OPTIMAL ALLOCATION OF MULTIPLE DISTRIBUTED GENERATORS IN DISTRIBUTION SYSTEM USING FIREFLY ALGORITHM

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Abstract: *Optimal allocation (sizing and siting) of multiple distributed generators (DGs) in the distribution system is an important issue in recent years. This paper, presents an effective technique for determining the optimal location and sizing of DGs for minimizing power losses, operational costs and improving the voltage profile and voltage stability index of radial distribution system(RDS). The entire problem is divided into two sub problems. First location of DGs is finding out by using the integrated approach loss sensitivity factor (LSF) and voltage stability factor (VSF) concepts. Next the sizes of DGs at these locations are determined by using Meta heuristic technique Firefly Algorithm (FA).The objective function is solved with satisfying equality and inequality constraints of the radial distribution system. The proposed method is implemented on IEEE 33 and 69 bus test systems with considering constant power load at different load levels. The obtained results of the proposed method are compared with other popular methods available in the literature for validation purpose.*

Key words: *Distributed generators (DG), Loss sensitivity factor (LSF), Voltage stability factor (VSF), Firefly Algorithm (FA), Power loss minimization*

1. Introduction

In the entire power system network, the power losses in the distribution system are high compared to the transmission systems because of radial nature and high R/X ratio [1]. Hence loss reduction is the major concern in the distribution system for the power system engineers. Network Reconfiguration, capacitor placement and distributed generation (DG) placement are three important methods for loss reduction in distribution networks. Out of these distributed generation placement is a viable solution to reduce power losses as minimum as possible in the distribution network, because of its unique nature of supplying both real and reactive power to the system. In recent years, the distribution network is treated as active network, because the distributed generators penetration in the distribution system is increased [2].The reasons for this trend is deregulation concept coming into the picture in power system networks.[3, 4].

DG (distributed generation) is a dispersed generation, small scale generation or decentralized generation, i.e. connected to the distribution network directly [3]. The major important aspect of DGs perspective of the distribution system is proper placement and sizing for obtaining maximum potential benefits, i.e. peak load saving, improved voltage stability, reduction of on peak operating cost, and minimizing power losses [5]. Improper allocation of DGs in the distribution system may affect the system in a negative manner that is power loss increases, the voltage profile decreases. So optimal allocation DG units in the distribution network is a challenging issue for researchers working in this field. In recent years, several numerical techniques like Mixed Integer Linear Programming (MILP) [6, 7], Mixed Integer Nonlinear Programming (MINLP) [8], Dynamic Programming (DP) [9], and analytical methods [10, 11] are used to find out the DG allocation problem in the distribution network.

The above mentioned techniques produce promising results and excellent convergence characteristics only if they are used for solving linear problems. The performance of these techniques depends on initial guess. Suppose if this value is not chosen properly, it converges to local solution rather than a global one. Moreover, these techniques are developed based on certain assumptions like differentiability, continuity and convexity which are not applicable for practical, nonlinear and non-differentiable optimization problems. So it is very essential to implement a new meta heuristic technique, which is capable to solve discrete nonlinear optimization problems.

So reduce the above mentioned problems and solve the DG allocation problem effectively with improving the distribution network performance, many search algorithms are used. Genetic Algorithm(GA)[12,13], Particle Swarm Optimization(PSO)[14], Combined GA and PSO[15],Artificial Bee Colony(ABC)[16], Ant Colony System(ACS)[17], Differential Evolution Algorithm(DEA)[18], Simulated Annealing(SA)[19] and Quasi Oppositional Teaching Learning Based Optimization(QOTLBO)[20] are successfully applied to solve DG allocation problem effectively with reducing power losses and improvement of voltage profile in distribution network.

From the above discussion most of the methods have achieved promising results in solving DG allocation problem in distribution systems, but there are certain limitations in terms of computational time, the operating efficiency of the system and the convergence rate of the solution. So it is necessary to reduce these problems a new population based search technique is necessary. In this paper an effective technique based on firefly algorithm is proposed for solving DG allocation in the distribution system. Also, from the literature, it is observed that most of the researchers used DGs with unity power factor in the distribution system and considering constant power load at full load condition only. Also, most of the authors did not consider the operating cost of DGs and achieved good power loss minimization and voltage profile improvement by installing multiple DGs of larger sizes.

This paper proposes an efficient technique to determine the optimal location and sizing of multiple distributed generators in the distribution system. The objectives are to minimize power loss, reducing total operating cost, improving voltage profile and voltage stability index with considering constant power load at different load levels. The entire problem is divided into two steps. The first step is to find out the optimal location of DGs, by applying both Loss Sensitivity Factor (LSF) and Voltage Stability Factor (VSF) concepts. The integrated approach of both LSF and VSF at each bus is determined and these values are form in descending order. Among all these buses, top three buses are considered for DG placement. Next Firefly algorithm, an search based technique is used to reduce the objective function by determining the best sizes of DG units at these locations. The advantage of the proposed method is the search technique firefly algorithm finds only the sizes of DGs not the locations. Due to this it reduces the search space, computational time to reach best solution and convergence characteristics is improved. The novelty of the proposed work is to solve multi objective function, including power loss minimization and total operating cost reduction with reduced DG sizes. Also voltage profile and voltage stability index values are improved up to the desired values. The proposed method is applied to well-known IEEE 33 and 69 bus test systems to check its viability. To check its superiority and validity it is compared with other popular methods.

The remaining sections of the paper are structured as follows: In section 2 problem formulation is explained, Integrated approach of loss sensitivity factor and voltage stability factor concept for finding out the optimal placement of DGs is explained in section 3, In section 4 a firefly algorithm for determining optimal sizing of DGs is explained, numerical results and discussion are explained in section 5 and followed by the conclusion is explained in section 6.

2. Problem formulation

2.1. Load flow analysis

Direct approach of distribution load flow solution is used to find out power loss and voltage corresponding to each branch [21]. The sample distribution system is shown in Fig.1

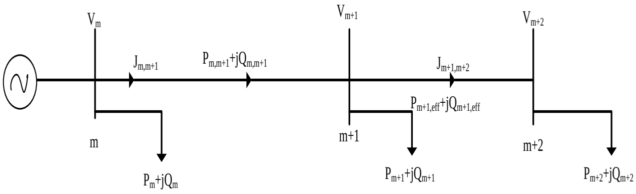

Fig. 1. Sample distribution system

From Fig.1. The voltage corresponding to that bus m+1 is determined by using Kirchhoff's voltage law and it is given by

$$V_{m+1} = V_m - J_{m,m+1}(R_{m,m+1} + jX_{m,m+1}) \tag{1}$$

The current injected at node m is determined and it is given in Eq.(2).

$$I_m = \left(\frac{P_m + jQ_m}{V_m} \right)^* \tag{2}$$

Branch current is determined at the buses m and m+1 by using Kirchhoff's current law and it is given by

$$J_{m,m+1} = I_{m+1} + I_{m+2} \tag{3}$$

The matrix representation of the branch current is given by

$$J = [BIBC][I] \tag{4}$$

The power loss corresponding to the buses m and m+1 is determined from Eq.(5).

$$P_{loss}(m, m+1) = R_{m,m+1} \left(\frac{P^2_{m,m+1} + Q^2_{m,m+1}}{|V_m|^2} \right) \tag{5}$$

The total power loss corresponds to all buses is the summation of losses in all sections which is determined by using Eq.(6).

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

Where b is the total number of branches

2.2. Power loss with placement of DG

Whenever DG units are placed at optimal location it will reduce power loss in a line, improves the voltage profile, voltage stability and peak demand saving. The power loss after placement of DG at corresponding buses m and m+1 can be computed as

$$P_{DG,loss}(m, m+1) = R_{m,m+1} \left(\frac{P^2_{DG,m,m+1} + Q^2_{DG,m,m+1}}{|V_m|^2} \right) \tag{7}$$

The total power loss with placement of DG can be calculated by the summation of the losses in all line sections of the system as follows

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

2.3. Real power loss minimization with DG placement

Power loss index (ILP) is the ratio of total power loss with placement of DG to the total power loss without placement of DG can be written as [22].

$$f_1 = ILP = \left(\frac{P_{DG,Totalloss}}{P_{Totalloss}} \right) \tag{9}$$

The overall amount of power loss can be reduced with placement of DG can be improved by minimizing ILP.

2.4. Operational cost minimization

The advantage of proper location and sizing of DGs is to reduce the total operating cost of the system. The operational cost of DISCOs consisting of two components. The first cost is the real power supplied from the substation. Whenever reducing the power losses in a system this cost can be minimized. The second cost is the cost of real power supplied by the installed DGs. Whenever real power drawn from DGs is reduced this cost is minimized. So total operating cost is minimized that is given as [23]

$$TOC = (C_1 P_{DG,Totalloss}) + (C_2 P_{DGT}) \tag{10}$$

Where C_1 and C_2 are the cost coefficients of real power supplied by substation and DGs in \$/kW. P_{DGT} is the total real power drawn from connecting DGs. The net operating cost of DG reduced is calculated as [23].

$$f_2 = \Delta OC = \frac{TOC}{C_2 P_{DGT}^{\max imum}} \tag{11}$$

Thus the total operating cost is minimized by minimizing the total power losses of the system and the total size of DG connected.

2.5. Voltage deviation index (IVD)

When the distributed generators are placed optimally in the distribution system, it improves the voltage profile of this system. This is given by voltage deviation index concept.

The voltage deviation index of the system can be defined as [22].

$$f_3 = IVD = \max \left(\frac{V_1 - V_m}{V_1} \right) \quad \forall m = 1, 2 \ldots.. n \tag{12}$$

During placement of DG in the system which gives higher voltage deviations from the actual value, the proposed technique minimizes the IVD closer to zero and improves voltage stability of the system.

2.6. Voltage stability index

It is very important to operate the power system in the safe and secured region under heavy load conditions, otherwise there is a possibility of voltage collapse. So it is very important to calculate the voltage stability index value under these conditions that is derived by Chakravorty and Das [24]. In this concept they are identifying the nodes at which has more voltage collapse in the system.

A sample two bus system with respective voltage magnitudes, power at receiving end bus and current flowing through the branch is given by Fig.2.

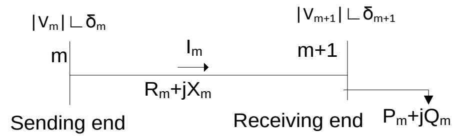

Fig.2. Two bus system

The voltage stability index value at receiving end bus m+1 is calculated from load flow that is given by Eq. (13).

$$VSI(m+1) = |V_m|^4 - 4[P_{m+1,eff} * X_m - Q_{m+1,eff} * R_m]^2 - 4[P_{m+1,eff} * R_m + Q_{m+1} * X_m]|V_m|^2 \tag{13}$$

For safety and secured operation of power system, it is better to maintain the high value of voltage stability index value that is given by Eq. (14).

$$f_4^{'} = \max(VSI(m+1)) \tag{14}$$

For minimization problem, the objective function is represented below

$$f_4 = \left(\frac{1}{f_4^1} \right) \tag{15}$$

2.7. Formulation of objective function and constraints:

Great attention should be paid to the proper formulation of the objective function (OF). In this method the objectives are to reduce the power loss index, voltage deviation index, total operating cost and improve voltage stability index of the system.

$$MinimizeOF = \min(\sigma_1 f_1 + \sigma_2 f_2 + \sigma_3 f_3 + \sigma_4 f_4) \tag{16}$$

Where

$$\sum_{q=1}^{4} \sigma_q = 1.0 \wedge \sigma_q \in [0,1] \tag{17}$$

In this multi objective function high priority is given to power loss index, total operating cost, and than voltage deviation index, voltage stability index. Accordingly the weights assigned in the objective function are 0.6, 0.3, 0.2 and 0.1 respectively. The objective function minimization should satisfy all the constraints related to respective electrical distribution network are discussed as follows.

Power balance constraints

$$\sum_{m=2}^{n} P_{DG,m} \le \sum_{m=2}^{n} P_m + \sum_{m=1}^{b} P_{lossm,m+1} \tag{18}$$

Voltage drop constraints

$$\left|V_1 - V_m\right| \le \Delta V_{\max} \tag{19}$$

Thermal limits

$$\left|J_{m,m+1}\right| \le \left|J_{m,m+1,\max}\right| \tag{20}$$

Distributed generation capacity limits

$$P_{DGT}^{\min imum} \le P_{DGT} \le P_{DGT}^{\max imum} \tag{21}$$

Where

$$P_{DGT}^{\min imum} = 0.1\sum_{m=2}^{n} P_m \quad and \quad P_{DGT}^{\max imum} = 0.6\sum_{m=2}^{n} P_m \tag{22}$$

If all the constraints are satisfied, then only the resultant solution is accepted otherwise it should be rejected.

3. Initial identification of DG placement using an integrated approach of LSF and VSF

Loss sensitivity factor (LSF) concept decides the buses needs for compensation or placement [25]. The LSF may decide the buses which have a considerable loss reduction in terms of active and reactive power injections are put in place. From the system shown in Fig.1.The LSF corresponding to the buses m and m+1 can be determined by using Eq. (23).

$$LSF(m, m+1) = \frac{\partial P_{lineloss}}{\partial P_{m+1,eff}} = \frac{2P_{m+1,eff} R_{m,m+1}}{\left|V_{m+1}\right|^2} \tag{23}$$

Again calculate the voltage magnitude of buses by using recently proposed voltage stability factor (VSF) concept [26]. This concept identified the weak buses in terms of voltage values in the entire search space and also gives good information about the system stability.

The voltage stability factor corresponds to the bus is determined by using Eq.(24). [26].

$$VSF_{m+1} = 2V_{m+1} - V_m \tag{24}$$

Finally the combined effect of both loss sensitivity factors and voltage stability factor concepts identified the weak buses properly for DG placement. Also the advantage of this method is to reduce the search space for optimization procedure. The optimal sizes at these identified locations are found out by using Firefly Algorithm.

4. Firefly Algorithm

Firefly algorithm (FA) is a recent Meta heuristic algorithm developed by Yang [27]. The concept of this algorithm is based on flashing signals produced by the fireflies. For easy implementation and understanding of firefly algorithm three standard rules are used [27].

1) All fireflies are unisexual and attracted the other fireflies irrespective of their sex.

2) Attractiveness function is proportional to the brightness and it decreases as the distance increases. Firefly with less brighter one attract the brightest one, if there is there is no brighter one nearer to this it will move randomly.

3) The brightness of firefly is associated with the objective function to be optimized.

According to the above rules firefly algorithm is represented in the form of pseudo code [27].

The objective function solved is mainly associated with the brightness of firefly [28]. The light intensity I(r) varies with the distance r and it obeys inverse square law that is given in Eq. (25).

$$I(r) = \frac{I_s}{r^2} \tag{25}$$

Where Is is the light intensity at the source.

Also light intensity I(r) varies with distance r monotonically and exponentially that is given in Eq. (26).

$$I(r) = I_0 e^{-\gamma r} \tag{26}$$

Where γ is the light absorption coefficient and I_0 is the original light intensity.

As a firefly's attractiveness is proportional to the light intensity seen by adjacent fireflies, the attractiveness β is defined by

$$\beta = \beta_0 e^{-\gamma r^2} \tag{27}$$

Where β_0 is the attractiveness at r=0

The distance between any two fireflies i and j at x_i and x_j is calculated as

$$r_{ij} = \| x_i - x_j \| = \sqrt{\sum_{k=1}^{d} (x_{i,k} - x_{j,k})^2} \tag{28}$$

In each generation every firefly is attracted towards the brighter firefly that is given by Eq. (29).

$$x_i = x_i + \beta_o e^{-\gamma r_{ij}^2}(x_j - x_i) + \alpha(rand - 0.5) \quad (29)$$

Where α is the randomization parameter and "rand" is a random number generator uniformly distributed in [0, 1].

4.1. Implementation of the Firefly algorithm to determine the optimal sizes of DGs and objective function minimization

Step1: Read the system data which include branch number, sending bus, receiving bus, resistance and reactance of the line, real and reactive power for each bus.

Step2: Run the load flow

Step3: Identify the optimal location of DGs using an integrated approach of LSF and VSF, from load flow the LSF and VSF of each bus is calculated by using Eq.(23). and Eq.(24).

Step4: Firefly Algorithm parameters are initialized, i.e. n, $iter_{max}$,α, β_{min}, γ, X_{min}, X_{max} [27].

Step5: Firefly algorithm is used to find out optimal sizes of DGs, and each firefly corresponds to occupy the candidate node location.

Step6: The attractiveness is proportional to light intensity that represents the optimal values of DG sizes that is determined from Eq. (27).

Step7: firefly with less brighter one i.e. i is attracted to another more brighter firefly j for best value of DG size is determined by using Eq. (28).

Step8: For updated light intensity evaluate the new solutions, i.e. best values of DG sizes.

Step9: Rank the fireflies by their light intensity and determined their optimal DG sizes.

Step 10: Repeat steps 4-8 until maximum iterations is reached.

5. Results and simulations

To test the validity of proposed method it is applied to IEEE 33 and 69 bus test systems for solving the corresponding objective function containing power loss index (ILP), total operating cost (TOC), voltage deviation index minimization and improving voltage stability index. In this multi objective function high priority is given to the power loss, total operating cost minimization, and then voltage profile, voltage stability improvement. Accordingly the weighting factors $\sigma_1, \sigma_2, \sigma_3$ *and* σ_4 used in the objective function are taken as 0.6, 0.3, 0.2 and 0.1 respectively, where $\sigma_1 + \sigma_2 + \sigma_3 + \sigma_4 = 1$. In the simulation, different test systems considering constant power load (CP) with different load levels are taken. The highest number of DGs confined to given test systems is three. Actually the number of DGs connected to given test systems prominently depends upon the size of the test system. Inserting more number of DGs in the given test system increases the power losses and TOC [29, 30]. To check the effectiveness and preeminence of the proposed method, the DGs operates at different power factors are simulated. The parameters selected for the firefly algorithm (FA) are same for both the test systems that are indicated in the Table1. The proposed method is implemented in MATLAB environment.

5.1. Test case1: 33-bus test system

The first test system used is 33 bus system with a total load of 3720 kW and 2300 kVAr respectively, data related to this test system is taken from [31]. The base case power losses are calculated from load flow by considering the constant power (CP) load at different load levels, i.e. half load (0.5), full load (1.0) and heavy load (1.6). The obtained values for these load levels are 48.78kW, 210.98kW, 603.36kW respectively. From the load flow, using an integrated approach of LSF and VSF concepts, identifies the weak buses properly for DG installation i.e. 13, 17 and 31. The optimal DG sizes at these installed locations are determined by Firefly Algorithm (FA). The optimal DG sizes at these determined locations, power loss index, percentage power loss reduction and total operating cost with placement of DG are tabulated in Table 2. The minimum voltage magnitude, power losses, voltage stability index and voltage deviation index with and without placement of DG are also given in Table2. From Table 2 it is noticed that power loss is reduced effectively after placement of DGs at all load levels. Also voltage stability index, minimum voltage magnitude and voltage deviation index values are improved effectively with placement of DGs at different load levels. Also voltage profile at all buses without and with placement of DGs is shown in Fig.3. From Fig.3. It is clear that voltage profile at all buses is improved effectively after optimal placement of DGs.

Table 1

FA parameters [27]

Parameters	Value
No of Fireflies	20
$iter_{max}$	50
α (scaling parameter)	0.25
β_{min} (attractiveness)	0.2
γ (absorption coefficient)	1

Table2
Performance analysis of proposed method at all different load levels for 33 bus test system

Item	CP load					
	Half load(0.5)		Full load(1.0)		Heavy load(1.6)	
	Without placement of DG	With placement of DG	Without placement of DG	With placement of DG	Without placement of DG	With placement of DG
Optimal DG size(kW) (bus)		140.5(13) 262.0(17) 494.2(31)		623.1(13) 261.3(17) 1012.0(31)		994.9(13) 424.7(17) 1672.9(31)
Power loss(kW)	48.78	21.68	210.98	87.83	603.36	235.33
% Reduction of power loss		55.55		58.37		60.99
ILP		0.4444		0.4162		0.3990
VSI_{min}(p.u.)	0.8251	0.9386	0.6610	0.8820	0.4785	0.8132
$V_{minimum}$(p.u) (bus)	0.9540(18)	0.9842(30)	0.9038(18)	0.9695(30)	0.8360(18)	0.9510(29)
IVD	0.0460	0.0158	0.0962	0.0305	0.1640	0.049
TOC($)		4570.22		9833.32		16403.32
Computational time(s)		0.44		0.46		0.52

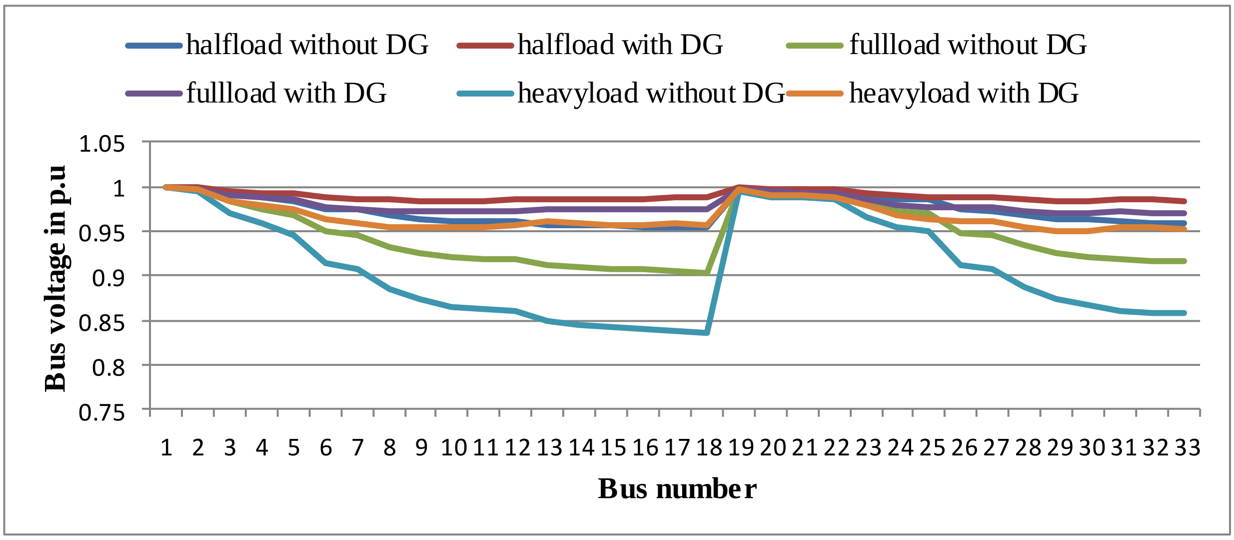

Fig.3. Comparison of node voltage profile at all load levels for 33 bus test system

From Table2, Fig.3. It is clear that the proposed method is more efficient in finding out the optimal allocation of DGs with improving power loss index(ILP), voltage deviation index(IVD), voltage stability index(VSI) and reducing the total operating cost of the system with less computational time.

To validate the effectiveness of the proposed method with DGs operating at two different power factors, i.e. unity and 0.866 are considered. First the obtained results of Firefly Algorithm (FA) with DGs operating at unity power factor are compared with the results of popular methods , i.e. GA, PSO, GA/PSO, QOTLBO and BFOA. The parameters selected for GA, PSO, GA/PSO, QOTLBO and BFOA are the same as in [15, 20, 23]. The obtained results are given in Table 3. From Table 3 it is clearly observed that TOC minimization and percentage power loss reduction of Firefly Algorithm (FA) method are improved significantly with reduced DG sizes compared to all other classical algorithms.

Next the proposed method with DGs operating at 0.866 power factor is simulated and the obtained results are tabulated in Table 4. From Table 4 it is clearly observed that total operating cost reduction and power

Table 3
Comparison and performance analysis of 33 test system at unity power factor

Method	GA [15]	PSO [15]	GA/PSO [15]	QOTLBO [20]	BFOA [23]	**FA**
Optimal location of DG (kW)	11 29 30	13 32 8	32 16 11	13 26 30	14 18 32	**13** **17** **31**
Optimal size of DG (kW)	1500 422.8 1071.4	981.6 829.7 1176.8	1200 863 925	1083.4 1187.6 1199.2	652.1 198.4 1067.2	**623.1** **261.3** **1012**
Total DG size (KVA)	2944.2	2988.1	2988	3470.2	1917.7	**1896.4**
$P_{DG,totalloss}$ (kW)	106.30	105.35	103.409	103.409	89.90	**87.83**
%Reduction of power loss	49.61	50.06	50.99	50.99	57.38	**58.37**
V_{minmum}(p.u.)(bus)	0.9809(25)	0.9806(30)	0.9808(25)	0.9827(25)	0.9705(29)	**0.9695(30)**
VSI_{min}(p.u.)	0.9173	0.9172	0.9169	0.9240	0.8916	**0.8820**
TOC($)	15396.2	15361.9	15353.6	17764.6	9948.1	**9833.2**

Table 4
Comparison and performance analysis of 33 test system at 0.866 power factor

Method	BFOA [23]	**FA**
Optimal location of DG (kW)	14 18 32	**13** **17** **31**
Optimal size of DG (kW)	679.8 130.2 1108.5	**757.1** **149.7** **964.8**
Optimal size of DG (KVAr)	392.2 75.17 639.6	**437.1** **86.43** **557.1**
Total DG size (KVA)	2215.3	**2161.7**
$P_{DG,totalloss}$ (kW)	37.85	**36.86**
%Reduction of power loss	82.06	**82.52**
V_{minmum}(p.u.)(bus)	0.9802(29)	**0.9792(25)**
VSI_{min}(p.u.)	0.9114	**0.9106**
TOC($)	9743.9	**9505.44**

loss reduction of FA method is improved effectively compared to the BFOA method with reduced DG sizes. Also voltage stability index and minimum voltage magnitude values are nearly same as compared to the BFOA method. From the above discussion firefly algorithm based method is more accurate in finding out the optimal solutions with maximum power loss reduction and improved voltage stability and reduced net operating cost.

The statistical analysis of the proposed method on 33 bus test with other methods is shown in Fig.4. It is observed that classical methods GA, PSO, GA/PSO and QOTLBO reduce the voltage deviation index and also improves the voltage stability index in an effective manner. But power loss index and net operating cost are very high compared to the FA method. Next comparison of proposed with BFOA method, the net operating cost and power loss index values are less in FA method. Also voltage stability index and the voltage deviation index is nearly same as BFOA method. From the observed results it is clear that the proposed method is accurate in finding the best solution.

Heuristic methods are easy to implement and best suited for solving nonlinear systems, but they intrinsically have considerable convergence and optimality issues. So it is very important to check the convergence ability of firefly algorithm.

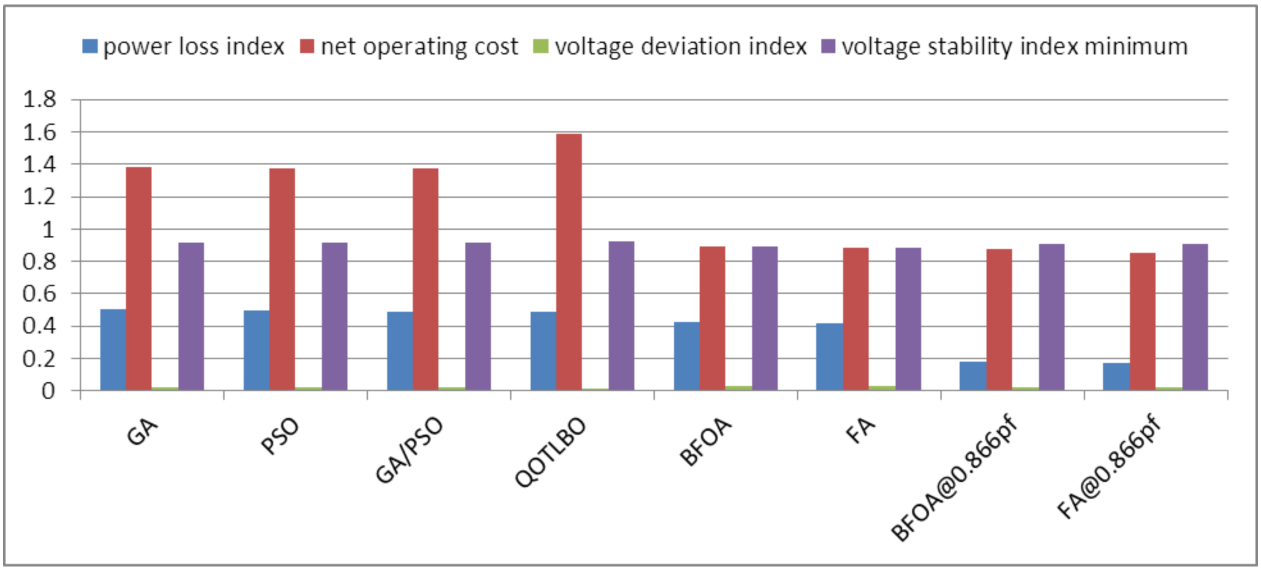

Fig.4. Statistical comparison and performance analysis of proposed method with other methods

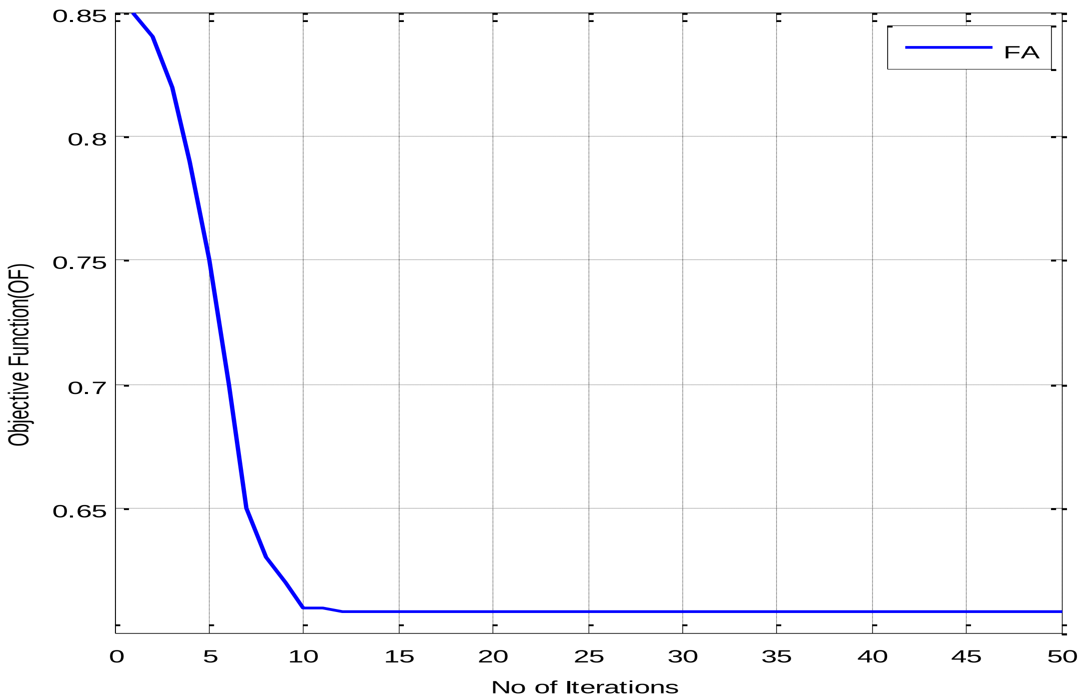

Fig.5. Convergence characteristics of objective function for 33 bus system

The convergence characteristics of FA with the solving corresponding objective function of this test system are shown in Fig.5. It is observed that firefly algorithm converges to the best solution with reduced objective function (OF) only in 14 iterations. Also, Firefly algorithm shows very quick convergence ability in finding the optimal DG sizes in the entire search space.

5.2. Test case2: 69- bus test system

The second test system used is 69 bus system with the load of 3800kW and 2690kVAr respectively, and data related to this test system is taken from [31]. The base case power losses are calculated from load flow by considering the constant power (CP) load at different load levels, i.e. half load (0.5), full load (1.0) and heavy load (1.6). The obtained values for these load levels 51.59kW, 224.98kW and 652.42kW respectively.

Table5
Performance analysis of proposed at different load levels for 69 bus test system

Item	CP load					
	Half load(0.5)		Full load(1.0)		Heavy load(1.6)	
	Without placement of DG	With placement of DG	Without placement of DG	With placement of DG	Without placement of DG	With placement of DG
Optimal DG size(kW) (bus)		692.1(61) 192.2(64) 195.3(27)		1142(61) 542(64) 366(27)		1435.4(61) 1386.1(64) 636.6(27)
Power loss(kW)	51.59	17.99	224.98	74.43	652.42	199.21
% Reduction of power loss		65.12		66.91		69.46
ILP		0.3487		0.3308		0.3053
VSI_{min}(p.u.)	0.8372	0.9606	0.6822	0.9100	0.5066	0.8693
$V_{minimum}$(p.u) (bus)	0.9567(65)	0.9903(65)	0.9092(65)	0.9775(61)	0.8445(65)	0.9672(61)
IVD	0.0433	0.0097	0.0908	0.0225	0.1555	0.0328
TOC($)		5469.96		10547.72		18087.34
Computational time(s)		2.99		3.08		3.11

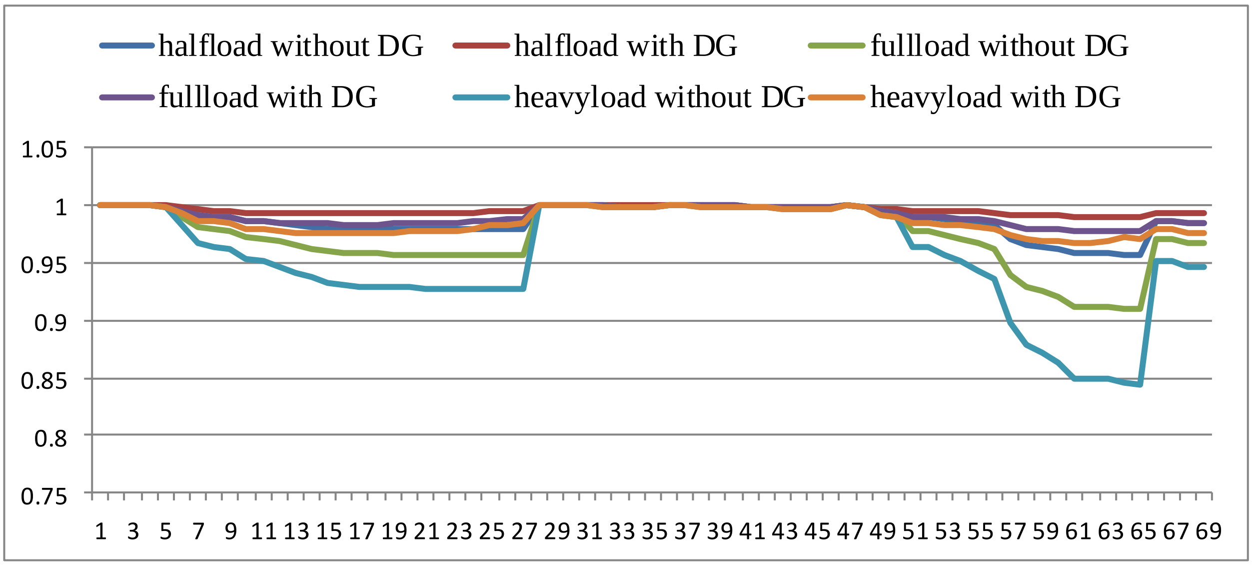

Fig.6. Comparison of node voltage profile at all load levels for 69 bus test system

The integrated approach of loss sensitivity factor (LSF) and voltage stability factor (VSF) concepts, identifies the weak buses properly for DG placement, the candidate buses selected for DG placement are 61, 64 and 27 and optimal DG sizes at these determined locations are calculated by FA method with less computational time.

The proposed method effectiveness is checked with considering constant power load at different load levels. The optimal DG sizes at these determined locations, power loss index, percentage power loss reduction and total operating cost with placement of DG are tabulated in Table 5. The total power loss, minimum voltage magnitude, voltage stability index and voltage deviation index with and without placement of DGs are also given in Table5. From Table 5 it is noticed that power loss is reduced effectively after placement of DGs at all load levels. Also voltage stability index, minimum voltage magnitude and voltage deviation index values are improved effectively with placement of DGs at different load levels.

Table 6
Comparison and performance analysis of 69 test system at unity power factor

Method	GA[15]	PSO[15]	GA/PSO[15]	QOTLBO[20]	BFOA[23]	FA
Optimal location of DG (kW)	21 62 64	61 63 17	63 61 21	15 61 63	61 65 27	**61** **64** **27**
Optimal size of DG (kW)	929.7 1075.2 992.5	1199.8 795.6 992.5	884.9 1192.6 910.5	811.4 1147 1002.2	1345.1 447.6 295.4	**1142** **542** **366**
Total DG size (KVA)	2997.4	2987.9	2988	2960.6	2088.1	**2050**
$P_{DG,totalloss}$ (kW)	89.00	83.20	81.10	80.58	75.23	**74.43**
%Reduction of power loss	60.44	63.02	63.95	64.14	66.56	**66.90**
V_{minmum}(p.u.)(bus)	0.9936(57)	0.9901(65)	0.9925(65)	0.9945(65)	0.9808(61)	**0.9775(61)**
VSI_{min}(p.u.)	0.9585	0.9554	0.9585	0.9585	0.9223	**0.9100**
TOC($)	15343.0	15272.3	15264.4	15125.3	10741.4	**10547.7**

Table7
Comparison and performance analysis of 69 bus test system at 0.866 power factor

Method	BFOA [23]	FA
Optimal location of DG (kW)	61 65 27	**61** **64** **27**
Optimal size of DG (kW)	1336.1 328.5 378.1	**1325** **350** **358**
Optimal size of DG (KVAr)	771.3 189.6 218.2	**765.1** **202.09** **206.71**
Total DG size (KVA)	2358.5	**2347.5**
$P_{DG,totalloss}$ (KW)	12.90	**12.99**
%Reduction of power loss	94.26	**94.22**
V_{minmum}(p.u.)(bus)	0.9896(64)	**0.9895(68)**
VSI_{min}(p.u.)	0.9586	**0.9580**
TOC($)	10265.1	**10216.9**

Also voltage profile at all buses without and with placement of DGs is shown in Fig.6. From Fig.6. The voltage profile at all load levels is improved effectively after optimal placement of DGs. From Table5 and Fig.6. It is clear that the proposed method improves the voltage profile and reduce the power losses effectively at all load levels after placement of DGs.

The performance of the proposed method with DGs operating at unity and 0.866 power factor are simulated. First the performance of the FA method with optimal placement of DGs at unity power factor is simulated and the obtained results are tabulated in Table 6. The results obtained by the FA method are compared with the other popular methods, i.e. GA, PSO, GA/PSO, QOTLBO and BFOA. The results clearly show that proposed method reduces the total operating cost and power losses effectively with reduced DG sizes compared to all other methods. Even though the voltage stability index and voltage profile values are improved effectively with GA, PSO, GA/PSO and QOTLBO methods, but the power loss reduction less and total operating cost is very high compared to FA method.

In the same manner the proposed method with DGs operating at 0.866 power factor is simulated and obtained results are tabulated in Table 7. From Table 7 it is observed that FA method reduces the power loss nearly same as BFOA method with reduced DG sizes. Also minimum voltage stability index values and voltage profile values are improved effectively for the proposed method. From the above discussion, it is clear that the proposed method reduces the power losses and total operating cost effectively with reduced DG sizes. Also maintains good voltage profile and voltage stability index values.

6. Conclusion

This paper proposes an integrated approach of loss sensitivity factor and voltage stability factor concepts to identify the optimal locations of DGs. At these identified locations the optimal size is determined using firefly algorithm. The proposed technique is implemented on IEEE 33 and 69 bus test systems. Implementation considering constant power load at different load levels is an added advantage. DGs operating at different power factors are considered that is unity and 0.866. The obtained results of the proposed method are compared with other popular methods, i.e. GA, PSO, combined GA/PSO, QOTLBO and BFOA methods. The results clearly indicate that the proposed method reduces power losses, total operating cost with reduced DG sizes compared to all other classical methods. Also voltage deviation index and voltage stability index values are effectively improved with the proposed method. From the obtained results, it is clear that optimal DG sizes at optimal locations reduces power losses, TOC and improves the voltage profile and voltage stability index values at all load levels. Also, it was clearly observed that power loss reduction, voltage profile and voltage stability index values are improved effectively with optimal placement of DGs at 0.866 power factor. So it can be concluded that the proposed method gives optimal solutions in terms of reducing objective function compared to the all other classical methods.

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