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Optimal placement and sizing of multiple distributed generating units in distribution networks by invasive weed optimization algorithm

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Abstract Distributed generation (DG) is becoming more important due to the increase in the demands for electrical energy. DG plays a vital role in reducing real power losses, operating cost and enhancing the voltage stability which is the objective function in this problem. This paper proposes a multi-objective technique for optimally determining the location and sizing of multiple distributed generation (DG) units in the distribution network with different load models. The loss sensitivity factor (LSF) determines the optimal placement of DGs. Invasive weed optimization (IWO) is a population based meta-heuristic algorithm based on the behavior of weeds. This algorithm is used to find optimal sizing of the DGs. The proposed method has been tested for different load models on IEEE-33 bus and 69 bus radial distribution systems. This method has been compared with other nature inspired optimization methods. The simulated results illustrate the good applicability and performance of the proposed method.

1. Introduction

DG is an emerging approach for providing electric power close to the load centers. It comprises the installation and operation of a portfolio of small size, compact and clean electric power generating units at or near the electric load [1]. The term Distributed Generation generally refers to small scale (typically 1 KW–50 MW) electric power generators that produce electricity at a site close to the customer or that are tied to an electric distribution system. DGs include synchronous generators, induction generators, reciprocating engines, micro turbines, combustion gas turbines, fuel cells, solar photovoltaic, wind turbines and other small power sources. There are many reasons for a customer to install a DG. It can be used to generate a customer's entire electricity supply for peak shaving or for standby or emergency generation, as a green power source or for increased reliability. DGs can be less costly as it eliminates the need for expensive construction of distribution and transmission lines. DGs can provide cost effective, environmental friendly, high power quality and more reliable energy solutions than conventional generation. The number of DG

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Nomenclature

P_k	real power load at bus k	Q_k	reactive power load at bus k
$P_{k,k+1}$	real power flowing in the line between busses k and $k+1$	$Q_{k,k+1}$	reactive power flowing in the between buses k and $k+1$
$P_{k+1,eff}$	total effective real power supplied beyond the bus $k+1$	$Q_{k+1,eff}$	total effective reactive power supplied beyond the bus $k+1$
V_k	voltage magnitude at bus k	I_k	equivalent current injected at node k
$J_{k,k+1}$	branch current in the line section between buses k and $k+1$	$J_{k,k+1,max}$	maximum branch current limit of line section between buses k and $k+1$
V_{min}	minimum voltage limits of the buses	V_{max}	maximum voltage limits of the buses
ΔV_{max}	maximum voltage drop limit between buses 1 and k	V_{worst}	worst voltage magnitude of the system
$R_{k,k+1}$	resistance of the line section between buses k and $k+1$	$X_{k,k+1}$	reactance of the line section between buses k and $k+1$
$P_{loss}(k,k+1)$	power loss in the line section between buses k and $k+1$ without DGs	$P_{DG,Tloss}$	total power loss of the system with DGs
P_{DGT}^{min}	minimum total power generation limit of the system	P_{DGT}^{max}	max total power generation limit of the system
$P_{DG,loss}(k,k+1)$	power loss in the line section between buses k and $k+1$ with DGs	$P_{DG,k}$	power supplied from DG at the bus k
		n	total number of buses
		b	total number of branches

units installed in the distribution system has been increasing significantly and their technical, economical and environmental impacts on the power system are being analyzed. Presently, the technical impacts of interest are voltage profile, power loss, power quality, reliability, protection, power control and stability [2,3].

Radial distribution systems have high R/X ratio. Therefore general load flow algorithms such as Newton Raphson or fast decoupled power flow solutions are not used. The backward forward sweep is one of the most effective methods for load flow analysis of radial distribution systems. The convergences of backward forward sweep method with different load models are analyzed in [4]. The backward forward sweep method is the most commonly used technique for radial distribution networks [5]. The effect of load models in DG planning is considered to assess the technical impacts and feasibility of DG planning. The load model can affect the location and size of DGs. The different types of load models such as residential, industrial, and commercial loads are investigated in [6]. The selection of optimal location and size of DG units in the distribution network is a complex optimization problem [7]. The dynamic programming method is presented in [8] for locating and sizing of DGs to enhance voltage stability and to reduce network losses simultaneously. Here the vulnerable buses from voltage stability point of view are determined by using bifurcation analysis and considered for installation of DGs. The number of DGs is so chosen, such that the system voltage profile is brought into the given permissible voltage security limits [8]. A new index considering stable node voltages referred to as power stability index is used to find the most sensitive bus for DG placement [9]. Here an analytical approach is used for finding the optimum size and location of DG to minimize power loss. A mixed-integer linear programming approach in solving the steady state operation of radial distribution system considering different load levels is modeled through linear expressions in [10]. The effect of load models on DG was investigated and was found to significantly affect the DG planning [11]. A novel approach, which determines the location of DG by loss sensitivity factor and size by simulated annealing method has been proposed in [12].

Many algorithms have been proposed by various researchers to determine the location and size of DGs. Particle swarm optimization (PSO) is a population based meta-heuristic algorithm which works in two steps such as calculating the particle velocity and updating the position. It reduces the computation time and requires little memory. But, PSO easily suffers from partial optimization [13–15]. Shuffled frog leaping is a population based algorithm which can be used for solving many complex nonlinear, multi-modal and non-differentiable problems. But the limitation is that it slows the convergence speed and also causes premature convergence [16,17]. Genetic algorithm (GA) is a method which is easy to understand and it can be used to solve non-differential, non-dimensional and non-continuous problems. GA applications that are performed in real time are limited due to random solutions and less convergence speed [18]. A combined GA and PSO algorithm is used for optimal placement and sizing of DG [19]. Bacterial foraging optimization algorithm (BFOA) is applied to solve various optimization problems in power systems due to its ability in searching the promising areas of the solution space but the complexity of BFOA algorithm forces the researchers to find a simple way to speed up the convergence [20]. A hybrid method based on improved particle swarm optimization algorithm (IPSO) and Monte Carlo simulation is applied for placement and sizing of DG [21]. Monte Carlo method is very flexible, and there is virtually no limit to the analysis but solutions are not exact. It depends on the number of repeated runs. Modified teaching-learning based optimization algorithm is one of the new optimization algorithms proposed for solving continuous nonlinear optimization problems. But it is limited to lower dimensional problems [22].

Invasive weed optimization (IWO) is an ecological inspired algorithm that mimics the weeds colonization. It is proposed for electromagnetic applications in [24]. IWO algorithm has been applied for various optimization problems including design of non-uniform circular antenna array [25], analysis of pareto improvement model in electricity market [26], design of aperiodic antenna arrays [27], linear antenna array synthesis [28], and multi-objective optimization problems and previous studies also show that it is used as a global optimizer for numerical benchmark as well as real world problems [29] and so on.

The proposed method is used to find the optimal sizing of multiple DGs for minimizing the loss and operational cost and improving the voltage stability in the radial distribution system with different types of loads. In this paper, Loss sensitivity factor (LSF) is used to find the optimal location of the DG. From this sensitivity factor the buses are ranked in the descending order to form a priority list. The most sensitive locations are chosen to install the DGs. The result obtained shows that the proposed method is comparable with multi-objective evolutionary algorithm and it has improved the convergence rate and computation time. This method has been tested on IEEE-33 bus and 69 bus test systems and the results are compared with the different methods. The simulated result illustrates the good applicability and performance of the proposed method.

The rest of the paper is organized as follows: Section 2 presents the formulation of the optimization problem. Section 3 describes the loss sensitivity factor for optimal placement of DG. Section 4 discusses about IWO algorithm. Section 5 discusses how the problem can be solved using the proposed method. Results obtained for the proposed problem are presented in Section 6. Conclusions are presented in Section 7.

2. Problem formulation

The main objective of the proposed method is to determine the optimal placement and sizing of DGs that minimizes the multi-objective function subject to various unit constraints and operational constraints of a distribution network.

2.1. Factors related to optimal placement of DGs and constraints specific to distribution network

2.1.1. Power flow equation

The load flow of a single source network can be solved iteratively from two sets of recursive equations. The first set of equations is for calculation of the power flow through the branches starting from the last branch and proceeding in the backward direction toward the root node. The other set of equations is for calculating the voltage magnitude and angle of each node starting from the root node and proceeding in the forward direction toward the last node. The recursive equations are determined as follows,

The effective active power ($P_{k,k+1}$) that flows through branch k from node k to $k+1$ can be calculated backward from the last bus and it is given as

$$P_{k,k+1} = P'_{k+1} + r_{k,k+1}\left(\frac{(P'_{k+1})^2 + (Q'_{k+1})^2}{V_{k+1}^2}\right) \tag{1}$$

where

$$P'_{k+1} = P_{k+1,eff} + P_{k+1}$$

P_{k+1} = real power load connected at bus $k+1$.

The voltage magnitude and angle at each bus are calculated in forward direction as

$$I_k = \left(\frac{V_k * ang(\delta_k) - V_{k+1} * ang(\delta_{k+1})}{R_{k,k+1} + jX_{k,k+1}}\right) \tag{2}$$

where $ang = angle$

$$I_k = \frac{P_k - jQ_k}{V_k ang(-\delta_k)} \tag{3}$$

Equating Eqs. (2) and (3),

$$V_{k+1} = \left(V_k^2 - 2(P_{k,k+1}R_{k,k+1} + Q_{k,k+1}X_{k,k+1}) + (R_{k,k+1}^2 + X_{k,k+1}^2) * \left(\frac{P_{k,k+1}^2 + Q_{k,k+1}^2}{V_k^2}\right)\right)^{1/2} \tag{4}$$

The real power losses of branch k can be calculated as,

$$P_{loss(k,k+1)} = R_{k,k+1}\left(\frac{P_{k,k+1}^2 + Q_{k,k+1}^2}{V_k^2}\right) \tag{5}$$

The total real power loss of radial distribution system can be calculated as

$$P_{Tloss} = \sum_{k=1}^{b} P_{loss(k,k+1)} \tag{6}$$

2.1.2. Power loss with DG

Determination of the optimal location of DGs reduces the power losses, enhances the voltage stability and reduces the cost. It improves the security of the supply and reliability.

$$P_{DG,loss}(k,k+1) = R_{k,k+1}\left(\frac{P_{DG,k,k+1}^2 + Q_{DG,k,k+1}^2}{|V_k|^2}\right) \tag{7}$$

Total power loss of the system with DGs is defined as

$$P_{DG,Tloss} = \sum_{k=1}^{b} P_{DG,loss}(k,k+1) \tag{8}$$

2.1.3. Power loss reduction

The power loss has to be reduced by installing the DG. Power loss index (ΔPL_{DG}) is the ratio of total power loss with DG to the total power loss without DG and it is given by

$$\Delta PL_{DG} = \frac{P_{DG,Tloss}}{P_{Tloss}} \tag{9}$$

By installing the DG we can maximize the net power loss reduction by minimizing ΔPL_{DG}.

2.1.4. Voltage deviation index

The voltage deviation index can be defined as

$$\Delta V_D = \max\left(\frac{V_1 - V_k}{V_1}\right) \quad \forall k = 1, 2 \ldots, n \tag{10}$$

By installing the DG, the proposed method will try to minimize the ΔV_D nearer to zero. So it improves the voltage stability and the network performance.

2.1.5. Operational cost minimization

One of the advantages of DG installation is to minimize the operational cost. The operational cost has two components. The first cost is for real power supplied from the substation.

This can be reduced by minimizing the total real power loss of the system. The second cost is the cost of real power supplied by the DG installed. This cost can be reduced by minimizing the amount of real power drawn from DG. So the total operating cost (TOC) can be minimized by using the formula which is given below,

$$TOC = (c_1 P_{DG,Tloss}) + (c_2 P_{DGT}) \tag{11}$$

where c_1, c_2 are the cost coefficient of real power supplied by the substation and DGs in \$/kw. P_{DGT} is the total real power drawn from installed DG. The net operating cost (ΔOC) of DG that can be reduced is given as,

$$\Delta OC = \frac{TOC}{c_2 P_{DGT}^{max}} \tag{12}$$

2.2. Objective function of the problem

The main objective function of the proposed multi-objective optimization method is to minimize the power loss, voltage deviation and total operating cost of the distribution system and it is given by

$$Minimize\, F = min(\alpha_1 \Delta PL_{DG} + \alpha_2 \Delta V_D + \alpha_3 \Delta OC) \tag{13}$$

where

$$\sum_{q=1}^{3} \alpha_q = 1.0, \alpha_q \in [0,1] \tag{14}$$

This objective function is subject to the following constraints.

Power balance constraint

$$\sum_{k=2}^{n} P_{DG,k} = \sum_{k=2}^{n} P_{k+} \sum_{k=1}^{b} P_{Loss,k,k+1} \tag{15}$$

Thermal limits

$$|J_{k,k+1}| \leqslant |J_{k,k+1,max}| \tag{16}$$

Voltage drop limits

$$|V_1 - V_k| \leqslant \Delta V_{max} \tag{17}$$

Distributed generation capacity limits

$$P_{DGT}^{min} \leqslant P_{DGT} \leqslant P_{DGT}^{max} \tag{18}$$

$$\text{where} \quad P_{DGT}^{min} = 0.1 \sum_{k=2}^{n} P_k \; and \; P_{DGT}^{max} = 0.6 \sum_{k=2}^{n} P_k \tag{19}$$

The violation of the inequality constraints are penalized in the objective function.

2.3. Load model

A load model is the mathematical representation of relationship between bus voltage magnitude, real power and reactive power.

$$P_k = \rho P_{k,actual} V_k^{\alpha} \tag{20}$$

$$Q_k = \rho Q_{k,actual} V_k^{\beta} \tag{21}$$

α, β are the load model coefficients. The values of these coefficients are as given in Table 1.

The load factor ρ is a multiplier by which the load power demand at all nodes is increased or decreased. These different load models at distinct load levels are used to check the robustness and capability of the proposed method for the practical implementation.

3. Loss sensitivity factor

Loss sensitivity factor is based on the principle of linearization of the original nonlinear loss equation around the initial operating point which helps to reduce the amount of solution space. Its application in the DG allocation is to find the optimal location of the DG is given by

$$LSF(k, k+1) = \frac{\partial P_{Lineloss}}{\partial P_{k+1,eff}} = \frac{2 P_{k+1,eff} R_{k,k+1}}{|V_{k+1}|^2} \tag{22}$$

According to the sensitivity factor the buses are ranked in the descending order to find the most sensitive location. The top ranked locations that are more sensitive are taken into account to install the DGs.

4. Overview of invasive weed optimization algorithm

IWO is the optimization algorithm developed by Mehrabian and Lucas in 2006. This numerical stochastic optimization algorithm inspired from the phenomenon of colonization of invasive weeds in nature is based on weed biology and ecology [24].

Weeds invade a cropping system by means of dispersal. Each invading weed takes the unused resources in the field and grows to the flowering weed and produces new weed independently. According to their fitness value the weeds are ranked and reproduce the new weeds by their own fitness and it was randomly dispersed over the search space and allows growing to flowering weeds. There is some kind of competition between the plants which limits the maximum number of plants in the colony. Plants in the lowering rank will be eliminated to reach the maximum number of plants. Surviving plants can produce new weeds based on their ranking in the colony. This process continues until the maximum number of iterations is reached or the fitness criterion is met.

4.1. Steps of IWO algorithm

There are four steps in the algorithm as described below

Step1. Initialization: A search space is taken and a certain number of weeds are initialized randomly in the entire search space.

Table 1 Various load types and exponent values.

Load type	α	β
Constant power (CP) [21]	0	0
Constant current (CC) [21]	1	1
Constant impedance (CI) [21]	2	2
Residential load (RES) [21]	0.92	4.04
Industrial load (IND) [21]	0.18	6
Commercial load (COM) [21]	1.51	3.4

Step2. Reproduction: The randomly produced weeds are now allowed to produce seeds. The production of seeds by a weed is dependent on its own fitness and the fitness of its colony. The weed having more fitness produces maximum number of seeds whereas the weed with least fitness produces minimum number of seeds. The seeds produced by weeds increase linearly starting with worst fitness and ending with the best fitness.

$$s(i) = s_{max} - abs\left(floor\left(s_{max} * \frac{g_{best-rk(i)}}{g_{best} - g_{worst}}\right)\right) \tag{23}$$

Step3. Spatial dispersion: The generated seeds are randomly distributed in the entire search space by normal distribution with zero mean and varying standard deviation. The constraint mean is maintained zero with varying variance. This step ensures that the seed is randomly distributed around the parent weed. The standard deviation (SD) decreases with increase in iterations in a nonlinear manner.

Let n be any real number (generally, we consider it as modulation index), the standard deviation of a particular iteration is given as

$$\sigma_{iter} = \frac{(iter_{max} - iter)^n}{(iter_{\max})^n} * (\sigma_{initial} - \sigma_{final}) + \sigma_{final} \tag{24}$$

This step ensures that the probability of dropping a seed in distant area decreases nonlinearly. By this we can group the fitter plants from that of the inappropriate plants.

Step4. Competitive Exclusion: There exists a competition between plants for survival. If a plant produces no offspring, it goes extinct. The initial plants in the colony reproduce plants very fast and all the plants will be considered in the colony. But the population cannot go more than maximum population (pop_{max}). So the plants with more fitness are taken into the colony and the less fitter plants are neglected. Now, in this step the plants in the colony are considered as parent plants and steps 2–4 are repeated again until the maximum number of iterations is reached. This is the selection procedure of IWO.

One important property of the IWO algorithm is that it allows all of the plants to participate in the reproduction process. Fitter plants produce more seeds than less fit plants, which tends to improve the convergence of the algorithm. Furthermore, it is possible that some of the plants with the lower fitness carry more useful information compared to the fitter plants. This property of IWO gives a chance even to the lesser fit plants to reproduce and if the seeds produced by them have good finesses in the colony they can survive to find the better solutions.

5. Implementation of proposed method to optimal placement and sizing

Step 1: Input the system data which includes the branch number, sending end bus, receiving end bus, resistance (R) and reactance (X) of the line, real power (P) and reactive power (Q) of each bus.
Step 2: Calculate the power flow of the entire system by using backward forward sweep method.
Step 3: To identify the location of the DG to be installed the LSF is used. From the power flow, the LSF for each bus is calculated by using Eq. (22)
Step 4: The IWO algorithm is used for sizing of DGs. The implementation of IWO algorithm to find the size of the DGs is that each seed corresponds to a candidate solution of the DG problem and each occupies a node. The capacity of the DGs is made to be bounded in specified range.

The following parameters are initialized.

s_{max}: Maximum number of weeds (10).
s_{min}: Minimum number of weeds (0).
s: total number of weeds in the population (100).
$\sigma_{initial}$: Initial standard deviation (2).
σ_{final}: Final standard deviation (0.0001).
n: Nonlinear modulation index (5).
Step 5: The DG values (weed values) are randomly initialized. The weeds with the highest fitness produce the maximum number of seeds and those with lowest fitness produce minimum seeds. The seed produced by a weed is calculated by using Eq. (23).
Step 6: The produced seeds are randomly distributed near the parent weed with zero mean and varying standard deviation. The standard deviation is calculated using Eq. (24).
Step 7: Now the generated seeds are added to the solution set and the fitness values are calculated for the combined set of weeds and seeds.
Step 8: The population is sorted in descending order of their fitness. Truncate the population with minimum fitness until the maximum population is reached and the fitness of the new solution set is calculated.
Step 9: The steps 5–8 are repeated until maximum number of iterations is reached.

6. Simulation results and discussion

To illustrate the effectiveness of the proposed approach it is tested on IEEE-33 bus and IEEE-69 bus systems for different load types. According to the importance given to each of the objectives – power loss minimization, voltage deviation index reduction and cost minimization – the weighting factors are taken as $\alpha_1 = 0.5$, $\alpha_2 = 0.4$, $\alpha_3 = 0.1$ and cost components are taken as $C_1 = 4$ \$/kW and $C_2 = 5$ \$/kW. C_2 is taken as slightly greater than C_1 by taking the maintenance and installation cost of DG into consideration [20]. The parameters of IWO considered are $s_{max} = 10$, $s_{min} = 0$, $s = 100$, $\sigma_{initial} = 2$, $\sigma_{final} = 0.0001$, $n = 5$. To test the efficiency of the proposed approach the test systems are simulated for different load types such as CP at loads of 0.5 (light), 1.0 (full), 1.6 (heavy), CC, CI, residential, industrial and commercial loads. In this study, it is considered that the DG is operated at two different power factors. The parameters initialized for the IWO algorithm are common for both the test systems. MATLAB software is used to run the power flow, for the development of IWO algorithm and to recognize the optimal location and sizing of DG units.

6.1. IEEE-33. bus system results

The system under study is the IEEE-33 bus system. The network parameters and related data can be found in [30]. The

Table 2 Performance analysis of IEEE-33 bus system for CP and CC load models.

Parameters	CP load						CC load	
	CP (light load)		CP (full load)		CP (Heavy load)			
	Without DG	With DG	Without DG	With DG	Without DG	With DG	Without DG	With DG
DG size (MW) (Bus no.)		0.3732(14) 0.0546(18) 0.4001(32)		0.6247(14) 0.1049(18) 1.0560(32)		0.9914(14) 0.4553(18) 1.7010(32)		0.5575(14) 0.0930(18) 1.1889(32)
Power loss (kW)	46.99	10.92	201.89	85.86	570.87	126.29	181.05	45.53
% loss reduction		76.76		57.47		77.88		74.85
ΔPL_{DG}		0.2324		0.4253		0.2212		0.2515
V_{worst} (p.u)	0.9583 (18)	0.9898 (25)	0.9134 (18)	0.9716 (29)	0.8538 (18)	0.9695 (25)	0.9117 (18)	0.9818 (25)
ΔV_D	0.0400	0.0037	0.0832	0.0237	0.1403	0.0318	0.0769	0.0158
TOC ($)		4183.18		9271.44		16243.66		9379.12
Computation time (s)		3.78		4.8		5.4		3.95

system has 33 buses, 32 lines with the total real and reactive power loads of 3.72 MW and 2.3 MVAr, respectively. The power losses of the CP (light), CP (full), CP (heavy), CC, CI, residential, commercial and industrial load systems has been calculated for the base case power flow (without DG). The values obtained are presented in Table 2 and Table 3.

Loss sensitivity factor is used for the placement of the DGs. The bus that has high sensitivity is capable of causing voltage instability. The LSFs of all buses are computed from power flow and then they are arranged in descending order. The first three buses are considered as an optimum places for DGs to be installed. The bus numbers chosen as per LSF are 14, 18 and 32. The DG installation at more than three locations does not result in significant reduction in power loss [23]. The optimum size of the DG is found by using IWO algorithm.

The optimum values of DGs to be installed as determined by the proposed IWO are as shown in the Table. The comparison of these power losses shows that there is a substantial reduction for all loads – light, full and heavy – and different load models. The corresponding percentage loss reduction and power loss reduction index are shown. Also shown in the Tables are the comparison of the minimum voltage magnitudes, V_{worst} along with its bus number. It is observed that with DG placement the minimum voltage magnitude has improved for all load models. Similar comparison of voltage deviation index, ΔV_D shows its value with DG is lower for all load models. From the values obtained for power loss, V_{worst} and ΔV_D it is proved that IWO is very effective in finding the optimal size of DGs to be installed. Also shown in the Table is the total operating cost, TOC for DGs installed. From Table 2 it has been observed that the total installed DG is the highest (3.14477 MW) for CP heavy load and it is the least (0.8279 MW) for CP light load. From Table 3 it has been observed that the total installed DG is the highest (1.8235 MW) for residential load and it is the least (1.1324 MW) for CI load.

6.1.1. Comparison of IEEE-33 bus system results

- The simulated results of IWO are compared with those of genetic algorithm (GA) [19], particle swarm optimization (PSO) [19], combined GA/PSO [19], simulated annealing (SA) [12] and bacterial foraging optimization algorithm (BFOA) [20] in Table 4.
- For validation purpose the test system is simulated with DGs operating at power factors of unity and 0.866 as was the case in the above referred systems.

  For unity p.f.
- Since IWO is a nature inspired algorithm, performance statistical measures have been implemented. Among the 100 independent runs the TOC obtained by IWO is $ 9271.44. The mean value of TOC is $ 9272.23. The value obtained by BFOA is $ 9948.1. This comparison shows a substantial reduction in the operating cost of $ 676.7. The optimal size of DG is 1.7856 MVA by IWO and 1.9176 MVA by BFOA.

Table 3 Performance analysis of IEEE-33 bus system for CI, RES, COM and IND load models.

Parameters	CI load		Residential		Commercial		Industrial	
	Without DG	With DG	Without DG	With DG	Without DG	With DG	Without DG	With DG
DG size (MW) (Bus no.)		0.3219(14) 0.0584(18) 0.7521(32)		0.5650(14) 0.1000(18) 1.1585(32)		0.5631(14) 0.0538(18) 1.1081(32)		0.4968(14) 0.0514(18) 0.9937(32)
Power loss (kW)	156.46	37.91	160.43	52.18	154.39	45.27	164.26	48.75
% loss reduction		75.77		67.47		70.68		70.32
ΔPL_{DG}		0.2423		0.3253		0.2932		0.2968
V_{worst} (p.u)	0.9185 (18)	0.9782 (11)	0.9174 (18)	0.9825 (25)	0.9190 (18)	0.9824 (25)	0.9170 (18)	0.9809 (25)
ΔV_D	0.07	0.0064	0.0711	0.024	0.0701	0.0192	0.0707	0.014
TOC ($)		5813.64		9326.22		8806.08		7904.5
Computation time (s)		4.29		4.3		3.9		3.8

Table 4 Comparison of IEEE-33 bus system results.

Method	$P_{DG,Tloss}$ (kW)	% Loss reduction	V_{worst} (p.u)(bus)	DG location	DG size (MW)	P_{DGT}(MVA)	Power factor	TOC ($)
GA[19]	106.30	49.61	0.9809(25)	11	1.5000	2.9942	Unity	15396.2
				29	0.4228			
				30	1.0714			
PSO [19]	105.35	50.06	0.9806(30)	13	0.9816	2.9881	Unity	15361.9
				32	0.8297			
				8	1.1768			
GA/PSO [19]	103.40	50.99	0.9808(25)	32	1.2000	2.9880	Unity	15353.6
				16	0.8630			
				11	0.9250			
SA [12]	82.03	61.12	0.9676(14)	6	1.1124	2.4677	Unity	12666.6
				18	0.4874			
				30	0.8679			
BFOA [20]	89.90	57.38	0.9705(29)	14	0.6521	1.9176	Unity	9948.1
				18	0.1984			
				32	1.0672			
IWO	85.86	57.47	0.9716(29)	14	0.6247	1.7856	Unity	9271.44
				18	0.1049			
				32	1.0560			
SA [12]	26.72	87.33	0.9826(25)	6	1.1976	2.9975	0.866	13086.3
				18	0.4778			
				30	0.9205			
BFOA [20]	37.85	82.06	0.9802(29)	14	0.6798	2.2153	0.866	9743.9
				18	0.1302			
				32	1.1085			
IWO	37.05	81.64	0.9838(25)	14	0.5176	1.9821	0.866	8730.7
				18	0.1147			
				32	1.0842			

The reduction in the operating cost (given by Eqn. (11)) is due to reduction in the percentage loss and DG size. Finally, V_{worst} of IWO has also improved.

- From the Table it is observed that the operating cost by IWO is the least of all the methods shown for comparison. The optimal size obtained by DG is the minimum of all other methods. The percentage loss reduction which is better by IWO is also the least of all the methods except SA. Also, V_{worst} of IWO has improved compared to other methods.

For 0.866 p.f.

- It has been demonstrated that the IWO algorithm determines the optimal location and size of DGs with increase in percentage power loss reduction, improved voltage stability margin and minimum operating cost.

The statistical comparison of voltage deviation index, power loss index and net operating cost for IEEE-33 bus system with genetic algorithm (GA) [19], particle swarm optimization (PSO) [19], combined GA/PSO [19], simulated annealing (SA) [12] and bacterial foraging optimization algorithm (BFOA) [20] is shown in Fig. 1. It is shown from the figure that the power loss index, voltage deviation index and TOC of IWO algorithm are reduced compared to other algorithms. The results show the efficiency of IWO algorithm for reduction of power loss, improvement in voltage profile and reduction in TOC. Convergence characteristics of different methods are shown in Fig. 2 to compare the quality of minimized objective function. It is clear that IWO needs only less iteration to achieve the minimized objective function. It is observed that IWO provides the highly minimized objective function compared to other nature inspired optimization approaches.

Voltage profiles and the line losses of IEEE-33 bus systems of various CP (light), CP (full), CP (heavy), CC, CI, residential, commercial and industrial load systems are shown in Figs. 3 and 4 with and without DGs. From Fig. 3 it is observed that the voltage profile has improved for all the types of loads after installing the DGs. The reduction in the power losses is observed in Fig. 4. This reveals the effectiveness of the proposed algorithm.

6.2. IEEE-69. bus system results

The system under study is IEEE-69 bus system. The network parameters and related data can be found in [30]. The system

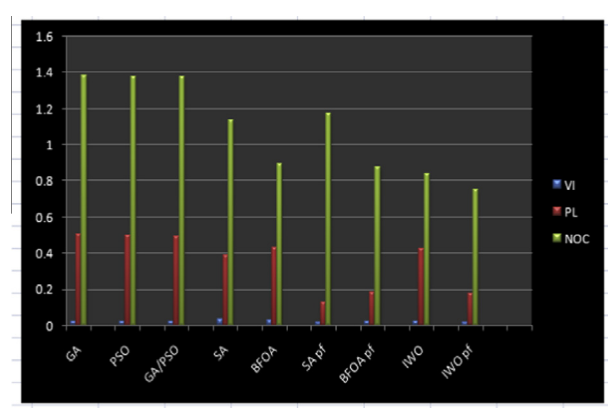

Figure 1 Comparison of performances of IWO for IEEE-33 bus system with other methods [20].

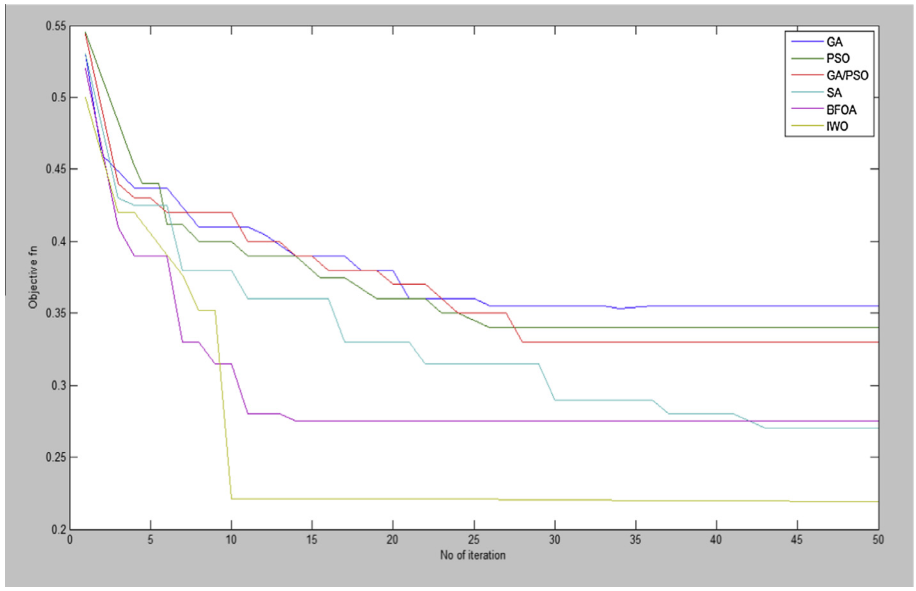

Figure 2 Comparison curve of convergence characteristics of IWO for IEEE-33 bus system with other methods [20].

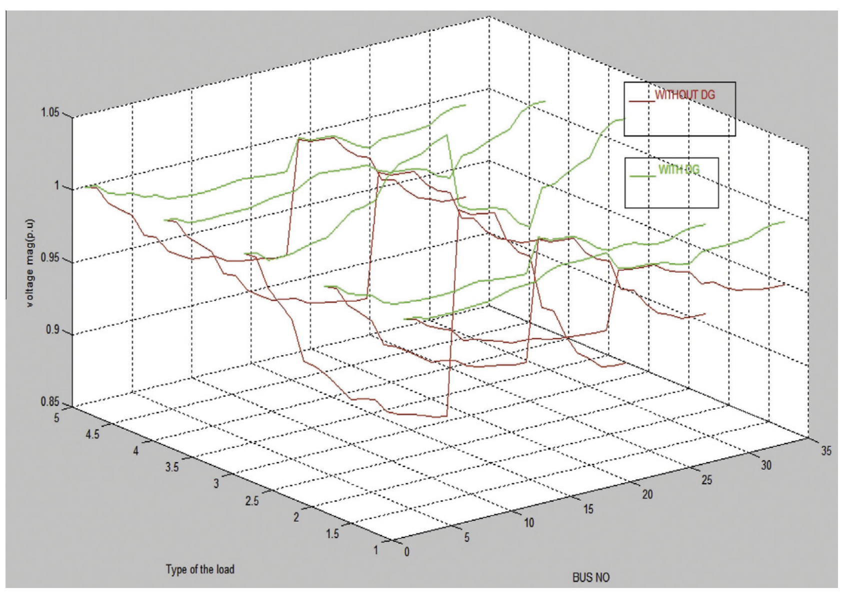

Figure 3 Comparison of voltage magnitude with and without DGs.

has 69 buses, 68 branches with the total real and reactive power load of 3.80 MW and 2.69 MVAr respectively. The power loss of the CP (light), CP (full), CP (heavy), CC, CI, residential, commercial and Industrial systems has been calculated for the base case power flow (without DG). The values obtained are presented in Table 5 and Table 6.

Loss sensitivity factor is used for the placement of the DGs. The bus which has high sensitivity is capable of causing voltage instability. The LSFs of all buses are computed from power flow and then they are arranged in descending order. The first three buses are considered as an optimum places for DGs to be installed. The bus numbers chosen as per LSF are 27, 65 and 61. The DG installation at more than three locations does not result in significant reduction in power loss [23]. The optimum size of the DG is found by using IWO algorithm.

The optimum values of DGs to be installed as determined by the proposed IWO are as shown in the Table. The comparison of these power losses shows that there is a substantial reduction for all loads – light, full and heavy – and different load models. The corresponding percentage loss reduction is shown. Also shown in the Tables is the comparison of the minimum voltage magnitudes, V_{worst} along with its bus number. It is observed that with DG placement the minimum voltage magnitude has improved for all load models. Similar comparison of voltage deviation index, ΔV_D shows its value with DG is lower for all load models. From the values obtained for power loss, V_{worst} and ΔV_D it is proved that IWO is very effective in finding the optimal size of DGs to be installed. Also shown in the Table is the total operating cost, TOC for DGs installed. From Table 5

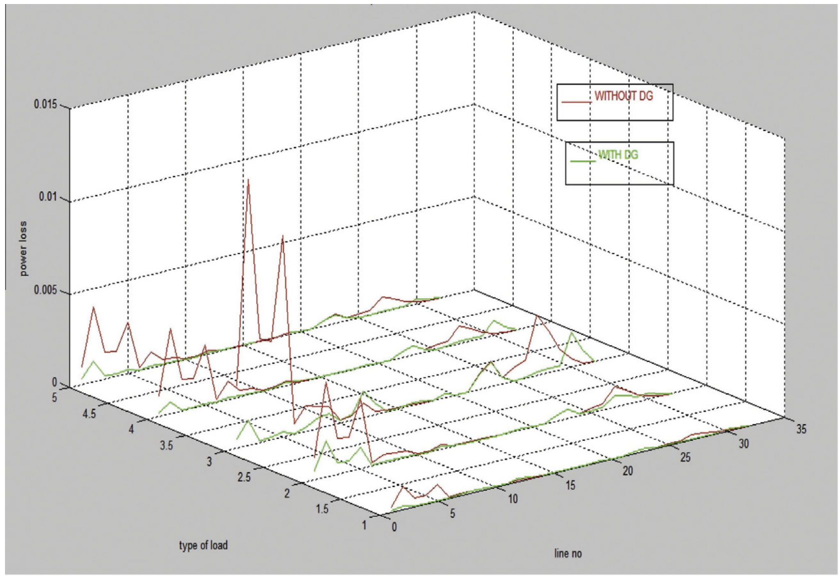

Figure 4 Comparison of line losses with and without DGs.

Table 5 Performance analysis of IEEE-69 bus system for CP and CC load models.

Parameters	CP load						CC load	
	CP (light load)		CP (full load)		CP (Heavy load)			
	Without DG	With DG	Without DG	With DG	Without DG	With DG	Without DG	With DG
DG size (MW) (Bus no.)		0.1000(27)		0.2381(27)		0.4236(27)		0.1746(27)
		0.2925(65)		0.4334(65)		0.5645(65)		0.3795(65)
		0.6334(61)		1.3266(61)		1.7762(61)		1.3890(61)
Power loss (kW)	51.58	7.06	224.59	74.59	647.75	242.87	188.81	27.54
% loss reduction		86.31		66.79		62.51		85.41
ΔPL_{DG}		0.1369		0.3321		0.3749		0.1459
V_{worst} (p.u)	0.9569	0.9937	0.9102	0.9802	0.8482	0.9796	0.9181	0.9872
	(65)	(18)	(65)	(18)	(65)	(17)	(65)	(18)
ΔV_D	0.0155	0.0047	0.032	0.0147	0.053	0.0183	0.0300	0.0101
TOC ($)		5157.74		10288.86		14792.98		9825.66
Computation time (s)		5.03		5.7		4.55		4.3

Table 6 Performance analysis of IEEE-69 bus system for CI, RES, COM and IND load models.

Parameters	CI load		Residential		Commercial		Industrial	
	Without DG	With DG	Without DG	With DG	Without DG	With DG	Without DG	With DG
DG size (MW) (Bus no.)		0.0256(27)		0.3636(27)		0.1152(27)		0.1971(27)
		0.1039(65)		0.3991(65)		0.3509(65)		1.2745(65)
		1.0015(61)		1.3460(61)		1.3548(61)		1.1905(61)
Power loss (kW)	159.26	27.39	165.42	37.37	157.53	33.14	171.80	31.52
% loss reduction		82.80		77.41		78.84		81.65
ΔPL_{DG}		0.1719		0.2259		0.2104		0.1835
V_{worst} (p.u)	0.9252	0.9741	0.9217	0.9944	0.9243	0.9851	0.9195	0.9868
	(65)	(24)	(65)	(50)	(65)	(21)	(65)	(18)
ΔV_D	0.0282	0.0156	0.0289	0.0038	0.0283	0.0084	0.0293	0.0128
TOC ($)		5764.56		10692.98		9237.06		13436.86
Computation time (s)		4.5		3.89		4.8		4.4

it has been observed that the total installed DG is the highest (2.7643 MW) for CP heavy load and it is the least (1.0259 MW) for CP light load. From Table 6 it has been observed that the total installed DG is the highest (2.6621 MW) for industrial load and it is the least (1.131 MW) for CI load.

Table 7 Comparison of IEEE-69 bus system results.

Method	$P_{DG,Tloss}$ (kW)	% Loss reduction	V_{worst} (p.u)(bus)	DG location	DG size (MW)	P_{DGT} (MVA)	Power factor	TOC ($)
GA [19]	89.0	60.44	0.9936(57)	21	0.9297	2.9974	Unity	15343.0
				62	1.0752			
				64	0.9925			
PSO [19]	83.2	63.02	0.9901(65)	61	1.1998	2.9879	Unity	15272.3
				63	0.7956			
				17	0.9925			
GA/PSO [19]	81.1	63.95	0.9925(65)	63	0.8849	2.9880	Unity	15264.4
				61	1.1926			
				21	0.9105			
SA [12]	77.1	65.73	0.9811(61)	18	0.4204	2.1813	Unity	11214.9
				60	1.3311			
				65	0.4298			
BFOA [20]	75.23	66.56	0.9808(61)	27	0.2954	2.0881	Unity	10741.4
				65	0.4476			
				61	1.3451			
IWO	74.59	66.78	0.9802(18)	27	0.2381	1.9981	Unity	10288.86
				65	0.4334			
				61	1.3266			
SA[12]	16.26	92.77	0.9885(61)	18	0.5498	2.3757	0.866	10352.0
				60	1.1954			
				65	0.3122			
BFOA [20]	12.90	94.26	0.9896(64)	27	0.3781	2.3587	0.866	10265.1
				65	0.3285			
				61	1.3361			
IWO	13.64	93.92	0.9946(68)	27	0.3709	2.0520	0.866	8939.56
				65	0.3156			
				61	1.0905			

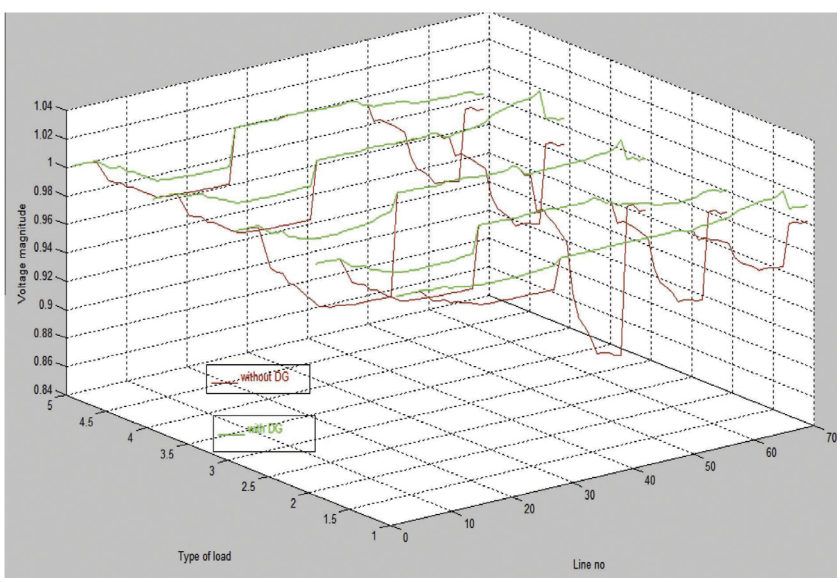

Figure 5 Comparison of voltage magnitude with and without DGs.

6.2.1. Comparison of IEEE-69 bus system results

- The simulated results of IWO are compared with those of genetic algorithm (GA) [19], particle swarm optimization (PSO) [19], combined GA/PSO [19], simulated annealing (SA) [12] and bacterial foraging optimization algorithm (BFOA) [20] in Table 7.
- For validation purpose the test system is simulated with DGs operating at the same power factors of unity and 0.866.

For unity p.f.

- Since IWO is a nature inspired algorithm, performance statistical measures have been implemented. Among the 100 independent runs the TOC obtained by IWO is $

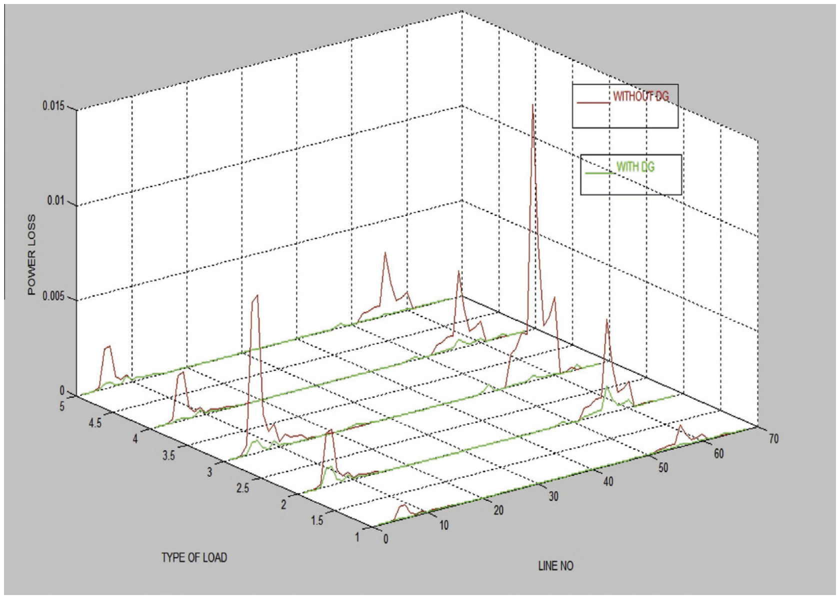

Figure 6 Comparison of line losses with and without DGs.

10288.86. The mean value of TOC is \$ 10289.12. The value obtained by BFOA is \$ 10741.4. This comparison shows a substantial reduction in the operating cost of \$ 452.5. The optimal size of DG is 1.9981 MVA by IWO and 2.0881 MVA by BFOA. The reduction in the operating cost (given by Eq. (11)) is due to reduction in the percentage loss and DG size. Finally, V_{worst} of IWO has also improved.

- From the Table it is observed that the operating cost by IWO is the least of all the methods shown for comparison. The optimal size obtained by DG is the minimum of all other methods. The percentage loss reduction is also the least of all the methods. Also, V_{worst} of IWO has improved compared to other methods.

For 0.866 p.f.

- It has been demonstrated that the IWO algorithm determines the optimal location and size of DGs with increase in percentage power loss reduction, improved voltage stability margin and minimum operating cost.

Voltage profiles and the line losses of IEEE-69 bus systems of various CP (light), CP (full), CP (heavy), CC, CI, residential, commercial and industrial load systems are shown in Figs. 5 and 6. From Fig. 5 it is observed that the voltage profile has improved for all the types of loads after installing the DG. The reduction in the line losses is observed in Fig. 6. This reveals the effectiveness of the proposed algorithm.

7. Conclusion

The proposed method has been tested on IEEE-33 bus and 69 bus systems. The optimal location and optimal size were determined using the LSF and IWO methods respectively. It is also implemented on these systems with different types of loads. The different power factors are also taken into account. The results obtained are compared with those of GA, PSO, GA/PSO, SA and BFOA methods. The value of the ΔV_D for all the load models is near to zero. This indicates that the voltage profile is improved by the placement of DG. The solution obtained using the constant power load models may not be feasible for industrial and commercial loads. Therefore the load model effects have been considered for proper planning of location and size of DGs. The comparisons show that the performance of the proposed multi-objective optimization method on minimization of power loss, enhancement of voltage stability and reduction in TOC with DGs at different power factors is better than the other methods. From the results obtained it can be concluded that the proposed method is highly suitable for determining the placement and size of the DG units in distribution networks.

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