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PLACEMENT OF DG AND CAPACITOR FOR LOSS REDUCTION AND RELIABILITY IMPROVEMENT IN RADIAL DISTRIBUTION SYSTEMS USING BFA

E. R. Biju and M. Anitha

Department of Electrical Engineering, Annamalai University, Tamil Nadu, India

E-Mail: kuttanbiju@rediffmail.com

ABSTRACT

This paper presents a methodology for determining the optimal location and capacity of Distributed Generator (DG) and capacitor in the radial distribution system in view of loss reduction and improvement in voltage profile and reliability. The overall objective function includes reliability index, power loss reduction, DG and capacitor investment cost and voltage deviation index. Customer and energy based indices i.e. SAIFI, SAIDI, CAIDI, AENS, and ASAI have been optimized by using the optimum values of failure rate. In this paper, the most recent Bacterial foraging algorithm (BFA) is used to find optimal location of single DG and capacitor in radial distribution systems. To evaluate the effectiveness of the proposed algorithm in finding best solutions, simulations are carried out with and without DG and capacitor installation on 10 bus and standard IEEE 33 bus radial distribution system. The obtained results are compared with binary particle swarm optimization algorithm (BPSO) for validation.

Keywords: distributed generator (DG), reliability indices, bacterial foraging algorithm, radial distribution system.

1. INTRODUCTION

In developing countries, the distribution feeders carry large currents to load points which lead to higher power loss resulting in poor power quality and the power losses are around 20% and in developed countries it is less than 10% [1]. Power systems are providing a reliable and economic supply of electric energy to their customers. The spare or redundant capacities in generation and network facilities have been inbuilt in order to ensure adequate and acceptable continuity of supply in the event of failure, forced outages of plant and removal of facilities in regular scheduled maintenance. Approximately 80% of all customer interruptions occur due to failures in the distribution system [2]. Power systems are currently focusing in reducing power losses, improving the voltage magnitude and reliability of customer. There are many approaches for the loss reduction like feeder reconfiguration, high voltage distribution system and conductor grading. All these approaches are not enough to reduce the power loss and improve the reliability except DG unit and capacitor placement in optimal locations. Sizing and allocation of DG and capacitor in radial distribution system is to reduce the power loss, improve voltage magnitude and customer reliability index.

Distributed generation is expected to play an increasing role in radial distribution system. DG is normally defined as small generations units installed at strategic points of the distribution system, mainly close to load centers [2]. In a radial distribution feeder, depending on the technology, DG units can driven a portion of total power to loads so that the feeder current reduces from the source to the location of DG units. Due to the problems associated with the establishment of new transmission lines, environmental pollution and due to restructuring and competition in power systems have increased the deployment of DGs to improve the reliability of the distribution systems. Other potential benefits of DGs are: power loss reduction, voltage support, ancillary services support etc. Though the use of DG has many benefits, it involves high capital cost to the system. The time necessary to start up the DG should also be taken into account for the reliability evaluation of distribution system. If this time is sufficiently short, the customers suffer a momentary interruption, while, if not, they suffer a sustained interruption.

Shunt capacitor are widely employed to compensate for the reactive power in the network and reduce the power loss in the lines and improve the voltage profile. The advantages with the addition of shunt capacitors banks are to improve the power factor, feeder voltage profile, power loss reduction and to increase available capacity of feeders. Therefore it is important to find optimal location and sizes of capacitors in the system to achieve the above mentioned objectives. In [3], capacitor placement was applied as a multiobjective problem to reduce the annual cost sum of the power loss and the capacitors, as well as to improve the voltage magnitude.

In the literature, many researchers have attempted to determine the optimum location and size of single DG unit and multiple DG units in the distribution system. In-Su et al [4] described an analytical method to determine the reliability of a distribution system with DG. They considered three modes of operations of DG such as stand by unit, peaking unit and mixed mode operation. Gozel *et al* [5] determined optimal allocation and sizing of DGs

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using an analytical method in view of minimum line loss. Singh and Verma [6] proposed multi-objective optimization for DG allocation considering load models. The case studies were presented to assess the impact of type of loads on DG allocation. Reza Baghipour *et al* [7] proposed binary particle swarm optimization algorithm to determine the optimum placement and sizing of distributed generation and capacitor banks. The optimal sizing and placement of these resources to minimize the power losses improve the voltage magnitude and enhance the system reliability indices [8] and [9].

This paper presents a methodology to find out the optimum placement and sizing of DG unit and capacitor of a radial distribution system by using BFA. Two sample distribution systems of 10 bus and IEEE 33 - bus standard radial distribution system are considered as test systems for the purpose of illustration. Results were obtained by the proposed algorithm for power loss minimization, voltage improvement, DG and capacitor installation cost reduction and reliability improvement of ENS (Energy Not Supplied) and ECOST (Expected interruption cost). The results of the proposed algorithm have been compared with other optimization technique, namely BPSO algorithm. Finally the energy and customer based reliability indices were evaluated using the optimized failure rates and repair times of the distributor segments with and without DG and capacitor installation.

2. RELIABILITY ANALYSIS OF DISTRIBUTION SYSTEM

Reliability analysis of electrical distribution system is considered as a tool for the planning engineer to ensure a reasonable quality of service and to choose between different system expansion plans that cost wise were comparable considering system investment and cost of losses. The analytical approach is based on assumptions concerned with statistical distributions of failure rates and repair times. The usual method of evaluating the reliability indices is an analytical approach based on failure mode assessment and the use of equations for series and parallel networks. The common indices used for evaluation: the expected failure rate (λ), the average outage time(r), and the expected annual outage time(U) which are adequate to the sample radial system. The basic reliability indices of the system are given by:

$$\lambda_{sys,i} = \sum_{k \in s} \lambda_k \quad (1)$$

$$U_{sys,i} = \sum_{k \in s} \lambda_k r_k \quad (2)$$

where λ_k, r_k and λ_k r_k are, respectively, the average failure rate, average outage time and annual outage time of the i^{th} component.

In this paper, expected interruption cost (ECOST) is included as part of the objective function. Evaluating ECOST enables the system planners to determine the acceptable level of reliability for customers, provided economic justifications for determining network reinforcement and redundancy allocation, identify weak points in a system, determine suitable maintenance scheduling and develop appropriate operation policies. ECOST is therefore a powerful tool for system planning [10]. ECOST at bus i is calculated as follows:

$$E\cos t_i = \sum_{i=1} L_{a(i)} C_i \lambda_i \quad (3)$$

where $L_{a(i)}$ is the average load connected to load point i in kw and C_i is the cost of interruption (in $/kw) for the i^{th} bus.

The total ECOST of the distribution feeder is calculated as follows:

$$E\cos t = \sum_{i=1}^{NB} E\cos t_i = \sum_{i=1}^{NB} L_{a(i)} C_i \lambda_i \quad (4)$$

where NB is the total number of load points in the feeder. In order to submit the importance of a system outage, energy not supplied index (ENS) is evaluated. This index reflects total energy not supplied by the system due to faults during study period and is calculated for each load bus i using the following equation:

$$ENS_i = L_{a(i)} U_i \quad (5)$$

A customer damage function (CDF) provides the interruption cost versus interruption duration for a specified group of customers. The CCDF is basically the sum of the individual customer damage functions in the customer mix. The Sector customer damage function (SCDF) of the residential, commercial and industrial sectors etc. can be combined to create a composite customer damage function (CCDF). CCDF shows the cost of interruption as a function of interruption duration. A typical CCDF [10] is illustrated in Figure-1. Since it accounts for reliability worth and the reliability level, ECOST is a comprehensive value based reliability index and was used for this study.

2.1 Figures

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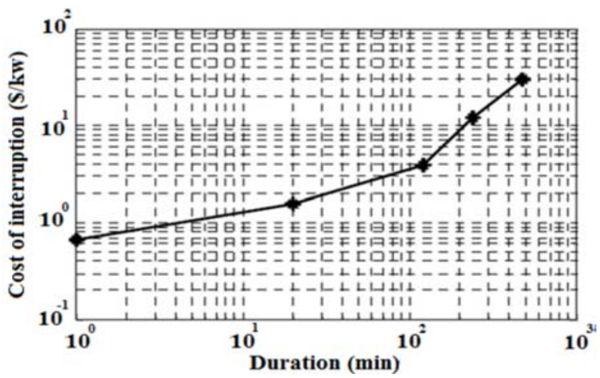

Figure-1. Typical CCDF.

3. DISTRIBUTION SYSTEM RELIABILITY ENHANCEMENT USING DG AND CAPACITOR

Majority of the customer interruptions are caused by equipment failures in distribution systems consisting of underground cables and overhead lines. Resistive losses increase the temperature of feeders which is proportional to the square of the current magnitude flowing through the feeder. Moreover increase in temperature causes insulation failure in underground cable and overhead lines which in turn increases the component failure rate. If DG and capacitor are installed at appropriate places, they can supply part of active and reactive power demands respectively. This reduces the resistive losses due to reduction of the magnitude of current. These impacts on reliability take into consideration as a failure rate reduction of distribution feeder components.

Before DG and capacitor placement, any feeder i has an uncompensated failure rate of λ_i^{uncomp}. If the reactive or active component of a feeder branch is fully compensated, its failure rate reduces to λ_i^{comp}. If the reactive and active components of current are not completely compensated, a failure rate is defined with linear relationship to the percentage of compensation. Thus, the compensation coefficient of the i^{th} branch is defined as:

$$\alpha_i = \frac{I_r^{new}}{I_r^{old}} * \frac{I_a^{new}}{I_a^{old}} \tag{6}$$

where I_r^{new}, I_r^{old} and I_a^{new}, I_a^{old} are the reactive and active components of the i^{th} branch current after and before compensation, respectively. The new failure rate of the i^{th} branch is computed as follows:

$$\lambda_{i-new} = \alpha_i \left(\lambda_i^{uncomp} - \lambda_i^{comp}\right) + \lambda_i^{comp} \tag{7}$$

4. CUSTOMER-BASED RELIABILITY INDICES

A survey by Electric Power Research Institute (EPRI) has identified that most frequently used customer oriented indices namely SAIFI, SAIDI, CAIDI, AENS and ASAI. These indices are defined as follows [11].

4.1 System average interruption frequency index (SAIFI)

$$SAIFI = \frac{Total\ numbers\ of\ customer\ \mathrm{int}\ erruptions}{Total\ number\ of\ customers\ served}$$

#

$$= \frac{\sum \lambda_{sys,i} N_i}{\sum N_i} \tag{8}$$

4.2 System average interruption duration index (SAIDI)

$$SAIDI = \frac{Sum\ of\ all\ customer\ \mathrm{int}\ erruptions\ durations}{Total\ number\ of\ customer\ served}$$

$$= \frac{\sum U_{sys,i} N_i}{\sum N_i} \tag{9}$$

4.3 Customer average interruption duration index (CAIDI)

$$CAIDI = \frac{Sum\ of\ all\ customer\ \mathrm{int}\ erruption\ durations}{Total\ number\ of\ customer\ \mathrm{int}\ erruptions}$$

$$= \frac{\sum U_{sys,i} N_i}{\sum \lambda_{sys,i} N_i} \tag{10}$$

4.4 Average energy not supplied (AENS)

$$AENS = \frac{Sum\ of\ system\ annual\ outage\ duration\ at\ load\ po\,\mathrm{int}}{Sum\ of\ average\ load\ po\,\mathrm{int}}$$

$$= \frac{\sum L_i U_{sys,i}}{\sum N_i} \tag{11}$$

4.5 Average service availability index (ASAI)

$$ASAI = \frac{Ccustomer\ hours\ service\ availability}{Customer\ hours\ servise\ demand}$$

$$=[(8760\text{-}SAIDI)/8760]*100 \tag{12}$$

Where L_i is average load connected at i^{th} load point, which may be obtained from load duration curve, $\lambda_{sys,i}$ is the system failure rate at i^{th} load point, N_i is total number of customers at load point i and $U_{sys,i}$ is system annual outage duration at i^{th} load point.

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5. PROBLEM FORMULATION

The main objective of this paper is to determine the optimal location and size of DG and capacitor in distribution systems in order to improve the system reliability and to reduce the power loss along with minimum installation cost of DG and capacitor. Distribution network losses and voltage of all nodes are found by backward - forward sweep distribution load flow analysis. In this paper a multi objective function is considered on the basis of active power loss index, reliability index, voltage profile index and DG and capacitor investment cost index which are defined as follows:

5.1 Multiobjective function

The multiobjective function of the problem is described as:

$$\text{Mininize} \quad J = \sum_{m=1}^{4} K_m J_m \tag{13}$$

$$K_m \in [0,1], \quad \sum_{m=1}^{4} K_m = 1 \tag{14}$$

Where, k_m are weighting factors assigned to each objectives are K_1=0.30, K_2=0.35, K_3=0.20 K_4=0.15 attributed to power loss, reliability, voltage deviation and DG's and Capacitor's Investment Cost Index, respectively.

5.2 Real power loss index (J_1)

Power losses are important factor in the design of distribution systems and are calculated by backward - forward sweep load flow method in radial distribution system. At a given time, the power loss index is given by

$$J_1 = \frac{P_{L,DG\&cap}}{P_L} \tag{15}$$

where $P_{L,DG\&Cap}$ is the total real power loss of the distribution system in presence of DG and capacitor and P_L is the total real power loss without DG and capacitor in the distribution system.

5.3 Reliability index (J_2)

Reliability index is given by

$$J_2 = \frac{E\cos t_{DG\&cap}}{E\cos t} \tag{16}$$

where Ecost $_{DG\&Cap}$ and Ecost is expected interruption cost of system with and without DG and capacitor installation, respectively.

5.4 Voltage deviation index (J_3)

Bus voltage is one of the most important characteristic of the system. One of the benefits of correct selection of location and size of DG and capacitor is improvement of voltage deviation. This index indicates higher voltage deviations from 1.0 per unit. VDI is expressed as

$$J_3 = \sum_{i=1}^{NB} |V_i - 1| \tag{17}$$

where NB is total number of the buses
V_i is the magnitude voltage on the i^{th} bus.

5.5 DG's and capacitor's investment cost index (J_4)

DG and capacitor are appropriate selections for minimizing both the line loss and improving the network reliability and voltage profile. However, the investment cost of DG and capacitor is a significant problem that prevents engineers using them widely. This index is calculated with the following equation:

$$J_4 = \frac{Cost_{DG}}{Cost_{MCD}} + \frac{Cost_{cap}}{Cost_{MCC}} \tag{18}$$

where $Cost_{DG}$ and $Cost_{Cap}$ are costs of DG and capacitor, respectively. $Cost_{MCD}$ and $Cost_{MCC}$ are costs of DG and capacitor in their maximum capacity, respectively.

6. BACTERIAL FORAGING ALGORITHM

BFA is an optimization method developed by Kevin M. Passino [12], based on the foraging strategy of Escherichia Coli (E. Coli) bacteria that live in the human intestine. Foraging strategy is a method of animals for locating, handling and ingesting their food. The foraging strategy of E.Coli is governed basically by four processes namely Chemotaxis, Swarming, Reproduction, Elimination and Dispersal.

6.1 Chemotaxis

Chemotaxis process is the characteristics of movement of bacteria in search of food and consists of two processes namely swimming and tumbling. A bacterium is said to be 'swimming' if it moves in a predefined direction, and 'tumbling' if moving in an altogether different direction. Let j be the index of chemotactic step, k be the reproduction step and l be the elimination dispersal event. Let θ^i (j,k,l) is the position of

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ith bacteria at jth chemotactic step, kth reproduction step and lth elimination dispersal event. The position of the bacteria in the next chemotactic step after a tumble is given by

$$\theta^i(j+1,k,l)=\theta^i(j,k,l)+C(i)*\frac{\Delta(i)}{\sqrt{\Delta^T(i)*\Delta(i)}} \quad (19)$$

If the health of the bacteria improves after the tumble, the bacteria will continue to swim in the same direction for the specified steps or until the health degrades.

6.2 Swarming

Bacteria exhibits swarm behavior i.e. healthy bacteria try to attract other bacteria so that together they reach the desired location (solution point) more rapidly. The effect of Swarming is to make the bacteria congregate into groups and move as concentric patterns with high bacterial density.

$$J_{cc}(\theta,P(j,k,l))=\sum_{i=1}^{n}J_{cc}\left(\theta,\theta^i(j,k,l)\right)$$
$$=\sum_{i=1}^{s}\left[-d_{attract}\exp\left(-W_{attract}\sum_{i=1}^{n}\left(\theta_m-\theta_m^i\right)^2\right)\right]+ \quad (20)$$
$$\sum_{i=1}^{s}\left[-d_{repellant}\exp\left(-W_{repellant}\sum_{i=1}^{n}\left(\theta_m-\theta_m^i\right)^2\right)\right]$$

6.3 Reproduction

In this step, population members who have had sufficient nutrients will reproduce and the least healthy bacteria will die. The healthier half of the population replaces with the other half of bacteria which gets eliminated, owing to their poorer foraging abilities. This makes the population of bacteria constant in the evolution process.

6.4 Elimination and dispersal

Gradual or sudden changes in the local environment where a bacterium population lives may occur due to various reasons e.g. a significant local rise of temperature may kill a group of bacteria that are currently in a region with a high concentration of nutrient gradients. Events can take place in such a fashion that all the bacteria in a region are killed or a group is dispersed into a new location. To simulate this phenomenon in BFA some bacteria are liquidated at random with a very small probability while the new replacements are randomly initialized over the search space.

7. SIMULATION RESULTS AND DISCUSSIONS

The proposed method was tested on 9 bus and 33 bus radial distribution systems. In order to evaluate the proposed algorithm, the objective function given in (13) is minimized using bacterial foraging algorithm. To calculate the power loss, backward - forward (BW-FW) distribution power flow method is utilized. Also to calculate the reliability, energy not supplied (ENS) and expected interruption cost (ECOST) is calculated. Simulations were carried out on 1.86 GHz system in MATLAB 7.5 version environment.

The following bacterial foraging algorithm parameters, S (20), N_c (30), $N_{s\ 12}$(), N_{re} (10) and N_{ed} (5) are considered for simulation. It is obtained that the better convergence for DG and capacitor location problem. Further, it is assumed that the section with the highest resistance has the biggest failure rate of 0.5 f/year and the section with the smallest resistance has the least failure rate of 0.1 f/year [13]. Based on this assumption, failure rates of other sections are calculated linearly proportional to these two values according to their resistances [11]. The available DG and capacitor size and their cost data are shown in Table-1.

Table-1. DG and capacitor size and costs.

DG		Capacitor	
Size KW	**Cost ($)**	**Size KVAr**	**Cost ($)**
250	2121	150	750
500	1500	300	975
750	1225	450	1140
1000	1061	600	1320
1250	949	900	1650
1500	866	1200	2040
1750	802		
2000	750		

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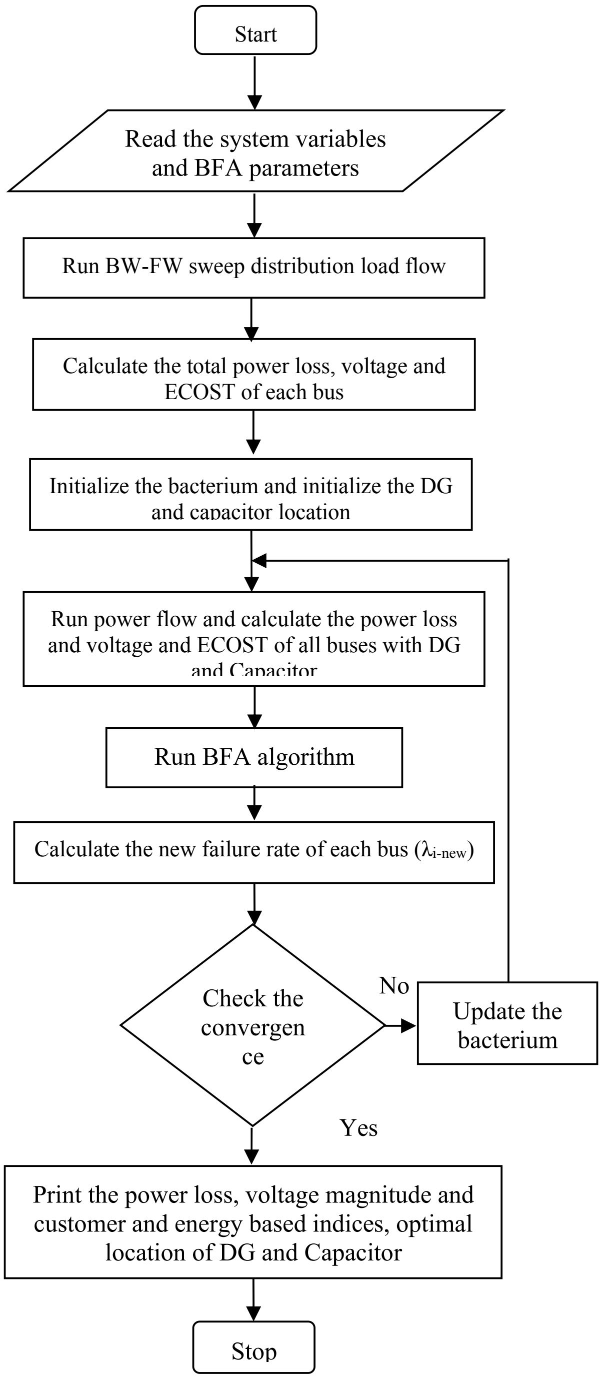

Figure-2. Implementation flowchart for BFA.

Furthermore, it is assumed if the reactive or active component of a distributor section current is fully compensated, its failure rate reduces to 85% of its uncompensated failure rate [13 - 14] and for partial compensation; the failure rate is calculated using (7). In both of test systems, it is assumed that there is only one breaker at the beginning of the main feeder and also that there is one sectionalizer at the beginning of each section. Besides, for each line, the repair time and total isolation and switching time are considered as 8 hours and 0.5 hours, respectively. Component failure rate is optimized using the compensation coefficient which in turn used to calculate the customer reliability indices (SAIFI, SAIDI, CAIDI, AENS and ASAI) with and without DG and capacitor [11].

Case 1: 10 -Bus test system

The suitability of the proposed algorithm in determining the optimal size and location of DG and capacitor is tested on 10 bus radial distribution system. The line and load data of the system are obtained from [13]. One line diagram of the 23KV, 10-bus system having single lateral radial distribution lines is shown in Figure-3.

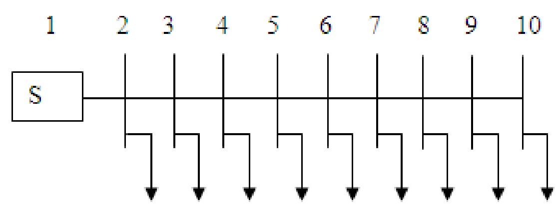

Figure-3. 10 bus radial distribution system.

The proposed algorithm is used to find the optimum location and size of DG and capacitor by minimizing the multiobjective function given in equation (13). Table-2 gives optimum location and size of DG and capacitor obtained using proposed method.

Table-2. Optimal location and size of DG and capacitor in 10 bus system.

	Installation	**Size**
DG	8	1250 KW
Capacitor	6	600 KVAr

Table-3 gives the ECOST, ENS, P_{LOSS}, Q_{LOSS}, VDI and minimum voltage magnitude obtained using the BF algorithm. In order to validate and compare the impact of DG and capacitor placement in the test system, the results are compared to the case in which there is no DG and capacitor in the system and are also compared with that of

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BPSO method. In this table, base case represents the system without DG and capacitor. % improvement achieved by the bacterial foraging algorithm compared with that of base case is also given in Table-3. From the results it is evident that the proposed method gives an improvement of 20.81% in ECOST, 9.76% in ENS, 12.84% in P_{LOSS}, 17.18% in Q_{LOSS}, 17.13% in VDI and 1.812% in voltage magnitude when compared to BPSO method. The results of BF algorithm is better than BPSO method. Figure-3 shows voltage magnitude of each bus of test system with and without DG and capacitor. This Figure shows that the voltage profile has been improved due to the optimal placement of DG and capacitor. Figure-4 shows line loss in each branch of the system with and without DG and capacitor.

Table-3. Comparison of the results with and without DG and capacitor installation in 10 bus system.

	ECOST($)	**ENS** (KWh/yr)	$\mathbf{P_{Loss}}$ (KW)	$\mathbf{Q_{Loss}}$ (KVAr)	**VDI** (p.u)	**Minimum voltage magnitude** (p.u)
Base case [15]	273090	89933.6	783.78	1036.6	0.6988	0.8375
After DG and capacitor installation BPSO [15]	245710	80762	235.63	412.3	0.3635	0.938
(%) improvement BPSO [15]	10.02	10.02	69.94	60.22	47.98	12.12
After DG and capacitor installation [BFA]	194561	72876.5	205.37	341.45	0.3012	0.9550
(%) improvement [BFA]	28.75	18.96	73.79	67.06	56.89	14.02

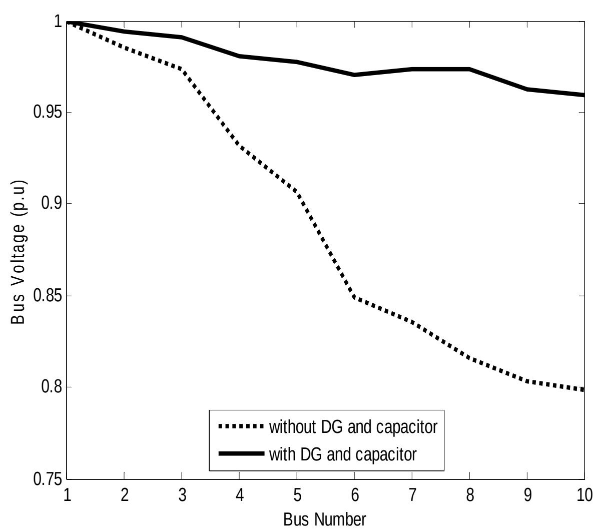

Figure-4. Voltage magnitude of 10 bus system.

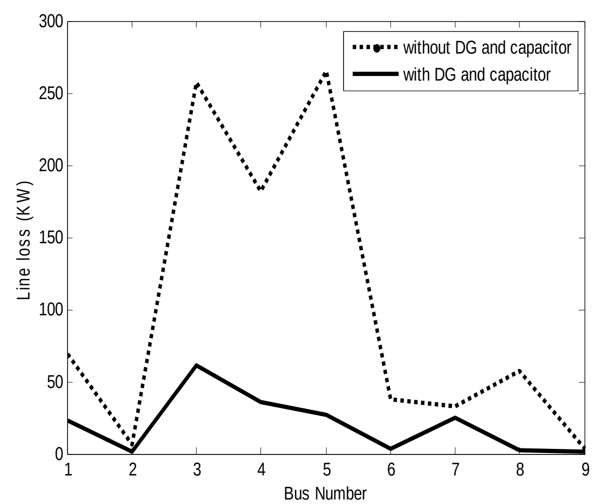

Figure-5. Line loss in each branch.

New failure rate is calculated corresponding to the optimal location of capacitor and DG using compensation coefficient given in equation (7). Using this, the customer and energy based indices (i.e.) SAIFI, SAIDI, CAIDI, ASAI and AENS are evaluated and are given in Table-4. With the installation of DG and capacitor in optimum location, it is seen that the reliability indices have been improved.

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Table-4. Customer and energy based indices.

Reliability indices	Without DG and capacitor	With DG and capacitor
SAIFI	0.9098	0.5083
SAIDI	4.4871	1.5525
CAIDI	4.9322	3.0541
ASAI	99.9488	99.9823
AENS	10.2576	4.5870

Case 2: IEEE 33-bus system

One line diagram of the 12.66KV, 33-bus system having 4 - lateral radial distribution lines is shown in Figure-6. The network data is taken from [16].

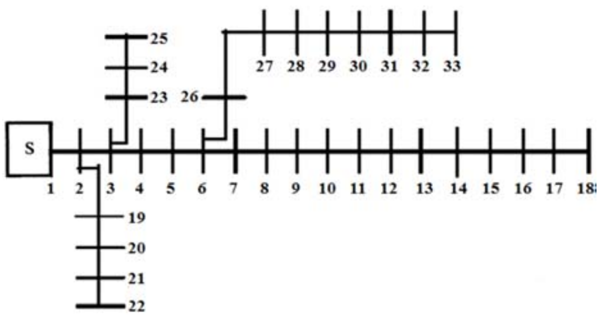

Figure-6. IEEE 33 bus system.

The proposed algorithm is used to find the optimum location and size of DG and capacitor by minimizing the objective function given in equation (13). Table-5 gives optimum location and size of DG and capacitor obtained using the proposed method.

Table-5. Optimal location and size of DG and capacitor in 33 bus system.

	Installation	Size
DG	12	1250 KW
Capacitor	9	450 KVAr

Table-6 gives the ECOST, ENS, P_{LOSS}, Q_{LOSS}, VDI and minimum voltage magnitude obtained using the BF algorithm. This table also shows the % improvement obtained in all the quantities using proposed algorithm when compared with base case. It can also be observed from the results that the proposed BF method achieves 14.93% in ECOST, 14.13% in ENS, 19.31% in P_{LOSS}, 10.33% in Q_{LOSS}, 19.37% in VDI and 1.58% in voltage magnitude. Figure-7 shows voltage magnitude of each bus of 33-bus radial distribution system with and without DG and capacitor. Figure-8 shows line loss in each branch of the system with and without DG and capacitor.

Table-6. Comparison of the results with and without DG and capacitor installation in 33 bus system.

	ECOST($)	**ENS** (KWh/yr)	P_{Loss} (KW)	Q_{Loss} (KVAr)	**VDI** (p.u)	**Minimum voltage magnitude** (p.u)
Base case [15]	162960	69338	314.45	213.3	0.4921	0.8823
After DG and capacitor installation BPSO [15]	146970	63481	144.73	96.54	0.3159	0.9358
(%) improvement BPSO [15]	9.81	8.45	53.97	54.74	35.8	6.06
After DG and capacitor installation [BFA]	125017	54509	116.78	86.56	0.2547	0.9506
(%) improvement [BFA]	23.28	21.86	62.86	59.41	48.24	7.74

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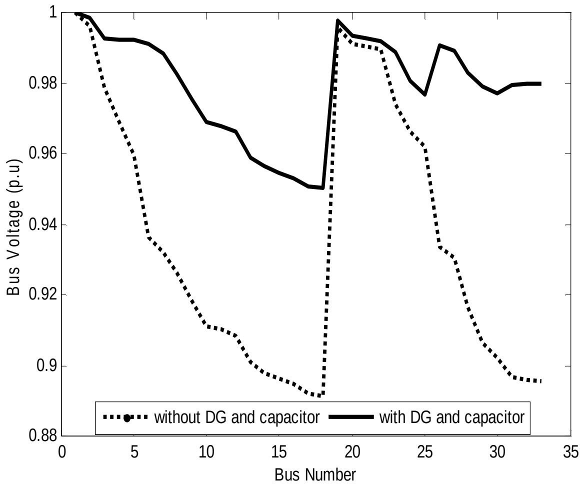

Figure-7. Voltage magnitude of 33-bus system.

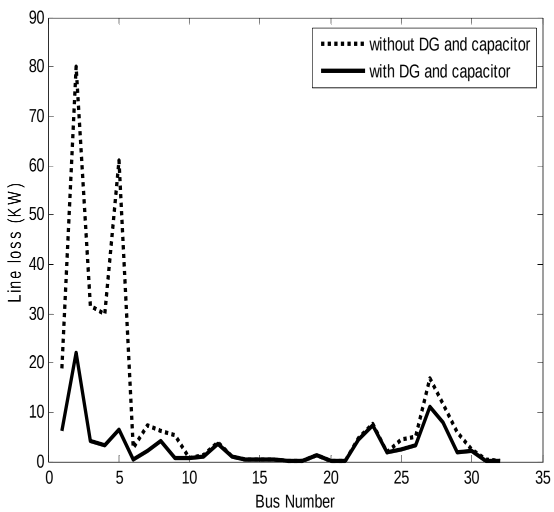

Figure-8. Line loss in each branch.

The failure rate has been optimized using compensation coefficient and the reliability indices, (i.e.) SAIFI, SAIDI, CAIDI, ASAI and AENS are calculated with and without DG and Capacitor and are presented in Table-7.

Table-7. Reliability indices for 33 bus test system.

Reliability indices	Without DG and capacitor	With DG and capacitor
SAIFI	2.2319	1.7218
SAIDI	7.4718	5.2191
CAIDI	3.3477	3.0311
ASAI	99.9147	99.9176
AENS	10.4490	8.5976

8. CONCLUSIONS

This paper, optimum size and location of DGs and capacitor for reliability improvement are determined using bacterial foraging algorithm. The other benefits obtained are power loss reduction, voltage profile improvement and better customer and energy based indices due to failure rate reduction. The proposed algorithm has been applied on two test system (i.e.) 10 bus and IEEE 33bus radial system. The results show that the proposed method is capable of giving better solution than previously published BPSO method.

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