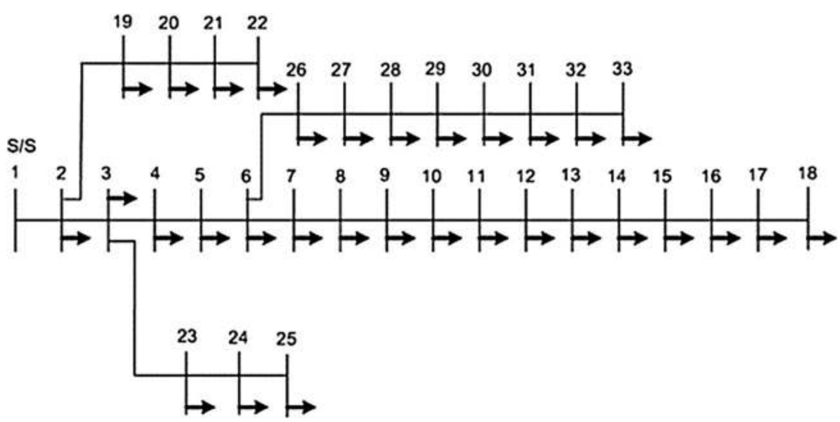

Fig. 6 Single-line diagram of 33-bus system

Table 2 Results of 33-bus system

	Without DG	With type I DG (kW)	With type II DG (kVAR)	With type III DG (kVA) at 0.9 pf lag	With type III DG (kVA) at upf pf
Location	–	15	15	15	15
DG size	–	1061	612.043	1255.89	1061
TLP (kW)	210.9974	133.503	183.932	108.406	133.503
TLQ (kVAR)	143.032	90.7376	125.615	74.7726	90.7376
Vmin	0.9038	0.9327	0.9224	0.939	0.9327

operating at 0.9 pf. 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

Table 3 Comparison of results with DG operating at 0.9 pf

	With DG	
	Voltage sensitivity index method (VVSN Murthy 2013)	**Proposed method**
Location	16	15
DG size	1200	1255.89
TLP (kW)	112.786	108.406
TLQ (kVAR)	77.449	74.7726
Vmin	0.9378	0.939

Table 4 Comparison of results with DG operating at unity pf

	With DG	
	Voltage sensitivity index method (VVSN Murthy 2013)	**Proposed method**
Location	16	15
DG size	1000	1061
TLP (kW)	136.753	133.503
TLQ (kVAR)	92.6599	90.7376
Vmin	0.9318	0.9327

loads, thereby decreasing the reactive power available from substation.

Voltage profiles of the IEEE 85-bus system with and without placement of different types of DGs are shown in Fig. 11. From figure it is clear that the type III DG operating at 0.9 pf has better voltage profile improvement.

Figure 12 shows convergence characteristics of IEEE 15, 33, 69 and 85 with 0.9 pf. The characteristics show that the WOA converged faster. Hence WOA is efficient, robust and capable of handling mixed integer nonlinear optimization problems.

Conclusions

A novel nature-inspired whale optimization algorithm is used to determine the optimal DG size in this paper. WOA is modeled 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 15, 33, 69 and 85-bus radial distribution systems with different types of DGs and compared with other algorithms. Better results have been achieved with WOA when compared with other algorithms. The simulation results indicated that the overall

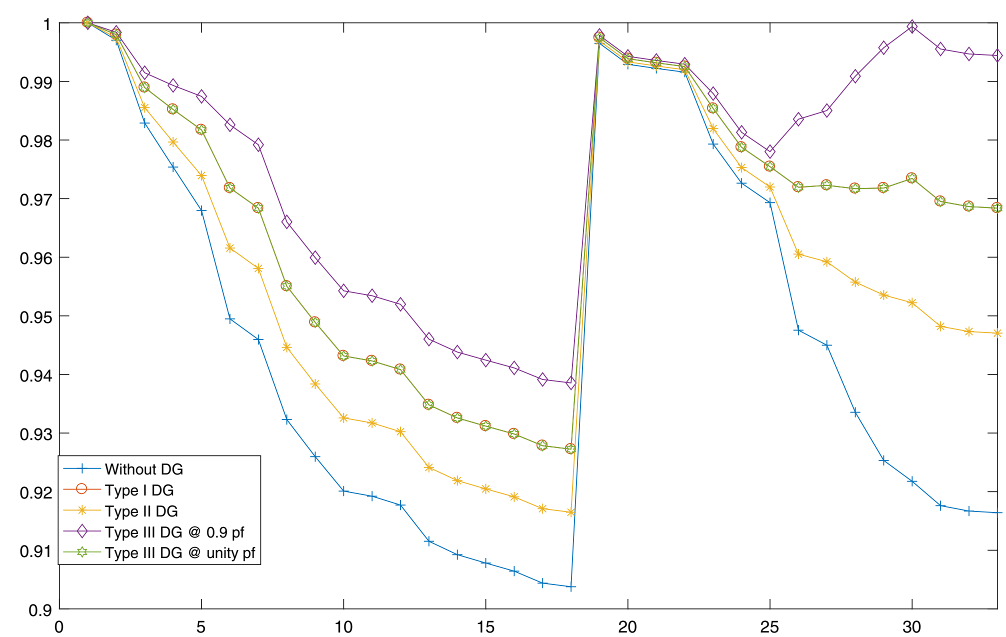

Fig. 7 Voltage profile 33-bus system

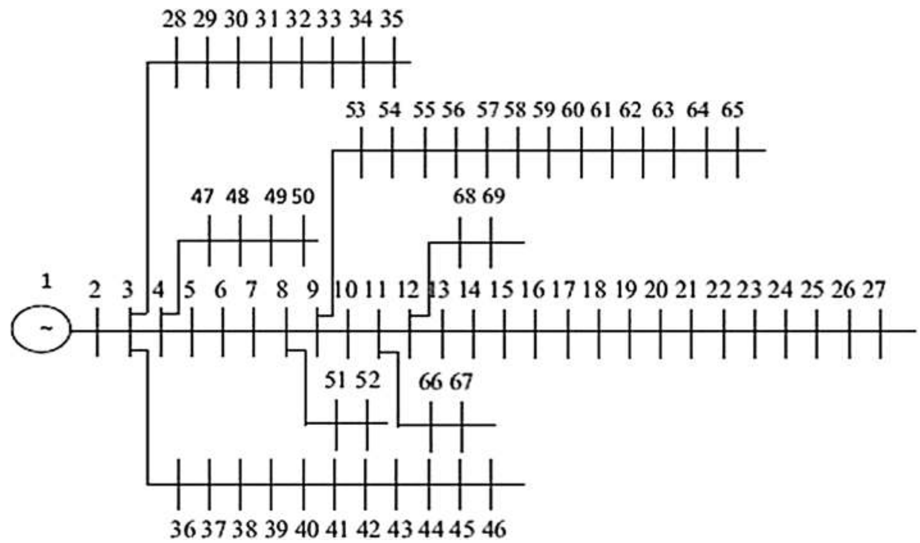

Fig. 8 Single-line diagram of 69-bus system

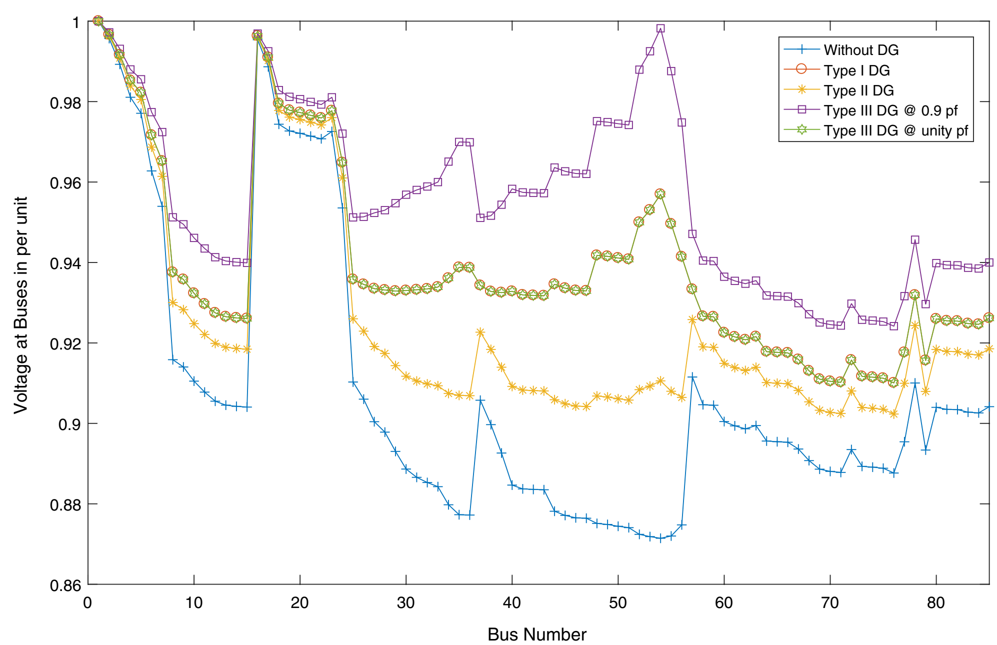

Fig. 9 Voltage profile of 69-bus system

Table 5 Results of 69-bus system

	Without DG	With type I DG (kW)	With type II DG (kVAR)	With type III DG (kVA) at 0.9 pf lag	With type III DG (kVA) at upf pf
Location	–	61	61	61	61
DG size	–	1872.82	1329.99	2217.39	1872.82
TLP (kW)	225.023	83.2279	152.064	27.9649	83.2279
TLQ (kVAR)	102.176	40.5381	70.5143	16.4606	40.5381
Vmin	0.9092	0.9683	0.9307	0.9724	0.9683

Table 6 Comparison of results with DG operating at 0.9 pf

	With DG	
	Voltage sensitivity index method (VVSN Murthy 2013)	**Proposed method**
Location	65	61
DG size	1750	2217.39
TLP (kW)	65.4502	27.9649
TLQ (kVAR)	35.625	16.4606
Vmin	0.9693	0.9724

Table 7 Comparison of results with DG operating at unity pf

	With DG	
	Voltage sensitivity index method (VVSN Murthy 2013)	**Proposed method**
Location	65	61
DG size	1450	1872.82
TLP (kW)	112.022	83.2279
TLQ (kVAR)	55.1172	40.5381
Vmin	0.966	0.9683

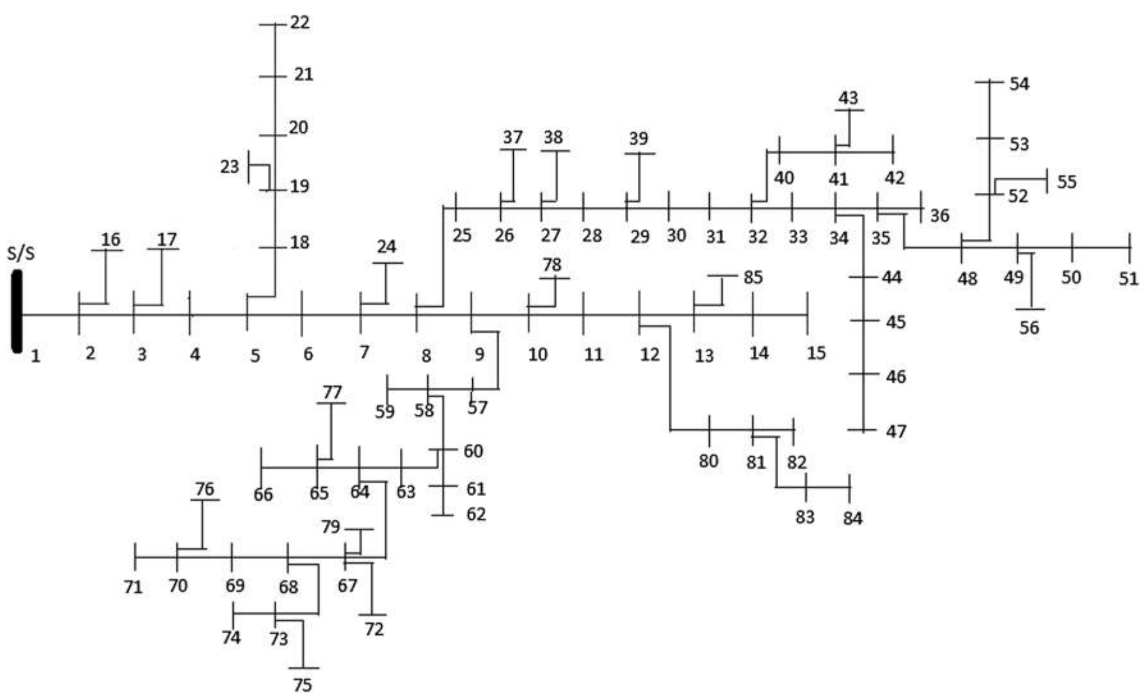

Fig. 10 Single-line diagram of 85-bus system

Table 8 Results of 85-bus system

	Without DG	With type I DG (kW)	With type II DG (kVAR)	With type III DG (kVA) at 0.9 pf lag	With type III DG (kVA) at upf pf
Location	–	55	55	55	55
DG size	–	946.347	873.846	1289	946.347
TLP (kW)	315.7	224.049	229.02	157.485	224.049
TLQ (kVAR)	198.356	136.299	140.136	90.9812	136.299
Vmin	0.8714	0.9109	0.903	0.9255	0.9109

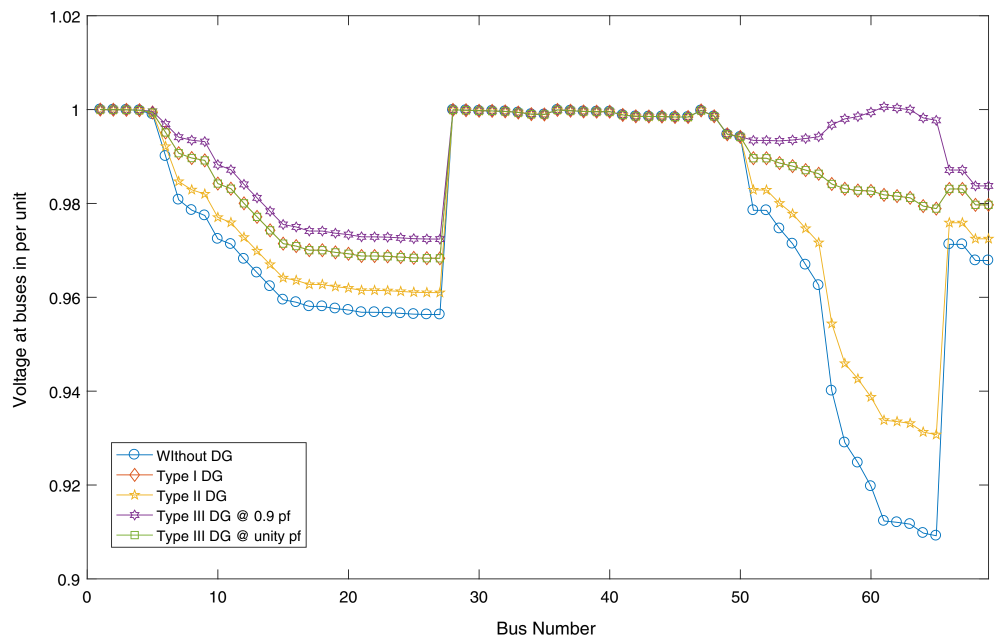

Fig. 11 Voltage profile of 85-bus system

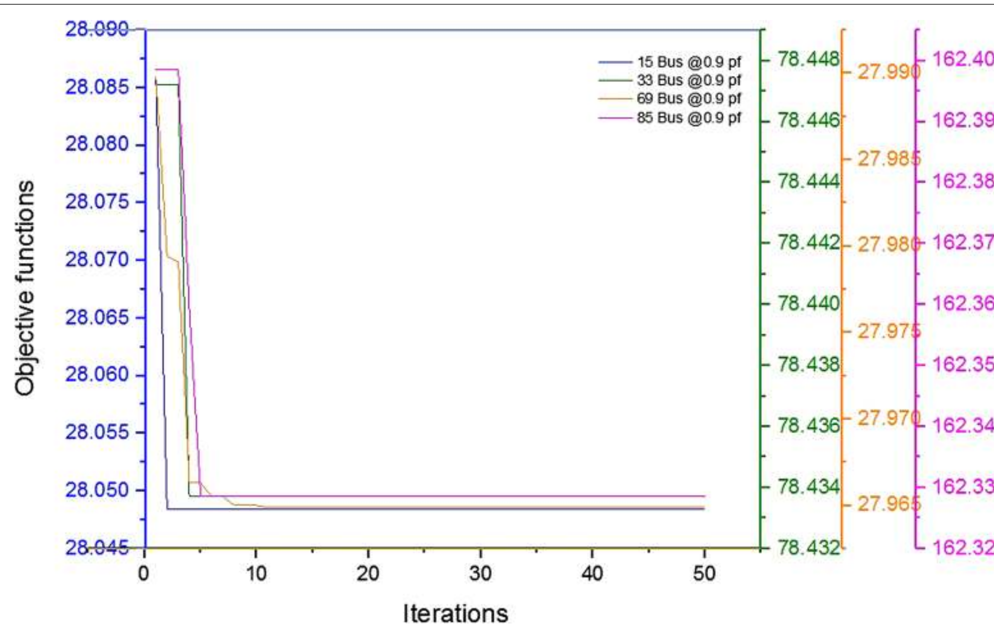

Fig. 12 Convergence characteristics

impact of the DG units on voltage profile is positive and proportionate reduction in power losses is achieved. It can be interfered 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.

List of symbols
$\overrightarrow{X}$: current position vector; $\overrightarrow{A}$, $\overrightarrow{C}$: coefficient vectors; $\overrightarrow{D}$: distance vector; $\overrightarrow{r}$: random vector; $\overrightarrow{X}$: current position vector; $\overrightarrow{X}^*$: best solution position; *b*: constant; *P*: random number in [0, 1]; P_d: power demand; P_{DG}: rating of DG; P_{loss}: power loss; PV: photovoltaic.

Authors' contributions
AB carried out the literature survey and participated in DG location section. AC participated in study on different nature-inspired algorithms for DG sizing. A carried out the DG sizing algorithm design and mathematical modeling. ABC participated in the assessment of the study and performed the analysis. ABC participated in the sequence alignment and drafted the manuscript. All authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

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