Ain Shams Engineering Journal (2016) 7, 959–971

Ain Shams University

Ain Shams Engineering Journal

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ELECTRICAL ENGINEERING

Optimal size and siting of multiple DG and DSTATCOM in radial distribution system using Bacterial Foraging Optimization Algorithm

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Received 6 February 2015; revised 29 June 2015; accepted 4 July 2015
Available online 18 August 2015

KEYWORDS

Bacterial Foraging Optimization Algorithm;
Loss sensitivity factor;
Power loss minimization;
Voltage profile index;
Distribution system

Abstract In this paper, a novel approach to determine the optimal location and sizing of Distribution Generation (DG) and Distribution STATic COMpensator (DSTATCOM) is analyzed, and the objective function is formulated for minimizing power loss, operational costs and voltage profile enhancement of the system subjected to equality and in equality constraints. Loss sensitivity factor (LSF) is used to pre-determine the optimal location of DG and DSTATCOM. The Bacterial Foraging Optimization Algorithm (BFOA) is proposed to determine the optimal size of the DG and DSTATCOM. In this paper, the DG and DSTATCOM are simultaneously allocated in radial distribution system and it is analyzed with different load models. To check the feasibility, the proposed method is tested on IEEE 33-bus and 119-bus radial distribution system and the results were compared with other existing technique.

1. Introduction

It is estimated that the 13% of the total power generation is dissipated as I^2R loss in the distribution system [1,2]. The majority of the distribution network loads are inductive in nature. So the network power factor will be lagging in nature. It leads to poor voltage profile, power loss may increase and at last the network security level will come down. In order to avoid such things, it is advised to place the compensation device in the distribution system. In this paper, the DG and DSTATCOM are used as a compensation device in the distribution system. DG is defined as electricity generation with limited size generator connected to the distribution system. Several factors have been responsible for the appearance of DG in radial distribution system. The environment issues such as to reduce the greenhouse effect, running down of fossil fuel and also current scenario is deregulation of electricity market that recommends the requirement for more flexible electric systems. The research shows that the placement of DG in distribution system will lead to the enhancement of voltage profile, reduction in power loss, increase in the system security level, etc. The shunt connected DSTATCOM is used to

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Peer review under responsibility of Ain Shams University.

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http://dx.doi.org/10.1016/j.asej.2015.07.002
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Nomenclature

P_{Lm}	real power load at bus m
P_m	real power flowing out of bus m
$P_{m+1,eff}$	total effective real power load fed through the bus $m+1$
I_m	equivalent current injected at node m
R_m	resistance of the line section between buses m and $m+1$
$P_{loss}(m, m+1)$	real power loss in the line connecting buses m and $m+1$
n	total number of buses
nb	total number of the branches
Q_{Lm}	reactive power load at bus m
Q_m	reactive power flowing out of bus m
$Q_{m+1,eff}$	total effective reactive power load fed through the bus $m+1$
V_m	voltage magnitude at bus m
X_m	reactance of the line section between m and $m+1$
$P_{T,Loss}$	total power loss of the system
$V_{m,\min}$	minimum voltage limits at bus m
$V_{m,\max}$	maximum voltage limits at bus m
$P_{cm}^{\min}$	minimum real power limits of compensated bus m
$P_{cm}^{\max}$	maximum real power limits of compensated bus m
$Q_{cm}^{\min}$	minimum reactive power limits of compensated bus m
$Q_{cm}^{\max}$	maximum reactive power limits of compensated bus m
$\Delta P_{TL}^{DG/DST}$	net power loss reduced by DG/DSTATCOM
$P_{T,loss}^{DG/DST}$	total power loss of the system with DG/DSTATCOM
$P_{DG/DST}$	Power supplied from DG/DSTATCOM

improve the voltage profile, power factor and voltage stability of the system [3]. The researchers developed many methods for optimal location and sizing of DG in distribution system. In [4–6] they combined both the location and sizing in one Optimization algorithm. Their objective was to reduce the investment cost, operating cost, power costs, etc. In [7], the author used analytical approach to determine the optimal size of DG with the objective of power loss reduction. The researchers in [8–10] analyzed the optimal location and sizing of a single DG, whereas others [11–13], analyzed the optimal location and sizing with multiple DG. Linear programming is introduced in [14], and it is easy to implement, but very difficult to reduce the models into a set of linear equations. In [15] the authors used analytical method to determine the optimal location and sizing of DG, but it failed to give the optimal size. The authors in [16] used approximate loss formula to determine the optimal location and the analytical approach was used to find the optimal size. Due to the difficulty arise from the analytical methods, meta-heuristic techniques had been introduced and used widely to solve the allocation of compensating devices. In [17] the determination of location and sizing of DG are carried out by using Bee Colony Algorithm, in which they tried to minimize the power loss. In [18] integrated approach based on improved PSO and Monte Carlo simulation are carried out for the allocation of DG to enhance the voltage stability of the system. The author in [19] used GA algorithm for the allocation of DG for the sake of system reliability. The honey Bee Mating Optimization Algorithm [20] had been used to determine the optimal size of DG with objective to reduce the energy cost and decrease voltage deviations. The Quasi-oppositional teaching learning based optimization was used to determine the optimal location and size of multiple DG with a multi-objective function [21]. Backtracking search optimization algorithm was used to determine the optimal location and size of DG with optimal power factors [22]. In [3], the author used immune algorithm to determine the optimal location and sizing of DSTATCOM in distribution system with the multi-objective of decreasing the total power loss, size of installing capacity of DSTATCOM and maintaining voltage and current of network in desired boundaries.

All the above researchers focused only on the optimization of either DG or DSTATCOM placement. However the objective was to minimize the power loss only. To benefit the entire distribution system effectively, it is necessary to integrate both DG and DSTATCOM in the distribution system with an objective of minimizing power loss, operational costs and the voltage profile enhancement of the system.

The present work is aimed to develop a fast and new technique to determine the optimal location and sizing of DG and DSTATCOM for minimizing the power loss and voltage profile index in the radial distribution system with different load models. The initial location of the DG and DSTATCOM is identified by using LSF. However, the final optimal location will be decided by using BFOA. Bacterial Foraging Optimization Algorithm is used to determine the optimal size of the DG and DSTATCOM. The novelty of this work is implementing an integrated approach of LSF and BFOA to determine the optimal location and sizing of DG and DSTATCOM for the sake of minimizing power loss, operational cost and voltage profile enhancement. Another advantage of this work is that the DG and DSTATCOM are placed simultaneously in the radial distribution system. The proposed method has been tested on radial distribution system and the results are tabulated. In order to show the effectiveness of the proposed method, the results obtained by the proposed method are compared with the other existing technique.

2. Problem formulation

2.1. Load flow analysis

The direct approach for distribution system load flow solution is used to find the power loss and also the voltage at each branch [23]. The single line diagram of a sample distribution system is shown in Fig. 1.

The voltage at node $m+1$ is given by

$$V_{m+1} = V_m - J_m * (R_m + jX_m) \quad (1)$$

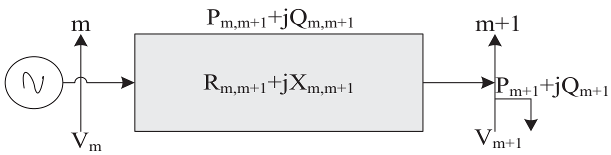

Figure 1 Sample distribution system.

The branch current at each line can be calculated in a matrix form as follows:

$$J = [BIBC] * [I] \tag{2}$$

where BIBC is the Bus current Injection to Branch Current matrix.

$$i_m = \frac{(P_{Lm} + jQ_{Lm})^*}{V_m} \tag{3}$$

The real and reactive power loss in the line section between buses m and $m + 1$ is calculated by using the following equation:

$$P_{loss}(m, m+1) = \left(\frac{P_m^2 + Q_m^2}{|V_m|^2}\right) * R_m \tag{4}$$

$$Q_{loss}(m, m+1) = \left(\frac{P_m^2 + Q_m^2}{|V_m|^2}\right) * X_m \tag{5}$$

The total real power loss of the system can be easily found by summing all the branch power losses and it is expressed in Eq. (6) as follows:

$$P_{T,Loss} = \sum_{m=1}^{nb} P_{Loss}(m, m+1) \tag{6}$$

2.2. Power loss reduction using DG/DSTATCOM placement

The net power loss reduced by DG/DSTATCOM placement is taken as the ratio of total power loss before and after DG/DSTATCOM placement of the system, and is given by

$$\Delta P_{TL}^{DG/DST} = \frac{P_{T,loss}^{DG/DST}}{P_{T,Loss}} \tag{7}$$

Net power loss reduced by DG/DSTATCOM placement in the system can be maximized by minimizing $\Delta P_{TL}^{DG/DST}$.

2.3. Voltage profile index

If the DG and DSTATCOM are placed optimally, it results in improving the voltage profile of the system. Suppose the index is closer to zero, then the network will operate in safe mode. The Voltage profile index [24] is given by,

$$\Delta V_D = \max\left(\frac{V_1 - V_m}{V_1}\right) \tag{8}$$

where V_1 is the voltage at the generating station (V_1 = 1.0 p.u.).

It is advised to keep the index value as small as possible to achieve the better voltage profile.

2.4. Voltage stability index

There are many indices which are used to check the power system security level. In this section, a new steady state voltage stability index is used to identify the node, which has more chance to voltage collapse [15,16]. In order to attain the stable operation of the radial distribution system, the voltage stability index (VSI) should be $m \geqslant 0$. The voltage stability at each node is calculated by using Eq.(9) as follows:

$$VSI(m+1) = |V_m|^4 - 4[P_{m+1,eff} * X_m - Q_{m+1,eff} * R_m]^2 - 4[P_{m+1,eff} * R_m + Q_{m+1} * X_m]|V_m|^2 \tag{9}$$

2.5. Operational cost minimization

The operational cost of DISCOs is divided into two components. The first term is the cost of real power supplied from the substation. This can be minimized by minimizing the total power loss of the system [1]. The second term is the cost of real/reactive power supplied by the DG/DSTATCOM installed. This cost can be minimized by minimizing the amount of real/reactive power drawn from DG/DSTATCOM. Thus the total operating cost can be expressed as

$$TOC = (c_1 P_{T,loss}^{DG/DST}) + (c_2 P_{DG/DST}) \tag{10}$$

where c_1 and c_2 are the cost coefficients of the real/reactive power supplied by the substation and DG/DSTATCOM in \$/kW/kVAr. $P_{DG/DST}$ is the total real/reactive power drawn from installed DG/DSTATCOM. The net operating cost reduction of DG/DSTATCOM is calculated as

$$\Delta oc = \frac{TOC}{c_2 P_{DG/DST}^{\max}} \tag{11}$$

The TOC of the system with DG/DSTATCOM installation can be minimized by minimizing Δoc.

2.6. Objective function

The objective function (F) of the proposed work is formulated to minimizing the power loss, voltage profile index and operational cost of the system.

The mathematical formulation of the objective function is given by

$$\text{Minimize(F)} = \text{Min}(\partial_1 * \Delta P_{TL}^{DG/DST} + \partial_2 * \Delta V_D + \partial_3 * \Delta OC) \tag{12}$$

Constraints

The optimal allocation of DG and DSTATCOM in distribution system is subjected to the following constraints:

Power balance

$$P_{ss} = \sum_{m=2}^{n} P_{Lm} + \sum_{m=1}^{nb} P_{Loss}(m, m+1) - \sum_{m=1}^{nb} P_{cap,m}$$

Voltage deviation limit

$$V_{m,\min} \leqslant |V_m| \leqslant V_{m,\max}$$

Real power compensation

$$P_{cm}^{\min} \leqslant P_{cm} \leqslant P_{cm}^{\max}, m = 1, \ldots, N_B$$

Reactive power compensation

$$Q_{cm}^{\min} \leqslant Q_{cm} \leqslant Q_{cm}^{\max}, m = 1, \ldots, N_B$$

3. Optimal location

The Loss sensitivity factor is used to pre-identify the optimal location of the DG and DSTATCOM. Initially the optimal location is determined by using LSF. However, the calculation of LSF is depending on the network topology, configurations, loading, etc. In order to overcome these issues the algorithm will search the optimal number of buses and select them for DG and DSTATCOM placement. The optimal size of the DG and DSTATCOM will be obtained using BFOA.

3.1. Loss sensitivity factor

The loss sensitivity factor is used to pre-identify the optimal location for DG and DSTATCOM placement. The node which has the highest value of LSF with respect to the real power has more chance to place DG and the node which has the highest value of LSF with respect to the reactive power has more chance to place DSTATCOM [25]. The top five LSF values are sorted in descending order and then trial and error method will be carried out to find the optimal location among these five busses. The bus which gives very less power loss will be selected as a candidate location of DG/DSTATCOM. The Eq. (13) is used to find the optimal location of the DG placement whereas the Eq. (14) is used to find the optimal location of the DSTATCOM placement.

Another advantage of using this method is to reduce the search space of the Optimization process.

The Eq. (4) is partially differentiated with respect to real power and it is given by

$$\frac{\partial P_{loss}(m,n)}{\partial P_{mn}} = \frac{2P_{m+1,eff}R_{m,m+1}}{|V_{m+1}|^2} \tag{13}$$

The Eq. (4) is partially differentiated with respect to reactive power and it is given by

$$\frac{\partial P_{loss}(m,n)}{\partial Q_{mn}} = \frac{2Q_{m+1,eff}R_{m,m+1}}{|V_{m+1}|^2} \tag{14}$$

4. Bacterial foraging optimization algorithm

BFOA is an efficient swarm intelligence based stochastic search technique developed by Passino [26,27]. Recently, BFOA has been applied to solve numerous optimization problems in power systems. Any natural evolutionary process is based on the their fitness criteria namely

1. Food searching ability.
2. Mobile behavior (self-charging).

The law of evolution will support the species which have better food searching ability. These species are capable of producing better species in future and hence propagation in evolutionary chain is facilitated. This property of evolution is foraging optimization.

Foraging strategy of E. coli.

4.1. Chemotaxis

Chemotaxis means movement of bacteria involving swimming and tumbling. If the movement is in a predefined way then it is called swimming and if in random direction it is known as tumbling.

Tumble = (Unite length of random direction * step length of that bacteria).

If swimming, The movement is already predefined.

4.2. Swarming

It means the margining of many bacteria toward the richest food source in a concentric pattern with high bacterial density.

4.3. Reproduction

The original set of bacterium undergoes various stages of Chemotaxis and reaches the reproduction stage. Then they get divided into two groups. The healthier group survives and the other group gets eliminated.

4.4. Elimination and dispersal

It is an adverse reaction which may sometimes take place even after the smooth event of evolution, which causes the elimination and dispersal process of the bacteria in the nearest environment.

The Uniqueness of BFOA lies in the Chemotaxis process in which the bacterium moves by an amount of $c\Delta$ if the objective function value is reduced for new location. Otherwise, it remains in the same position. This unique characteristic of BFOA leads to achieve good convergence behavior and also very near global optima solution can be achieved.

The steps involved in the BFOA are as follows:

Step 1: Initialization.

- P: The number of variables to be optimized ($p = 3$).
- S: The number of bacteria used for searching the total area (100).
- N_s: The number of iteration (50).
- Nc: The number of chemotactic steps (4).
- N_{re}: The maximum number of reproduction steps (4).
- N_{ed}: The maximum number of elimination-dispersal events (2).
- P_{ed}: The probability of elimination-dispersal process (0.5).
- $C(i)$: The step change of size in the random direction$(0.05 * ones(S, 1))$.
- θ^i: Assign the location, minimum and maximum limits of the DG/DSTATCOM.

$\theta^i = (\theta_1^i, \theta_2^i, \theta_3^i) \quad foralli = 1, 2, \ldots, S$

where θ_1, θ_2 and θ_3 are the sizes of the DG/DSTATCOM at corresponding buses.

Step 2: iteration loop: $q = q + 1$
Step 3: Elimination-dispersal loop: $l = l + 1$
Step 4: Reproduction loop: $k = k + 1$
Step 5: Chemotaxis loop: $j = j + 1$

For $i = 1, 2, \ldots, S$, chemotactic step for bacterium I is as follows.

a. Calculate the objective function, $X(i, j, k, l)$.

Let $X(i, j, k, l) = X(i, j, k, l) + X_{cc}(\theta^i(j, k, l), P(j, k, l))$. F_{cc} is calculated by

$$X_{cc}(\theta, P(j, k, l)) = \sum_{i=1}^{S} X_{cc}(\theta, \theta^i(j, k, l)) = \sum_{i=1}^{S}\left[-d_{attrac}\exp\left(-w_{attract}\sum_{m=1}^{p}\theta_m - \theta_m^i\right)^2\right] + \sum_{i=1}^{S}\left[h_{repelent}\exp\left(-w_{repelent}\sum_{m=1}^{p}\theta_m - \theta_m^i\right)^2\right] \quad (15)$$

b. Let $X_{last} = X(i, j, k, l)$
c. Tumble: It will generate a random vector Δ for every element $\Delta_m(i), m = 1, 2, \ldots, p$
d. Move: Let

$$\theta^i(j+1, k, l) = \theta^i(j, k, l) + C(i)\frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}} \quad (16)$$

This will give the size of C (i) along the tumble direction for bacterium i.

e. Calculate$X(ij + 1, k, l)$.
f. Swim: Let $m = 0$ (counter for swim length).
g. While $m < N_s$, Let $m = m + 1$,
h. If $X(i, j+1, k, l) < X_{last}, letX_{last} = X(i, j+1, k, l)$ *and move* $\theta^i(j+1, k, l)$

The Eq. (16) and θ^i are used to calculate new $X(i, j+1, k, l)$ else, let $m = N_s$, termination of while statement.

Step 6: Go to next bacterium $(i+1) if\ i \neq S$.
Sep 7: if $j < N_c$, go to step 5.
Step 8: Reproduction.

The $S/2$ bacteria with highest X values will die and the left over $S/2$ bacteria with the best values were divided and placed at the same location as their parents.

Step 9: If $k < N_{re}$, then go to step 4.
Step 10: Elimination and dispersal.

Select a best bacterium which has low F and go to step 5. For $i = 1, 2, \ldots s - 1$ with P_{ed}, eliminate and disperse each bacterium such that the bacterium in the population remains constant. The dispersal bacteria will give the new DG/DSTATCOM size at corresponding location.

Step 11: If $l < N_{ed}$, then go to step 3.
Step 12: If $q < N$, go to step 2, or else end. Calculate the F for final bacterium population. Find out the bacterium which gives the minimum F and it gives the optimal sizes of DG/DSTATCOM. Finally run the load flow analysis with obtained DG/DSTATCOM size to corresponding location and display the result.

5. Simulation results

5.1. Numerical results

To demonstrate the effectiveness of the proposed method using LSF and BFOA, it is applied to well known IEEE 33-bus and 119-bus radial distribution system. To give more importance for power loss minimization and voltage profile enhancement, weighting factors ∂_1, ∂_2 and ∂_3 used in the objective function are taken as 0.5, 0.4 and 0.1 respectively as shown in Table 1. Similarly the cost coefficients c_1 and c_2 used to calculate TOC are taken as 4 \$/kW and 5 \$/kW for both the test systems [1]. The parameter initialized for BFOA in the above section is common for both the test systems. The flowchart of the proposed technique is shown in Fig. 2.

In this paper, it is planned to analyze the distribution system with eight different cases. They are as follows:

Case 1. System without DG and DSTATCOM.
Case 2. System with only DG at Unity Power Factor (upf).
Case 3. System with only DG at optimal Power factor.
Case 4. System with Multiple DG at upf.
Case 5. System with Multiple DG at optimal power factor.
Case 6. System with only DSTATCOM
Case 7. System with both DG (upf) and DSTATCOM.
Case 8. System with Multiple DG (upf) and DSTATCOM.

An analytical software tool has been developed in MATLAB to run load flow, calculate power loss and to determine optimal location and size of DG/DSTATCOM.

5.2. IEEE 33-bus radial distribution system

The IEEE 33-bus radial distribution system consists of 33 buses and 32 branches. The bus data and line data of this

Table 1 Performance analysis of co-efficient of multi-objective function for 33-bus system.

Parameter Setting			Bus no.	Size (kW)	P_{loss} (kW)	V_{min} (p.u)	TOC (\$)
∂_1	∂_2	∂_3					
0.2	0.5	0.3	6	2697	111.17	0.9438	13,930
0.3	0.2	0.5	6	1986	116.14	0.9337	10,395
0.5	0.4	0.1	6	2200	113.14	0.9368	11,453

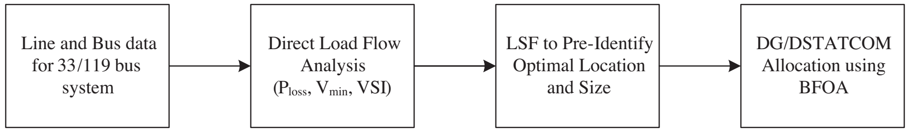

Figure 2 Flowchart of the proposed technique.

system are taken from [28]. The base values are 100 MVA and 12.66 kV and the total real and reactive power loads of this system are 3715 kW and 2300 kVAr.

Authors in [1,31], obtained the total real and reactive power loss for base case as 210.98 kW and 143.13 kVAr, while others in [3,29] obtained 202.67 kW and 135.14 kVAr respectively. This was happened because researchers [1,30] have taken the resistance and reactance values of 7th line as 1.7114 Ω and 1.2351 Ω, whereas in [3,29] it is found to be 0.7114 Ω and 0.2351 Ω as explained clearly in [29]. Hence, in this paper the base power loss for DG placement is 210.98 kW and for DSTATCOM placement it is 202.67 kW.

The schematic diagram of the 33-bus system is shown in Fig. 3. The first bus in this system is considered as feeder of electric power from generation/transmission network. The rest of the buses are considered as candidate location of DG and DSTATCOM. There are eight cases which are considered in this section. They are as follows:

5.2.1. Case 1. 33-bus system without DG and DSTATCOM

The total real and reactive power loss of this case is 210.98 kW and 143.13 kVAr. The minimum voltage of the system is 0.9038 p.u at 18th bus. The minimum VSI of this case is 0.6610 p.u.

5.2.2. Case 2. 33-bus system with only DG at upf

In this case the maximum limit of the DG unit is 70% of the total kW loading of this network (3715 * 0.7 = 2601 kW at full load). The total power loss after DG placement is 113.14 kW with minimum voltage of 0.9368 p.u. The DG is optimally located in 6th bus with the size of 2200 kW. The minimum VSI of this system is improved from 0.6610 p.u to 0.7640 p.u after DG placed. The results are compared with existing method and are tabulated in Table 3. It is observed that the proposed method significantly reduces the power loss and enhances the voltage stability of the system.

5.2.3. Case 3. 33-bus system with only DG at optimal power factor

The total loss after placement of DG is 76.14 kW. The optimal place and size of the DG are 6th bus and 2019/0.86 kW/P.F respectively. The type "C" DG is capable of delivering both real and reactive power.

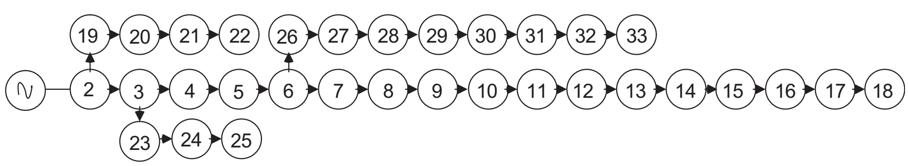

Figure 3 The schematic diagram of the 33-bus radial distribution system.

Table 2 Performance analysis of the proposed method after installation of DG/DSTATCOM on 33-bus system.

	Base Case (Case I)	With compensation via proposed method						
		Case II Single DG (Type A)	Case III Single DG (Type C)	Case IV Multiple DG (Type A)	Case V Multiple DG (Type C)	Case VI Single DSTATCOM	Case VII Single DG & DSTATCOM	Case VIII Multiple DG & DSTATCOM
DG size in kW (bus)	–	2200 (6)	2019/0.86 (6)	779 (14)	600/0.89 (14)	–	1239.8 (10)	850 (12)
				880 (25)	598/0.83 (25)			750 (25)
				1083 (30)	934/0.88 (30)			860 (30)
DSTATCOM size in kVAr (bus)	–	–	–	–	–	1102.7 (30)	1094.6 (30)	400 (12) 350 (25) 850 (30)
P_{loss} (kW)	210.98	113.14	76.14	73.53	27.50	144.38	70.87	15.07
% reduction in P_{loss}	–	46.37%	63%	65.14%	86.96%	28.76%	65%	92.56%
V_{min} (p.u)	0.9037	0.9368	0.9456	0.9677	0.9757	0.9240	0.9615	0.9862
VSI_{min} (p.u)	0.6610	0.7640	0.7933	0.8689	0.8979	0.7228	0.8465	0.9376
TOC	–	11,453	16,400	14,004	16,770	6091	11,955	20,360
Computational time (s)	NA	12.14	12.65	12.54	12.58	12.14	12.89	12.96

Table 3 Comparison and performance analysis of 33-bus system.

Method	Method	P_{loss} (kW)	% Loss reduction (%)	DG size in kW (Location)	Optimal PF
Multiple DG (Type A)	Backtracking search Algorithm [22]	89.05	57.8%	632 (12) 487 (28) 550 (31)	Unity
	QOTLBO [21]	74.1	64.9%	880.8 (12) 1059.2 (24) 1071.4 (29)	Unity
	Proposed Method (BFOA)	**73.53**	**65%**	779 (14) 880 (25) 1083 (30)	**Unity**
Multiple DG (Type C)	Backtracking search Algorithm [22]	29.65	85.97	698 (13) 402 (29) 658 (31)	0.86 0.71 0.70
	Proposed Method (BFOA)	**27.50**	**86.97%**	**600 (14)** **598 (25)** **934 (30)**	**0.89** **0.83** **0.88**
Single DSTATCOM	Immune Algorithm [3]	171.81	15.22%	962.49 kVAr (12)	–
	Proposed Method BFOA	**144.38**	**28.75%**	**1102.7 (kVAr) (30)**	–

5.2.4. Case 4. System with multiple DG at upf

The total loss after placement of DG at upf is 73.53 kW. The optimal size and location of this case are chosen as 779 kW at 14th bus, 880 kW at 25th bus and 1083 kW at 30th bus as shown in Table 2.

5.2.5. Case 5. System with multiple DG with optimal power factor

The power loss of this case is reduced to 27.50 kW from 210.98 kW after the placement of DG of 600/0.89 kW at 14th bus, 598/0.83 kW at 25th bus and 934/0.88 kW at 30th bus. The minimum voltage magnitude is increased from 0.9037 p.u to 0.9757 p.u.

5.2.6. Case 6. 33-bus system with only DSTATCOM

In this case the maximum limit of the DSTATCOM unit is 100% of the total kVAr loading of this network (2300 kVAr at full load). The total power loss after DSTATCOM placement is 144.38 kW with minimum voltage of 0.9240 p.u at 18th bus. The DSTATCOM is optimally located in 30th bus with the optimal size of 1102.7 kVAr. The minimum VSI of this system is improved from 0.6890 p.u. to 0.7228 p.u. The comparison of proposed method with immune algorithm is shown in Table 3, and the total power loss of the proposed method is 144.38 kW which is less when compared with 171.81 kW by immune algorithm.

5.2.7. Case 7. 33-bus system with single DG and DSTATCOM

In this case, the DG and DSTATCOM are optimally placed at 10th and 30th buses respectively. The total power loss after DG and DSTATCOM placement is 70.87 kW with minimum voltage of 0.9615 p.u. The minimum VSI of this system is improved from 0.6610 p.u to 0.8465 p.u.

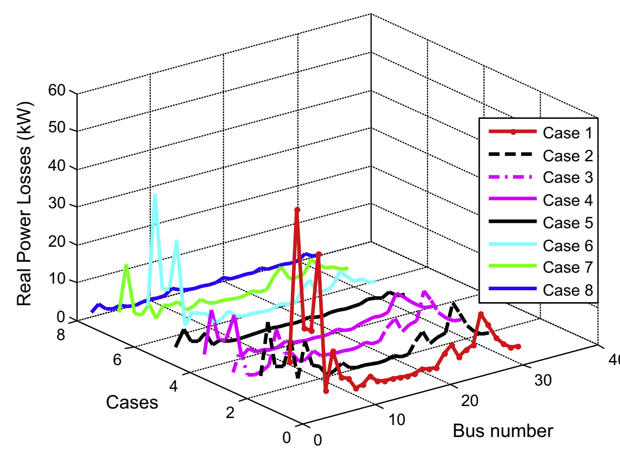

Figure 4 Real power line loss of 33-bus system at full load.

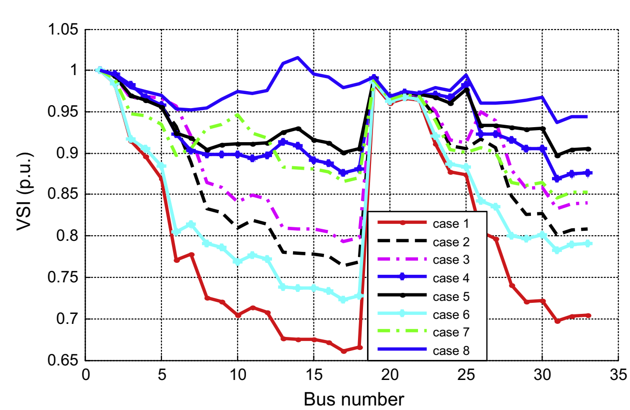

Figure 5 VSI of 33-bus system at full load.

Table 4 Performance analysis of proposed method on 33 bus system at different load models.

Parameters	Residential load		Commercial load		Industrial load	
DG size in kW (bus)	–	800 (12) 790 (25) 900 (30)	–	700 (12) 775 (25) 850 (30)	–	740 (12) 800 (25) 900 (30)
DSTATCOM size in kVAr (bus)	–	240 (12) 300 (25) 600 (30)	–	300 (12) 310 (25) 690 (30)	–	250 (12) 300 (25) 680 (30)
P_{loss} (kW)	154.42	12.11	148.78	11.65	157.83	11.68
% Loss Reduction	–	92.15%	–	92.16%	–	92.59%
$V_{\min}$ (p.u)	0.9246	0.9828	0.9262	0.9834	0.9237	0.9886
$VSI_{\min}$ (p.u)	0.7251	0.9272	0.7307	0.9298	0.7219	0.9495
TOC	–	18,198	–	18,172	–	18,397

5.2.8. Case 8. 33-bus system with multiple DG at upf and DSTATCOM

In this case, the multiple DG and DSTATCOM are optimally placed at 12th, 25th and 30th buses. The total power loss after the multiple DG and DSTATCOM placement is 15.07 kW with minimum voltage of 0.9862 p.u. The minimum VSI of this system is improved from 0.6610 p.u to 0.9862 p.u.

Fig. 4 shows the real power line loss under different cases. It is very clear that case 4 and case 8 largely reduce the power loss when compared with other cases. Fig. 5 shows the voltage stability index of the system under different cases discussed in this paper. To analyze the performance of the proposed method in deep, it is also tested under different types of load [33] such as residential load, commercial load and industrial load as presented in Table 4. It is observed that the percentage loss reduction is almost the same even with the different types of load models.

5.3. IEEE 119-bus radial distribution system

In order to validate the performance of the proposed method, it is also applied to the large scale radial distribution system with 119 buses and 118 branches. The schematic diagram of the IEEE 119-bus radial distribution system is shown in

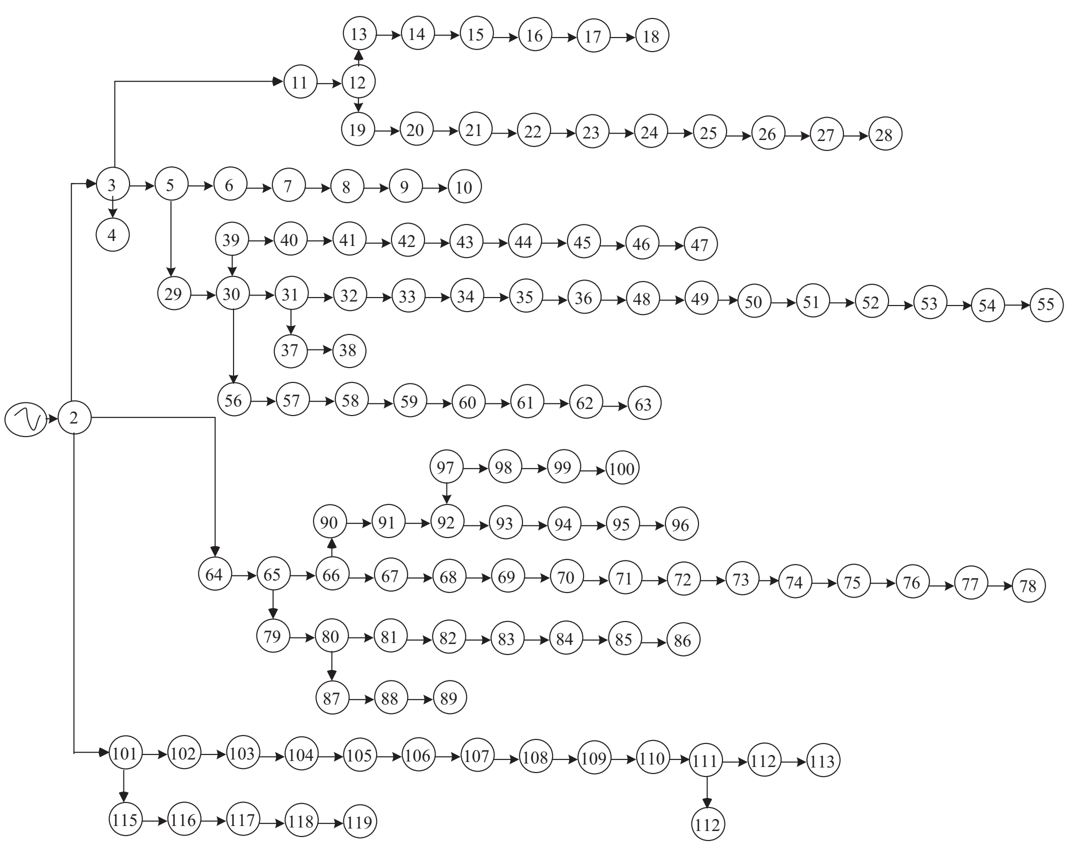

Figure 6 The schematic diagram of the 119-bus radial distribution system.

Table 5 Performance analysis of the proposed method after installation of DG/DSTATCOM on 119-bus system.

	Base Case (Case I)	With compensation via proposed method						
		Case II Five DG (Type A)	Case III Five DG (Type C)	Case IV Seven DG (Type A)	Case V Seven DG (Type C)	Case VI Five DSTATCOM	Case VII Five DG & DSTATCOM	Case VIII Seven DG & DSTATCOM
DG Size in kW (bus)	–	2750 (38) 2000 (46) 2800 (71) 2160 (91) 2950 (109)	2952/0.76 (38) 2141/0.83 (46) 2803/0.84 (71) 2346/0.79 (91) 3029/0.77 (109)	1545 (32) 1968 (39) 2073 (47) 2670 (72) 1534 (85) 2106 (91) 3118 (109)	1910/0.75 (32) 2120/0.7 (39) 1870 /0.86(47) 2510/0.87 (72) 1540 /0.79(85) 2250/0.85 (91) 3030/0.8 (109)	– –	2696 (38) 1945 (47) 2412 (74) 2186 (91) 2984 (109)	1756 (20) 2645 (39) 2042 (47) 2391 (70) 1536 (85) 2012 (91) 2815 (109)
DSTATCOM size in kVAr (bus)	–	–	–	–	–	2514 (38) 1425 (46) 1521 (74) 1715 (91) 2021 (118)	2480 (38) 1300 (47) 1580 (74) 1700 (91) 2400 (109)	1300 (20) 2510 (39) 1165 (47) 1520 (70) 1000 (85) 1640 (91) 2400 (109)
P_{loss} (kW)	1298.1	578.97	229.2	526.34	143.24	871.4	227.9	132.1
% reduction in P_{loss}	–	55.4%	82.34%	59.45%	88.96%	32.87%	82.44%	89.9%
$V_{\min}$ (p.u)	0.8688	0.9536	0.9651	0.9497	0.9688	0.9062	0.9640	0.9761
$VSI_{\min}$ (p.u)	0.5589	0.8196	0.8645	0.8124	0.8805	0.6314	0.8607	0.9048
TOC	–	65,616	117,480	77,175	133,270	62,806	109,330	134,190
Computational time (s)	–	23.24	23.54	24.96	25.65	23.21	24.65	25.96

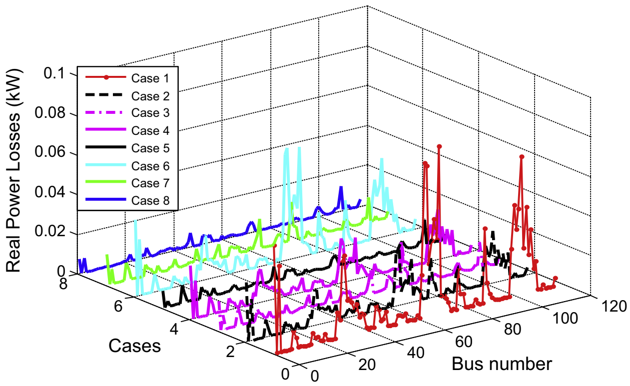

Figure 7 Real power line loss of 119-bus system at full load.

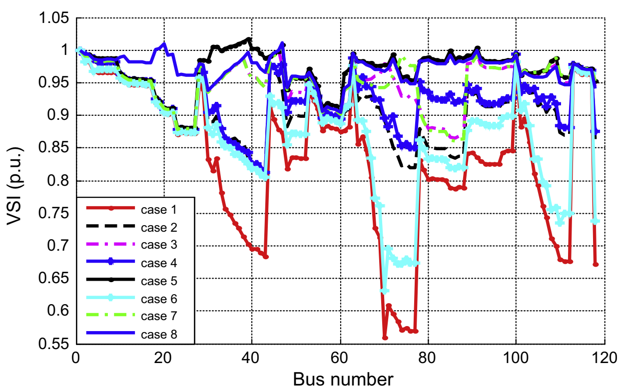

Figure 8 VSI of 119-bus system at full load.

Fig. 6. The bus data and line data for this system are taken from [32]. The total real and reactive power loads of this system are 22709.72 kW and 17041.07 kVAr respectively.

5.3.1. Case 1. 119-bus system without DG and DSTATCOM

The total power loss of this case is 1298.1 kW. The minimum voltage of the system is 0.8688 p.u. The minimum VSI of this case is 0.0.5589 p.u.

5.3.2. Case 2. 119-bus system with only DG at upf

In this case the maximum limit of the DG unit is 60% of the total kW loading of this network. (22709.72 * 0.7 = 15896.8 kW at full load). The total power loss after DG placement is 578.97 kW with minimum voltage of 0.9536 p.u. The DG is optimally located in 38th, 46th, 71st, 91th and 109th buses with the optimal size of 2750 kW, 2000 kW, 2800 kW, 2160 kW and 2950 kW respectively. The minimum VSI of this system is improved from 0.5589 p.u to 0.8196 p.u after DG placed. The results are compared with existing method and are tabulated in Table 5. It is observed that the proposed method significantly reduces the power loss and enhances the voltage stability of the system.

5.3.3. Case 3. 119-bus system with only DG at optimal power factor

The total loss after placement of DG is 229.2 kW. The optimal place and size of the DG are 38th, 46th, 71st, 91th, 109th and 2952/0.76 kW, 2141/0.83 kW, 2803/0.84 kW, 2346/0.79 kW, and 3029/0.77 kW respectively.

5.3.4. Case 4 119-bus System with multiple DG at upf

The total loss after placement of DG at upf is 526.34 kW. The optimal size and location of this case are chosen as 1545 kW at

Table 6 Comparison and performance analysis of 119-bus system.

Method	Method	P_{loss} (kW)	% loss reduction (%)	DG size in kW (Location)
Multiple DG (Type A)	QOTLBO [21]	581.40	55.21	3013.5 (49) 2543.5 (72) 1665.5 (82) 1766.2 (91) 3137.6 (109)
	Proposed method (BFOA)	578.97	**55.39**	2750 (38) 2000 (46) 2800 (71) 2160 (91) 2950 (109)
Multiple DG (Type C)	QOTLBO [21]	576.18	55.61	1246.3 (24) 732.2 (42) 3539.2 (47) 2679.2 (74) 1248.3 (78) 1086.5 (94) 3243.2 (108)
	Proposed method (BFOA)	526.34	**59.45**	1545 (32) 1968 (39) 2073 (47) 2670 (72) 1534 (85) 2106 (91) 3118 (109)

The bold values define the significance of proposed method over other methods in terms of power loss minimization.

Table 7 Performance analysis of proposed method on 119-bus system at different load models.

Parameters	Residential Load		Commercial load		Industrial load	
DG size in kW (bus)	–	1325 (20)	–	1965 (20)	–	2098 (20)
		2435 (39)		2214 (39)		2458 (39)
		1425 (47)		1625 (47)		1901 (47)
		2035 (70)		1825 (70)		2392 (70)
		1435 (85)		1725 (85)		1564 (85)
		1715 (91)		1752 (91)		2245 (91)
		2635 (109)		2725 (109)		2701 (109)
DSTATCOM size in kVAr (bus)	–	1250 (20)	–	1355 (20)	–	1100 (20)
		1825 (39)		1725 (39)		1700 (39)
		935 (47)		950 (47)		800 (47)
		842 (70)		940 (70)		645 (70)
		824 (85)		820 (85)		686 (85)
		1282 (91)		1050 (91)		1035 (91)
		1560 (109)		1768 (109)		1525 (109)
P_{loss} (kW)	936.37	112.26	895.88	108.85	966.5	111.71
% loss reduction	–	88%	–	87.8%	–	88.4%
$V_{\min}$ (p.u)	0.8948	0.9767	0.8990	0.9770	0.8911	0.9773
$\mathrm{VSI}_{\min}$ (p.u)	0.6237	0.9073	0.6400	0.9085	0.6059	0.9094
TOC	–	108,060	–	112,630	–	114,700

32nd bus, 1968 kW at 39th bus, 2073 kW at 47th bus, 2670 kW at 72nd bus, 1534 kW at 85th bus, 2106 kW at 91th bus and 3118 kW at 109th bus as shown in Table 6.

5.3.5. Case 5 119-bus System with multiple DG with optimal power factor

The power loss of this case is reduced to 143.24 kW from 1298.1 kW after the placement of DG of 1910/0.75 kW at 32th bus, 2120/0.7 kW at 39th bus, 1870/0.86 kW at 47th bus, 2510/0.87 kW at 72th bus, 1540/0.79 kW at 85th bus, 2250/0.85 kW at 91th bus and 3030/0.8 kW at 109th bus. The minimum voltage magnitude is increased from 0.8688 p.u to 0.9688 p.u.

5.3.6. Case 6. 119-bus system with only DSTATCOM

In this case the maximum limit of the DSTATCOM unit is 100% of the total kVAr loading of this network (17041 kVAr at full load). The total power loss after DSTATCOM placement is 871.4 kW with minimum voltage of 0.9062 p.u. The minimum VSI of this system is improved from 0.5589 p.u. to 0.6314 p.u.

5.3.7. Case 7. 119-bus system with both DG and DSTATCOM

In this case, the total power loss after DG and DSTATCOM placement is 227.9 kW with minimum voltage of 0.9640 p.u. The minimum VSI of this system is improved from 0.5589 p.u to 0.9048 p.u.

5.3.8. Case 8. 119-bus system with multiple DG at upf and DSTATCOM

In this case, the multiple DG and DSTATCOM are optimally placed. The total power loss after the multiple DG and DSTATCOM placement is 132.1 kW with minimum voltage of 0.9761 p.u. The minimum VSI of this system is improved from 0.5589 p.u to 0.9048 p.u.

Fig. 7 shows the real power line loss under different cases. It is very clear that cases 4 and 8 significantly reduce the real and reactive power loss when compared with other cases. Fig. 8 shows the voltage stability index of the system under different cases discussed in this paper. To analyze the performance of the proposed method in deep, it is also tested under different types of load models as tabulated in Table 7.

5.4. Overall analysis

From the above discussion, it is very clear that, the simultaneous allocation of DG and DSTATCOM in the radial distribution system will lead to achieve the maximum benefits of the system. On the other hand, the Type "C" DG also largely minimizes the power loss. Hence, it is concluded that either Type "C" DG or simultaneous allocation of DG and DSTATCOM is necessary to place in radial distribution system to achieve better power loss reduction and enhancement of voltage profile, etc.

6. Conclusion

In this paper, a new combined approach of LSF and BFOA is proposed for optimal location and sizing of DG and DSTATCOM with an objective of minimizing power loss and enhancing the voltage profile of the system. The proposed method is tested on IEEE 33-bus and 119-bus radial distribution system with different load factors. From the simulation results, it is very clear that the simultaneous allocation of DG and DSTATCOM or Type "C" DG in radial distribution system will largely reduce the total power loss, enhancement of voltage profile and system reliability. Thus, it is concluded that the great improvement in the voltage profile, loss reduction, enhancement of VSI and increase in the system security level is possible with simultaneous allocation of DG and

DSTATCOM or Type "C" DG. The simulation result shows that the proposed method gives better results when compared with other existing methods. The proposed integrated approach can be applied to any kind of radial distribution system.

Acknowledgments

The authors gratefully acknowledge support from the management, VIT University, Vellore, India. The authors would like to sincerely thank the reviewers for their valuable comments and recommendations to improve the quality of the paper.

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