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ORIGINAL PAPER

Integration of distributed generation for assessment of distribution system reliability considering power loss, voltage stability and voltage deviation

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Abstract This paper presents a combined scheme for solving optimal distributed generation (DG) placement and reliability assessment problem of distribution network. This has been solved through meta-heuristic based novel Modified Gbest-guided artificial bee colony (MGABC) optimization algorithm for the purpose of power loss reduction, index of voltage stability (IVS) improvement and voltage level enhancement. In addition to that, it also identifies the optimal values of rate of failure and time of repair of various distribution lines for enhancement of distribution reliability. Therefore to achieve these proposed objectives, three multi-objective functions are formulated. First multi-objective function is formed by combining purchased active power cost from grid, power loss cost, DG installation cost, DG operation and maintenance (O&M) cost, reliability cost, IVS and total voltage deviation. Second objective function is reliability based cost function with the consideration of DG units and the third one is comprehensive multi-objective function associated with first and second objective functions for solving DG placement and reliability enhancement problem simultaneously. The proposed problem is demonstrated on 8-bus distribution system. Obtained numerical outcomes illustrate that, simultaneous solving DG placement problem and reliability enhancement problem leads to reduction of total operating cost, total voltage deviation, power loss and improvement in IVS significantly. Furthermore, the results obtained through MGABC optimization algorithm are compared to other intelligence technique for highlighting the capability and superiority of proposed methodology.

Keywords DG placement · Distribution network reliability · Modified Gbest-guided artificial bee colony algorithm · Power loss · Voltage deviation

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Abbreviations

$FR_{sys,i}$	Average rate of failure
NC_i	Number of customer at ith load point
FR_i	Rate of failure of ith load point
$FR_{i,min}$ and FR_i^0	Minimum and modified value of rate of failure at ith load point
S	Total number of distribution lines
RR_i	Repair time of ith load point
$RR_{i,min}$ and RR_i^0	Minimum and modified value of repair time at ith load point
NL	Number of distribution lines
AL_i	Customer average load at ith bus
C_{Loss}	Cost of power loss
C_p	Purchase active power cost from grid
DG_{instt}	DG installation cost
DG_O & M	O & M cost of DG
IVS_T	Summation of IVS
$V_{deviation}$	Total voltage deviation
α_k and β_k	Cost coefficients
n	Total number of buses
FR_k and RR_k	Rate of failure and time of repair for kth branch
FR_{eq} and RR_{eq}	Equivalent rate of failure and time of repair.
OU_{eq}	Yearly outage period after inclusion of DG units
FR_s and RR_s	Total rate of failure and repair time of a load point.
FR_{dg} and RR_{dg}	Rate of failure and time of repair of DG.
FR_{sdg} and OU_{sdg}	Rate of failure and time of outage for parallel arrangement of DG and a network.
FR_{sw} and RR_{sw}	Rate of failure and time of service restoration of manual switch.
P_{ij} and Q_{ij}	Active and reactive power flow between ith and jth bus
P_j^{DG}	Real power supplied by DG
V_i	Voltage at ith bus
P_j^F and Q_j^F	Active and reactive power flow beyond jth bus
$P_{Loss}(i, j)$	Real power loss between ith and jth bus
n	Total number of buses
S_{DG} and S_{Load}	Total kVA rating of DG and a network
V_{rated}	Nominal rated voltage 1 pu
K_p	Cost coefficient of power loss (0.06 US $/kW)
E_p	Electricity market price (49 US $/MWh)
P_{Load}	Total real power load of a network
T	Time period (8760 hours)
$DG_{cap,i}$	DG capacity
K_{DG}^i	Cost coefficient of DG installation (400000 US $/MW)
$K_{DG}^{O\&M}$	DG O&M cost coefficient (36 US $/MWh)
$P_{real,i}$	Real power supplied by DG
φ_{ij}	Random number between -1 and 1

DG	Distributed generation
ADCOST	Incentive offered by DG in per kW cost
EENSO	Expected energy not supplied without DG
EENSD	Expected energy not supplied with DG
NDG	Number of DGs
IVS	Index of voltage stability
ABC	Artificial bee colony
GABC	Gbest-guided artificial bee colony
MGABC	Modified Gbest-guided artificial bee colony

1 Introduction

Distribution system load demand is increasing worldwide day by day, due to the widespread of infrastructure, industrial and commercial sectors. Due to this, distribution system utilities face lot of challenges, such as to maintain good quality of power supply, fulfill load demand and reduce failure rate as well as time of repair of several distribution lines etc. Incorporation of DG units into a network offers several benefits like power loss reduction [1–10], voltage profile improvement [5–9,11], reduction in voltage deviation [8,12], improvement in voltage stability [13], minimize total operating cost [14,15] and deferred system expansion cost [16] to consumers as well as utilities. However, only inclusion of DG does not guarantee to improve system efficiency, it may affect the system performance if the position and rating of DG units are not identified correctly. Hence, proper position and rating of DG play a vital role. It can be deployed either demand side or utility side throughout a distribution system to maintain power balance and enhance system reliability and efficiency [17]. Distribution network reliability may be improved by improving the value of rate of failure and time of repair of distribution segments [18].

Although more concentration is required for low reliability issues meanwhile, many authors have provided a significant contribution in this research area [19–40]. Billinton and Wang [19], presented an analytical and monti-carlo simulation approach for evaluation of distribution system reliability. Again Billinton and Wang [20], suggested reliability worth distribution system considering two cost models. First is average model and second is probalistic distribution model. Wang and Billinton [21], presented an incorporation of wind based DG in the distribution network for reliability enhancement. Etemadi and Fotuhi-Firuzabad [22], presented an optimal placement of shunt capacitor for enhancement of distribution system reliability as well as minimize the power loss through particle swarm optimization (PSO) algorithm. Wang and Singh [23], adopted an ant colony optimization (ACO) approach for the incorporation of protection devices (reclosers) and DGs at optimal locations for reliability improvement. Atwa and El-Saadany [24], presented an assessment of distribution network reliability after inclusion of wind based DGs at isolated mode. Jang and Singh [25], developed a new models and concepts for computing a distribution network reliability with the consideration of protection system failures effect into account. Amanmulla et al. [26], developed a new methodology for network reconfiguration to improve reliability and reduce total power losses using Binary PSO. Lette dasilva et al. [27], presented a combined analytical and monti-carlo simulation approach for identifying power transfer capability to other feeders after incorporating Distributed Energy Resources (DERs). Meneses and Mantovani [28], developed a mathematical model for analyzing the effect on distribution network after inclusion of DG. The main focus is to compute exchange cost between reliability and operation of distribution network at islanding mode.

Awad et al. [29], presented a two stage model for Energy Storage Systems (ESS) placement at optimal allocation in distribution network for reliability improvement. Ref. [30], provided a customer preferences based reliability enhancement options such as utility deploy DG, sectionalizing switches and tie-switches configuration. Zon et al. [31], introduced a probalistic based analytical approach for assessment of system reliability after inclusion of dispatchable and non dispatchable renewable DGs. Paterakis et al. [32], used a Mixed Integer Linear Programming (MILP) technique for solving multi-objective network re-configuration problem with the consideration of power loss and commonly used reliability indices. Ray et al. [33], implemented a Differential Search Algorithm (DSA) to identify modified value of rate of failure and time of repair of several distributor segments for reliability enhancement with and without inclusion of DG units. Awad et al. [34], examined the impact on reliability cost and operation cost after allocating dispatchable DG into the network. Kumar et al. [35], implemented a Cat Swarm Optimization (CSO) for improvement of distribution network reliability by incorporating of multiple DG units at optimal allocation. Arya et al. [36], identified and modified the values of failure rate as well as repair time of distribution line using Coordinated Aggregated PSO. Again Arya et al. [37], presented a Differential Evaluation (DE) algorithm for enhancement of system reliability after inclusion of DG units. Kavousi-Fard and Niknam [38], introduced a new self adaptive modified clonal selection algorithm to solve network reconfiguration problem for reliability improvement. Saboori et al. [39], suggested an efficient approach to identify optimal allocation and size of ESS for reliability enhancement. Narimani et al. [40], solved a multi-objective network re-configuration problem through Enhanced Gravitational Search Algorithm (EGSA) for minimization of total power loss, operation cost and reliability cost.

From the above aforementioned work, it is noticed that most of the artificial techniques are suffered from premature convergence. Therefore, many researchers used modified and hybrid optimization algorithms to determine optimal and feasible outcomes of the problem. It can be done by incorporating some factor or parameter in the algorithm equations for improving the strength and eliminating the frailty. This has encouraged the present authors to modify the optimization algorithm. The proposed MGABC algorithm improves the searching ability as well as convergence nature of basic GABC algorithm by modifying the probability equation. Moreover, power loss, total cost including reliability cost, IVS and total voltage deviation are not reported yet in the available literatures on optimal DG placement and reliability enhancement of distribution network problems. Hence, in this paper both the problems are solved simultaneously. To check the feasibility and effectiveness of the proposed methodology, it has been implemented on 8-bus distribution system. The obtained numerical outcomes also have been compared to the other intelligent techniques which are available in the published literature.

The authors' contributions in this work are as follows:

- GABC optimization algorithm has been modified for improving the performance and solution quality of the problem.
- A new comprehensive multi-objective function is formulated by combining DG placement and reliability enhancement problem.

Following matters are addressed by the authors:

- Identify optimal allocation, size of DG units and evaluate modified values of failure rate as well as repair time of different distributed segments simultaneously through MGABC algorithm and also, satisfy all equality and inequality operating constraints.
- Evaluation of consumer and energy oriented based reliability indices within the threshold limit with and without incorporation of DG units.
- Impact on power loss, IVS, total voltage deviation and total operating cost has been analyzed after inclusion of DG units.

1.1 Organization of paper

The paper is organized as follows: Sect. 2 represents mathematical problem formulation, which includes objective functions with some equality and inequality operating constraints. Sections 3 and 4 describes an IVS and voltage deviation respectively. Cost analysis portion has been defined in Sect. 5. Brief introduction about proposed MGABC optimization algorithm and its procedure for implementation are mentioned in Sect. 6. Discussions on numerical outcomes are discussed in Sect. 7 and conclusions are illustrated in Sect. 8.

2 Mathematical problem formulation

In this section, a new mathematical multi-objective function is designed (16) that include technical and economical factors such as power loss, voltage stability, voltage deviation, purchase active power cost from grid, DG installation cost, DG O&M cost and reliability cost. These propositions are combined together and then solved simultaneously using weighting factors approach, subjected to some equality and inequality operating constraints as given (17)–(31). In addition to that, it also evaluates the distribution system reliability indices with in the desired limit and these are discussed below.

2.1 Reliability indices

Over the last few years the distribution system reliability has received significantly less attention as compared to the generating system. The main reason is the distribution system relatively cheaper than the generating systems. Primary aim of electrical power utilities is to offer economic and best quality of power supply to the consumer for maintaining system efficiency and reliability. The three important reliability parameters of the distribution network [18] are (i) average failure rate (ii) average outage

time (iii) average annual outage time. Distribution system reliability may be evaluated by various approaches such as analytical and simulation. The distribution system reliability indices are classified into two categories (i) Customer Oriented Based (ii) Energy Oriented Based. For checking the performance of distribution utilities such indices are very useful and they are discussed below.
A System Average Interruption Frequency Index (SAIFI) [18]

$$SAIFI = \frac{\sum FR_{sys,i}\ NC_i}{\sum NC_i} \tag{1}$$

Average failure rate of the system is calculated using (2).

$$FR_{sys,i} = \sum_{i \in s} FR_i \tag{2}$$

B System Average Interruption Duation Index (SAIDI) [18]

$$SAIDI = \frac{\sum OU_{sys,i}\ NC_i}{\sum NC_i} \tag{3}$$

Here $OU_{sys,i}$ is the duration of annual outage and it is computed using (4).

$$OU_{sys,i} = \sum_{i \in s} FR_i\ RR_i \tag{4}$$

C Customer Average Interruption Duation Index (CAIDI) [18]

$$CAIDI = \frac{\sum OU_{sys,i}\ NC_i}{\sum FR_{sys,i}\ NC_i} \tag{5}$$

D Average Energy Not Supplied (AENS) [18]

$$AENS = \frac{\sum AL_i\ OU_{sys,i}}{\sum NC_i} \tag{6}$$

E Expected Energy Not Supplied (EENS) [18]

$$EENS = \sum AL_i.OU_{sys,i} \tag{7}$$

The details of average and minimum values of rate of failure and time of repair for each distribution line are specified in appendix Table A.1. Similarly Table A.2 represents an average load and number of customers connected across each bus.

In this work, three objective functions are formulated. First one is a multi-objective function; which is a combination of different objectives of a problem such as total operating cost, IVS and total voltage deviation of a network. Second objective function is a reliability based cost function with the consideration of DG units. And, third one is comprehensive multi-objective function formulated by combining first and second objective functions. The detailed discussions on these objective functions are indicated below:

2.2 Objective functions

A. Multi-objective function for minimization of total cost, IVS and voltage deviation considering distribution system reliability

The main target is to analyze the impact of optimal placing and sizing of DG units in a distribution system. Therefore, multi-objective function is designed by considering total operating cost, IVS, and total voltage deviation considering distribution system reliability without including DGs with suitable weighing factors. Whereas the total operating cost is a combination of power loss cost, purchase active power cost from the grid, DG installation cost, DG O&M cost and reliability cost of the distribution network. This may be expressed using (8).

$$MinimizationF = w1 \times \left(C_{Loss} + \sum_{i=1}^{NL} \left[\frac{FR_i^0 - FR_i}{FR_i - FR_{i,\min}} \right] + \sum_{i=1}^{NL} \left[\frac{RR_i^0 - RR_i}{RR_i - RR_{i,\min}} \right] \right) + \left(C_p + DG_{instt} + DG_{O\&M} \right) + w2 \times IVS_T + w3 \times V_{deviation} \tag{8}$$

Here $w1$, $w2$ and $w3$ are the weighing factor. Fifth and sixth term of an objective function indicates the distribution system reliability cost of distribution network without including DG units.

B. Minimization of distribution system reliability cost including DGs

Incorporation of many DG units may influence the distribution network reliability to a great extent. If DG start for a short duration of time, the time of outage will be improved, which can reduce the cost related with the modified values of rate of failure and time of repair. However, during the same time, the incentive offered by DG per kW cost may be increased. Contemplating on these facets jointly, the fitness function under such situations indicates the modified cost of rate of failure, time of repair and cost of energy supplied by DG [33]. The reliability based cost function after DG inclusion may be represented as

$$MinimizationF = \sum_{k=1}^{n-1} \frac{\alpha_k}{FR_k^2} + \sum_{k=1}^{n-1} \frac{\beta_k}{RR_k} + ADCOST\,(EENSO - EENSD) \tag{9}$$

The cost coefficients of rate of failure and time of repair for each distribution lines are indicated in appendix Table A.3.

The values of rate of failure and time of repair for each distributor segments are computed with the consideration of series connected switch with a parallel arrangement of DG unit and a network. The values of rate of failure and outage period for this arrangement are calculated using (10) and (11) respectively.

$$FR_{sdg} = FR_s.FR_{dg}.\left(RR_s + RR_{dg}\right) \tag{10}$$
$$OU_{sdg} = FR_s.FR_{dg}.RR_s.RR_{dg} \tag{11}$$

Here, the unit of FR_s is *failure/year (f/yr)*, RR_s is *hour* and OU is *hour/year (hr/yr)* for obtaining FR_{sdg} in *failure/year (f/yr)* and OU_{sdg} in *hour/year (hr/yr).* The yearly equivalent rate of failure and time of repair can be evaluated after inclusion of DG units using (12), (13) and (14).

$$FR_{eq} = \frac{FR_s.FR_{dg}.\left(RR_s + RR_{dg}\right)}{8760} + FR_{sw} \tag{12}$$
$$OU_{eq} = \frac{FR_s.FR_{dg}.RR_s.RR_{dg}}{8760} + FR_{sw}.RR_{sw} \tag{13}$$
$$RR_{eq} = \frac{OU_{eq}}{FR_{eq}} \tag{14}$$

C. Comprehensive multi-objective function for minimization of total operating cost, IVS and total voltage deviation considering distribution system reliability including DGs

A comprehensive multi-objective function is formulated by adding up the fitness function (8) and (9) and then solved simultaneously. The positions and sizes of DG units, rate of failure and repair time of various distribution segments are found simultaneously through proposed algorithm. This comprehensive multi-objective function of the problem can be represented using (15).

$$\begin{aligned} Minimization F = w1 \times \Bigg(& C_{Loss} + \sum_{k=1}^{n-1} \frac{\alpha_k}{FR_k^2} \\ & + \sum_{k=1}^{n-1} \frac{\beta_k}{RR_k} + ADCOST\,(EENSO - EENSD) \Bigg) \\ & + C_p + DG_{instt} + DG_{O\&M} + w2 \times IVS_T + w3 \times V_{deviation} \end{aligned} \tag{15}$$

In equation (8) and (15) all terms are normalized through weighing factor approach. In this multi-objective function the cost portion i.e. DG installation cost, DG O&M cost and purchase active power cost is very high whereas power loss cost and reliability cost is very low as compared to other cost, so it has been multiplied with the higher value of weighing factor ($w1$). The terms IVS and total voltage deviation having fewer roles during optimization, these values are totally depending upon the load flow calculations but for the sake of equalization of weighing factors, these are multiplied with the weighing factor ($w2$) and ($w3$). The purpose of multiplying weighing factor is to optimize/normalize each term of multi-objective function properly. The values of weighing factors $w1$, $w2$ and $w3$ used in this study are 60, 20 and 20% respectively.

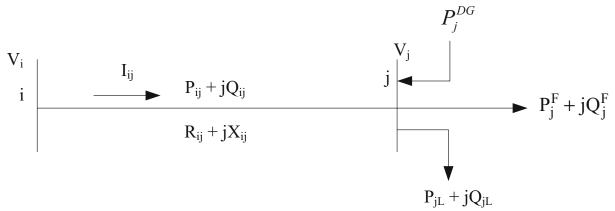

Fig. 1 Equivalent branch of an electrical distribution network

2.3 Operating constraint

2.3.1 Equality constraints

2. 3.1.1 Load flow calculations
Consider a distribution line *i-j* having series resistance R_{ij} and series reactance X_{ij}. The active and reactive load is P_{jL} and Q_{jL} connected across jth bus. A typical equivalent branch diagram of an electrical distribution network is illustrated in Fig. 1. Active and reactive power flow between the buses is calculated using (16) and (17). Receiving end bus voltage V_j is calculated using (18) [41]. The set of equations (16) to (18) have been derived with the help of Kirchoff's law.

$$P_{ij} = P_j^F + P_{jL} - P_j^{DG} + \frac{R_{ij}}{V_i^2}\left(P_{ij}^2 + Q_{ij}^2\right) \tag{16}$$

$$Q_{ij} = Q_j^F + Q_{jL} + \frac{X_{ij}}{V_i^2}\left(P_{ij}^2 + Q_{ij}^2\right) \tag{17}$$

$$V_j^2 = V_i^2 - 2\left(P_{ij}R_{ij} + Q_{ij}X_{ij}\right) + \frac{R_{ij}^2 + X_{ij}^2}{V_i^2}\left(P_{ij}^2 + Q_{ij}^2\right) \tag{18}$$

Current flowing through a branch *ij* is evaluated using (19)

$$I_{ij} = \sqrt{\frac{P_{ij}^2 + Q_{ij}^2}{V_i^2}} \tag{19}$$

Active and reactive power loss between ith and jth bus are calculated using (20) and (21) respectively. Summation of these power losses across each branch represents the total power loss of a network and it may be defined using (22)

$$P_{Loss}(i, j) = I_{ij}^2 R_{ij} \tag{20}$$

$$Q_{Loss}(i, j) = I_{ij}^2 X_{ij} \tag{21}$$

$$P_{TLoss} = \sum_{\substack{i=0 \\ i \neq j}}^{n-1} P_{Loss}(i, j) \tag{22}$$

2.3.1.2 DG penetration level
DG penetration level is evaluated using (23)

$$PL = \frac{S_{DG}}{S_{Load}} \times 100 \tag{23}$$

2.3.2 Inequality constraints

2.3.2.1 DG capacity limit
It is assumed that, DG can penetrate up to 50% of total load of the network and it may be expressed as [42]

$$\sum_{i \in n} S_{DG,i} \leq 0.50 \times S_{Load} \tag{24}$$

2.3.2.2 Voltage limit
Voltage of each bus should be in between maximum and minimum range and it may be defined using (25)

$$V_i^{\min} \leq V_i \leq V_i^{\max} \quad i \in n \tag{25}$$

2.3.2.3 Reliability constraints
Inequality constraints of customer oriented based reliability indices (26)–(31) can be defined as

$$SAIFI - SAIFI_{Th} \leq 0 \tag{26}$$

$$SAIDI - SAIDI_{Th} \leq 0 \tag{27}$$

$$CAIDI - CAIDI_{Th} \leq 0 \tag{28}$$

$$AENS - AENS_{Th} \leq 0 \tag{29}$$

Rate of failure value and time of repair for various distribution segments must lie within boundary conditions.

$$FR_{i,\min} \leq FR_i \leq FR_i^0 \tag{30}$$

$$RR_{i,\min} \leq RR_i \leq RR_i^0 \tag{31}$$

$SAIFI_{Th}$, $SAIDI_{Th}$, $CAIDI_{Th}$ and $AENS_{Th}$ are the threshold values of reliability indices. $FR_{i,\min}$, FR_i and FR_i^0 represents the minimum value, modified value and average value of rate of failure respectively. Similarly $RR_{i,\min}$, RR_i and RR_i^0 are the minimum value, modified value and average value of time of repair respectively.

Some assumptions have been considered in this study

- DG can supply only active power.

- The maximum DG penetration level is not more than 50% of total kVA loading of the network.
- The considered test system is balanced.
- Substation/slack bus voltage is 1 p.u.
- Harmonics effect is neglected.

3 Index of voltage stability

IVS is a numerical solution that indicates the closeness of the system to collapse. The purpose of IVS is to calculate the stability of the buses and locate sensitive buses of the network. Voltage collapse begins from most sensitive bus and spread further to another sensitive bus. The IVS value of each bus may be improved, if DG is optimally incorporated with the distribution network. Thus, the system stability will be improved and reduced the possibilities of voltage collapse. The IVS value of each bus of the distribution system is calculated using (32) [43].

$$IVS_j = |V_i|^4 - 4\left\{P_{jL}X_{ij} - Q_{jL}R_{ij}\right\}^2 - 4\left\{P_{jL}R_{ij} + Q_{jL}X_{ij}\right\}|V_i|^2 \tag{32}$$

Condition for a stable operation of distribution system is $IVS_j \geq 0$ whereas $j = 2,\ldots,n$. Where IVS_j value is found to be minimum that indicate the most critical bus and has more chances to voltage collapse.

4 Voltage deviation

Bus voltage magnitude is the most significant indication for analyzing power behavior. If the large variations occur in voltage level, it represents the poor performance of the system. The total voltage deviation of the system is evaluated using (33).

$$V_{deviation} = \sum_{i \in n} \frac{|V_{rated} - V_i|}{V_{rated}} \tag{33}$$

5 Cost analysis

5.1 Cost of power loss

The total cost of power loss of distribution network is evaluated using (34)

$$C_{Loss} = K_p \times P_{TLoss} \times T \tag{34}$$

5.2 Purchased active power cost from grid

Purchased active power cost from grid is evaluated using (35).

$$SS_c = E_p \times P_{Load} \times T \tag{35}$$

5.3 Cost of DG installation

The cost of DG installation can be evaluated using (36)

$$DG_{instt} = \sum_{i=1}^{NDG} DG_{cap,i} \times K_{DG}^{i} \tag{36}$$

5.4 DG O&M Cost

O&M cost of DG depends upon the active power supplied by DG into the system. It can be evaluated using (37).

$$DG_{O\&M} = \sum_{i=1}^{NDG} P_{real,i} \times K_{DG}^{OM} \times T \tag{37}$$

6 Optimization algorithm

6.1 Artificial bee colony (ABC)

ABC optimization algorithm is a most popular meta-heuristic technique to solve various numerical optimization tasks and it was developed by Basturk and Karaboga [44]. This algorithm is motivated from the social nature of honey bees. It is a combination of three different kind of bees namely employed bee, onlooker bee and scout bee, where an onlooker and scout bee are unemployed bee. Employed bees seek out a food source and exploit it while the onlooker bees wait in the hive. An employed bee provides the details to the onlooker bees regarding a food source. As per the information received, the onlooker bees choose a better food source.

$$F_{ij} = F_{\min,j} + rand\left(F_{\max,j} - F_{\min,j}\right) \tag{38}$$

Here $F_{min,j}$ and $F_{max,j}$ represents the maximum and minimum values of jth variable at ith solution and $rand$ indicates the random number, which lies between [0 1]. The probability of deciding a better food location by an onlooker bee is evaluated using (39).

$$P_{prob,i} = \frac{fit_i}{\sum_{k}^{N} fit_k} \tag{39}$$

where fit_i is the objective function value at ith candidate solution and $k\,\varepsilon\{1, 2, \ldots, D\}$. The term D represents a total number of decision variables. fit_k is the fitness function value of every cycle. If the solution values are not improved in the pre defined trial then scout bee locate a new food source in a random manner using (38). The entire population has a solution, the equation (40) represent the solution of the ith food source.

$$F_i = \{F_{i1}, F_{i2}, \ldots, F_{iD}\} \tag{40}$$

In the first step, the candidate solution is determined in a random manner using (38). Both employed and onlooker bees searching a new food source using (41).

$$F_{new,ij} = F_{ij} + \varphi_{ij}\left(F_{ij} - F_{kj}\right) \tag{41}$$

Here, F_{kj} is a food location which is related to the employed bees or nearer to F_{ij}.

6.2 Gbest-guided artificial bee colony (GABC) algorithm

The performance of ABC algorithm is excellent for exploration but unfortunate poor in exploitation. In sort, for improving the characteristics of ABC algorithm an additional term is inserted in an equation (41) [45]. The modified equation (42) can be represented as

$$F_{new.ij} = F_{ij} + \varphi_{ij}(F_{ij} - F_{kj}) + c(F_j + F_{ij}) \tag{42}$$

Where c is a tuning parameter and its value lies between [0, 2], the selection of c parameter is chosen correctly for a better solution. F_j represents a global best solution of the present iteration. The probability of onlooker bees to select a better food source (39) is same as ABC algorithm.

6.3 Modified GABC (MGABC) algorithm

Further enhance the characteristics and performance of GABC algorithm, the probability equation of onlooker bees has been modified from (39) by (43) for a better food source solution.

$$P_{\text{mod},i} = \frac{0.9 \times fit_i}{fit_{best}} + 0.1 \tag{43}$$

where fit_{best} is the global best fitness value among all solutions.

6.4 Implementation of MGABC algorithm to solve DG placement and reliability enhancement problem

In this method, the proposed MGABC algorithm is implemented for solving optimal DG placement and reliability enhancement problem. It also determines the IVS values of each bus along with total voltage deviation of the network.

An optimal topology can be represented for finding better solution

$$K^1 = \left[DG^1 Reliability^1\right]$$

In the K^1 vector, DG^1 is a six column matrix and it can be defined as

$$DG^1 = \left[\underbrace{Location^1_{DG1} Location^1_{DG2} Location^1_{DG3}}_{DGLocation} \underbrace{Size^1_{DG1} Size^1_{DG2} Size^1_{DG3}}_{DGSize}\right]$$

And $Reliability^1$ is a 1×2 matrix as follows

$$Reliability^1 = \left[Failure^1_{rate} Repair^1_{time}\right]$$

In the $Reliability^1$ vector, $Failure^1_{rate}$ and $Repair^1_{time}$ is a seven column matrix and it is represented as

$$Failure^1_{rate} = \left[FR^1_1 \quad FR^1_2 \quad FR^1_3 \quad FR^1_4 \quad FR^1_5 \quad FR^1_6 \quad FR^1_7\right]$$

$$Repair^1_{time} = \left[RR^1_1 \quad RR^1_2 \quad RR^1_3 \quad RR^1_4 \quad RR^1_5 \quad RR^1_6 \quad RR^1_7\right]$$

Where $Location^1_{DG}$ and $Size^1_{DG}$ are the initial DG units allocation and ratings respectively. $Failure^1_{rate}$ and $Repair^1_{time}$ are the initial value of rate of failure and time of repair for different distribution line respectively. By updating MGABC algorithm, the jth solution vectors are produced with the updated location, size of DG units and rate of failure and time of repair for every distributor segments are as follow.

$$K^j = \left[DG^j Reliability^j\right]$$

For every jth solution, load flow calculations are performed and evaluate objective function values. This function value has been compared to the previous solution values and better solution has been elected while discarded the worst. Figure 2 indicates the procedure for solving DG placement and reliability enhancement problem through MGABC algorithm.

7 Simulation and numerical results

In this section, the proposed methodology is tested on 8-bus distribution network. This system has one main feeder and two sub-feeders. It is operated at 12.66 kV with 100 MVA base. The block diagram of this test system is illustrated in Fig. 3 and the network details such as load and line data are available in appendix Table A.4. In this work, it is assumed that DG can supply only active power to the network at unity power factor. This complete computational work has been executed on MATLAB environment. Adopted control parameters of MGABC algorithm for solving this problem is shown in Table 1. To know the effectiveness and feasibility of proposed methodology, following cases have been studied.

Case-1: Multi-objective function for minimization of total operating cost, IVS and voltage deviation with the consideration of distribution system reliability without including DGs (8).

Case-2: Minimization of reliability based cost function including DGs (9).

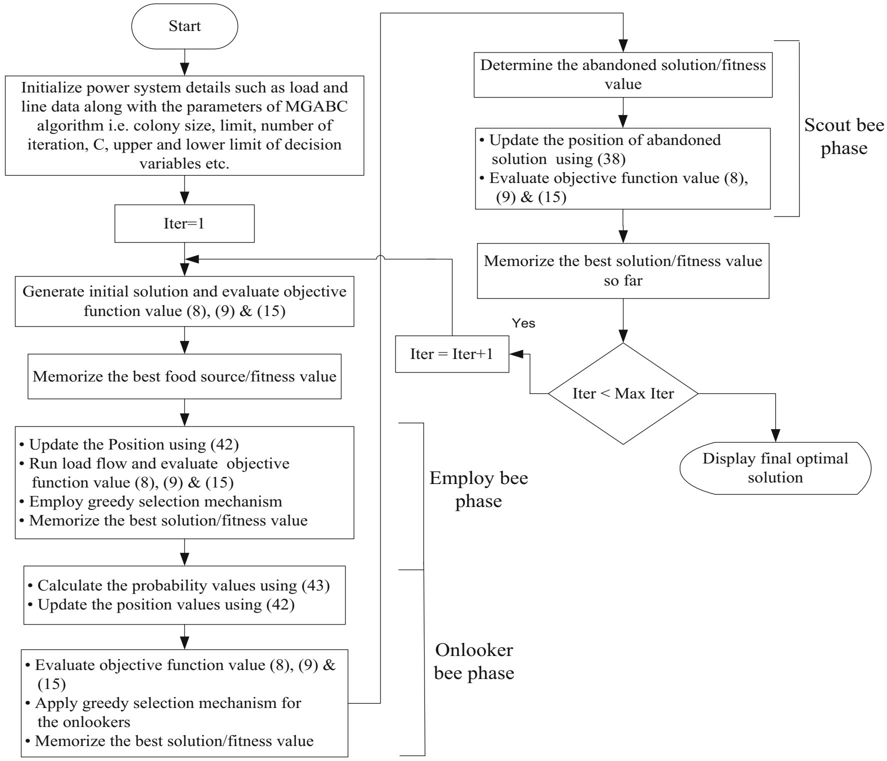

Fig. 2 Flowchart for solving DG placement and reliability enhancement problem through MGABC algorithm

Case-3: Comprehensive multi-objective function for minimization of total operating cost, IVS and voltage deviation with the consideration of distribution system reliability including DGs (15).

7.1 Discussion on numerical results

The proposed algorithm has been utilized to recognize finest allocation and size of DG units. And, also evaluates the modified values of rate of failure and time of repair of various distribution segments simultaneously, in order to achieve minimum power loss, reduced total operating cost, enhanced system reliability, improved voltage profile along with IVS and reduced total voltage deviation. Here, the total operating cost is a combination of purchased active power cost from grid, cost of power loss, DG installation cost, O&M cost and reliability cost of the network. Case wise detailed discussions on numerical outcomes are discussed below.

Case 1: In this case, the total real power loss is diminished from 136.92 to 22.25 kW after DG placement and loss reduction is 83.75%. DG optimal locations are 3, 5 and 7 and their respective sizes on these buses are 624, 679 and 655 kW. Minimum network voltage and IVS are also enhanced to a significant value after DG inclusion.

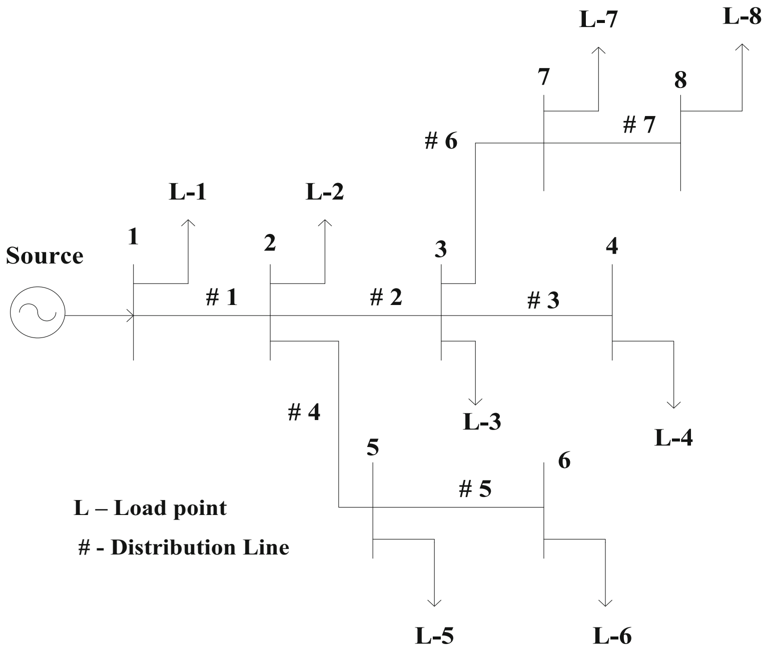

Fig. 3 Block diagram of 8 bus radial distribution network

Table 1 Adopted control parameters of MGABC Algorithm

Cases	Colony size	Food source	Number of employed bees	Number of onlooker bees	Limit	C	MCN
Case 1	50	Colony size/2	50	3 × Colony size	4	1.5	100
Case 2	50	Colony size/2	50	3 × Colony size	3	1.5	400
Case 3	50	Colony size/2	50	3 × Colony size	4	1.5	200

In addition to that, the purchased active power cost from grid is 841310 US $, power loss cost is 11695 US $, DG installation cost and O&M cost is 783200 and 617474 US $ respectively. The total operating cost is 2253700 US $, minimum system voltage and IVS is 0.9774 and 0.9297 pu respectively. The total voltage deviation of a network before and after DG inclusion is 0.3390 and 0.1160 pu respectively. Furthermore, these numerical outcomes have been compared with the ABC and GABC algorithm for knowing the effectiveness and feasibility of MGABC algorithm as mentioned in Table 2. The optimal values of rate of failure and time of repair of each distribution segment are determined through ABC, GABC and MGABC algorithms as tabulated in Table 3. Figure 4, represents the convergence characteristic comparison between these algorithms and it is observed that the MGABC algorithm is capable to reach optimal solution rapidly.

Case 2: The optimum values of rate of failure and time of repair of every distribution lines are evaluated through proposed algorithm to minimize the reliability cost of the

Table 2 Simulation results and comparison between ABC, GABC and MGABC algorithm for case 1

Algorithms	Purchase active power cost (US $)	Power loss cost (US $)	DG installation cost (US $)	DG O&M cost (US $)	Reliability cost (US $)	IVS (pu)	Power loss (kW)	Voltage deviation (pu)	Fitness function value (8)
ABC	842168	11748	782400	616844	26.78	7.619	22.35	0.1171	2594860.20
GABC	840881	11686	783600	617790	21.55	7.625	22.23	0.1158	2593709.82
MGABC	841310	11695	783200	617474	19.52	7.624	22.25	0.1160	2593629.97

Table 3 Optimum value of rate of failure and time of repair evaluated through ABC, GABC and MGABC algorithm for case 1

Variables	ABC	GABC	MGABC
FR_1/year	0.2315	0.2326	0.2346
FR_2/year	0.0929	0.0942	0.0980
FR_3/year	0.1839	0.2023	0.2050
FR_4/year	0.1551	0.1890	0.1900
FR_5/year	0.1782	0.1974	0.2000
FR_6/year	0.0819	0.0861	0.1000
FR_7/year	0.0989	0.0983	0.1000
RR_1(h)	6.9061	6.8164	6.9300
RR_2(h)	7.5714	7.8572	7.9000
RR_3(h)	7.6058	7.8055	7.2301
RR_4(h)	11.700	11.70	11.700
RR_5(h)	11.5779	11.2473	11.800
RR_6(h)	7.7365	7.6854	8.000
RR_7(h)	8.6455	11.0836	12.000
Total reliability cost (US $)	26.7835	21.5505	19.5219

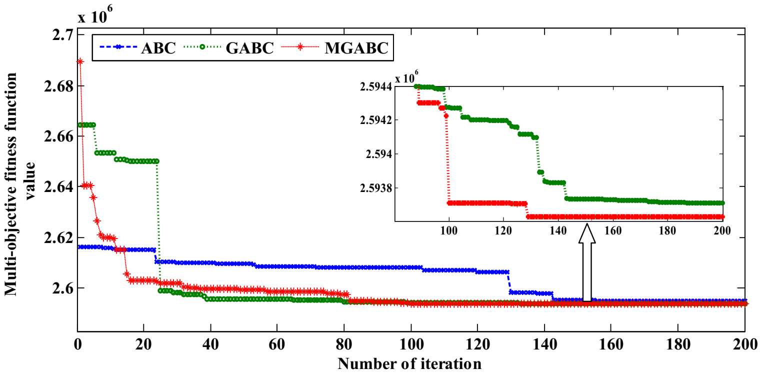

Fig. 4 Convergence characteristic performance comparison for case 1

network after incorporation of DG units. *ADCOST* is assumed to be 1.5 US $ and *EENSO* is evaluated using (7) and its evaluated value is 10000 US $. The obtained numerical outcomes are compared with the published DSA technique results along with ABC and GABC algorithm as tabulated in Table 4 for showing the effectiveness and capability of proposed technique. The reliability based cost function (9) values evaluated through ABC, GABC and MGABC algorithm are 20664, 20532 and 20465 US $ respectively. In addition to that, the convergence characteristic performance comparison between ABC, GABC and MGABC optimization techniques is portrayed in Fig. 5. Therefore, it can be stated that the proposed technique is more capable for

Table 4 Optimum value of rate of failure and time of repair evaluated through various algorithms for case 2

Variables	DSA [33]	ABC	GABC	MGABC
FR_1/year	0.2397	0.2336	0.2438	0.2318
FR_2/year	0.1602	0.1751	0.1705	0.1726
FR_3/year	0.3269	0.2741	0.2842	0.3311
FR_4/year	0.35775	0.35951	0.3202	0.3371
FR_5/year	0.2174	0.2441	0.2271	0.2171
FR_6/year	0.0935	0.1422	0.1497	0.1347
FR_7/year	0.1367	0.1205	0.1350	0.1373
RR_1(h)	6.00	6.2550	6.3131	6.3025
RR_2(h)	6.00	6.3704	6.4382	6.2276
RR_3(h)	14.3039	6.8776	8.6256	7.0112
RR_4(h)	11.8298	8.3028	8.8953	9.1011
RR_5(h)	17.7203	12.4583	13.2752	13.6584
RR_6(h)	12.00	11.4729	8.5970	11.9158
RR_7(h)	17.4869	9.1647	17.0875	15.9290
Total reliability cost (US $)	21804	20664	20532	20465

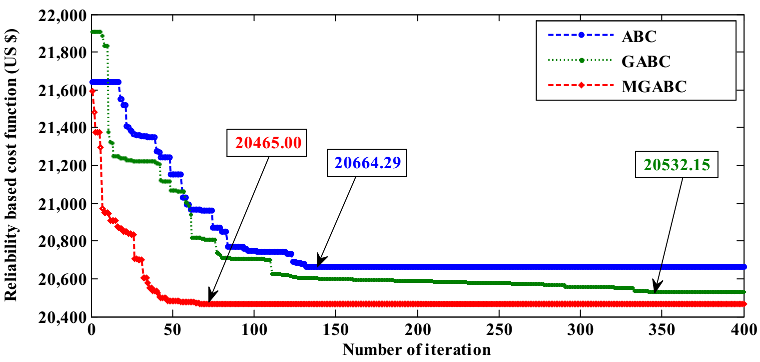

Fig. 5 Convergence characteristic performance comparison for case 2

finding an optimal solution. Moreover, customer oriented based reliability indices of a network are also evaluated within the desired limit as indicated in Table 8.

Case 3: In this case, both case 1 and case 2 are combined together. Then, MGABC algorithm is utilized to determine exact location, size of DG units and modified the values of rate of failure and time of repair for different distribution segments simultaneously. After incorporation of DGs at optimal position, the active power loss becomes 22.24 kW and loss reduction is 83.76%. The optimal locations of DGs are at bus no. 3, 5 and 7 and the respective sizes on these buses are 654, 687 and 618 kW. Thereby, it improves voltage level, reduces total real power loss and also evaluates the system reliability indices within desired limit. Moreover, various costs have been evaluated

Table 5 Simulation results and comparison between ABC, GABC and MGABC algorithm for case 3

Algorithms	Purchase active power cost (US $)	Power loss cost (US $)	DG installation cost (US $)	DG O&M cost (US $)	Reliability cost (US $)	IVS (pu)	Power loss (kW)	Voltage deviation (pu)	Fitness function value (15)
ABC	860626	12875	765200	603283	22570	7.6037	24.50	0.1217	2638295.77
GABC	854616	12045	770800	607698	22981	7.6151	22.92	0.1186	2617802.23
MGABC	840881	11692	783600	617790	21730	7.6219	22.24	0.1164	2615116.32

Table 6 Optimum values of rate of failure and time of repair evaluated through ABC, GABC and MGABC algorithm for case 3

Variables	ABC	GABC	MGABC
FR_1/year	0.2264	0.2476	0.2316
FR_2/year	0.1608	0.1593	0.1420
FR_3/year	0.3210	0.2832	0.2318
FR_4/year	0.2786	0.2184	0.2996
FR_5/year	0.2316	0.2192	0.2204
FR_6/year	0.0909	0.1214	0.1222
FR_7/year	0.0779	0.1248	0.1444
RR_1(h)	6.5799	6.6982	6.5177
RR_2(h)	6.5122	6.7352	6.9046
RR_3(h)	8.1267	6.5354	7.2324
RR_4(h)	9.3375	10.3025	10.6551
RR_5(h)	11.5545	13.5484	13.4000
RR_6(h)	10.0252	9.4078	10.3894
RR_7(h)	15.2704	14.0607	12.0815
Total reliability cost (US $)	22570	22981	21730

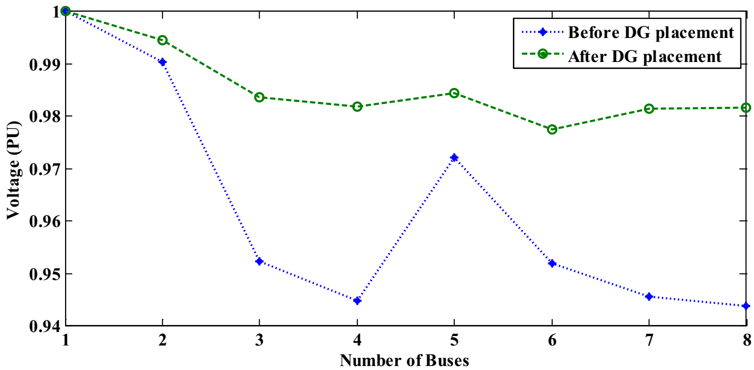

Fig. 6 Voltage profile comparison before and after DG placement

after inclusion of DG units. The purchase active power cost from grid is 840881 US $, power loss cost is 11692 US $, DG installation cost and O&M cost is 783600 and 617790 US $ respectively. Distribution system reliability cost after inclusion of DG unit is 21730 US $ and finally, the total operating cost of a network become 2.27 million US $. In addition, numerical outcomes obtained through proposed algorithm are compared to ABC and GABC algorithm as shown in Table 5. The optimum value of failure rate and time of repair of each distribution lines are also determined through these algorithms as indicated in Table 6. Voltage profile comparison with and without inclusion of DG units is depicted in Fig. 6. Figure 7 indicates the convergence characteristic performance comparison between ABC, GABC and MGABC algorithm.

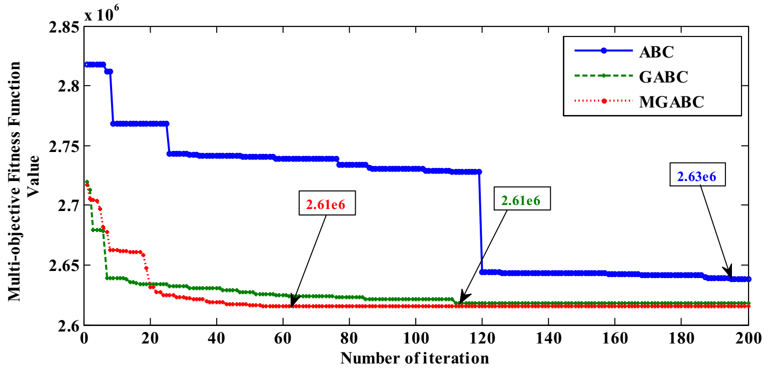

Fig. 7 Convergence characteristic performance comparison for case 3

Table 7 Case 1 and case 3 simulation results for 8-bus distribution system

Particulars	Base case	Case 1	Case 3
∑kW loss	136.92	22.25	22.24
% kWloss reduction	–	83.75	83.76
∑kVar loss	162.93	34.09	33.99
% kVar loss reduction	–	79.08	79.14
Location and size of DG (kW)	–	3–624	3–654
		5–679	5–687
		7–655	7–618
∑DG penetration level	–	46.80%	46.83%
Best fitness value	–	2593629	2615116
Average fitness value	–	2593691	2635209
Worst fitness value	–	2593997	2681154
Standard deviation	–	126.51	21588
$\lvert V_{min}\rvert$(pu)	0.9439	0.9774	0.9775
$\lvert V_{max}\rvert$(pu)	0.9904	0.9946	0.9946
$\lvert IVS_{min}\rvert$(pu)	0.7939	0.9297	0.9284
$\lvert IVS_{max}\rvert$(pu)	0.9650	0.9809	0.9809
$\sum \lvert V_{deviation}\rvert$(pu)	0.3390	0.1160	0.1164

It can be noticed that, the MGABC algorithm is more proficient rather than other algorithms for finding optimal solutions. The computational time of CPU to evaluate optimal solution including load flow calculations and reliability analysis is around 28.09 seconds.

Case 1 and case 3 numerical outcomes' comparison in terms of power loss, DG penetration level, minimum and maximum voltage, IVS and voltage deviation are mentioned in Table 7. Table 8 represents the cost analysis portion for all considered cases, which include purchased active power cost, power loss cost, DG installation cost, O&M cost and reliability cost. Furthermore, various reliability indices are also

Table 8 Cost analysis of various cases for 8-bus distribution system

Cases	Purchased active power cost (US $)	Power loss cost (US $)	DG installation cost (US $)	DG O&M cost (US $)	Reliability cost (US $)	Total cost (US $)
Case 1	841310	11695	783200	617474	19.52	2253700
Case 2	–	–	–	–	20465	20465
Case 3	840881	11692	783600	617790	21730	2275694

evaluated within the desired limit through ABC, GABC and MGABC algorithm for case 1, case 2 and case 3 as indicated in Table 9. Hence, the aforementioned results indicate the superiority and capability of proposed algorithm to achieve good quality solution in an effective way.

In future, DSTATCOM, DSSSC and various DERs can be optimally incorporated in the unbalanced and harmonic systems for improving the network performance in terms of power quality, total cost, power loss and voltages etc. by formulating a new multi-objective fitness function. Such problems can be solved via newly developed/modified/hybrid optimization algorithms.

8 Conclusions

In this study, GABC meta-heuristic optimization algorithm has been modified and implemented successfully for solving DG placement and reliability enhancement multi-objective problem simultaneously. In this work, three cases have been considered. In Case 1, a multi-objective function is formulated for evaluating finest allocation and rating of DG units for reducing total operating cost, voltage deviation and improve IVS. In Case 2, distribution system reliability based objective function is formulated including DG units for modifying the value of rate of failure and time of repair for every distributor segments. In Case 3, both case 1 and case 2 objective function has been combined together to formulate a new comprehensive multi-objective function. This is solved through proposed MGABC algorithm for identifying optimal allocation, size of DG units and modified the values of rate of failure and time of repair for different distribution segments. Thereby, it reduces the total operating cost, power loss, total voltage deviation, improve IVS, voltage level and also satisfies all inequality and equality operating constraints as well. Furthermore, the obtained numerical outcomes through proposed algorithm of case 2 are compared to DSA technique which is available in published literature for showing the effectiveness. From the outcomes, it reveals that the proposed approach is better and has fast converging rate to reach optimal solution. In addition, it requires a less effort for tuning the control parameters and capable to solve more complex engineering optimization problems.

Table 9 Evaluation of distribution system reliability indices for case 1, case 2 and case 3 via ABC, GABC, MGABC algorithms

Indices	Base case	ABC			GABC			MGABC			Threshold limit
		Case 1	Case 2	Case 3	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3	
SAIFI	0.72	0.3872	0.4618	0.4254	0.4024	0.4636	0.4395	0.4115	0.4542	0.4329	0.50
SAIDI	8.45	3.0190	3.5099	3.1874	3.1789	3.4412	3.3530	3.2915	3.5009	3.4267	4.0
CAIDI	11.7361	7.7973	6.7451	6.7684	7.8988	6.6130	6.9460	7.9989	6.8234	7.2345	8.0
AENS	26.41	9.1983	9.9999	9.4307	9.6897	10.000	9.8197	9.9455	10.000	9.9999	10.0

Appendix

See Tables A.1, A.2, A.3, A.4.

Table A.1 Average and minimum value of rate of failure and time of repair [33]

Distribution line	# 1	# 2	# 3	# 4	# 5	# 6	# 7
FR_j/ year	0.6	0.3	0.5	0.8	0.3	0.15	0.15
$FR_{j,min}$/year	0.2	0.05	0.1	0.1	0.15	0.05	0.05
Average RR_j(h)	15	14	18	30	22	12	18
$RR_{j,min}$(h)	6	6	4	8	7	6	6

Table A.2 Average load and number of customers [33]

Load buses	Average load $\boldsymbol{L_i}$ **(kW)**	Number of customers, $\boldsymbol{N_i}$
LP–2	1000	200
LP–3	700	150
LP–4	400	100
LP–5	500	150
LP–6	300	100
LP–7	200	250
LP–8	150	50

Table A.3 Values of cost coefficients [33]

Distribution segment	$\boldsymbol{\alpha_k}$ (US $)	$\boldsymbol{\beta_k}$ (US $)
# 1	246	10000
# 2	40	7290
# 3	81	7200
# 4	250	20000
# 5	32	18000
# 6	4.5	3840
# 7	5	9360

Table A.4 Load and line data of 8-bus distribution network

From	To	R (ohm)	X (ohm)	P (kW)	Q (kVAr)
1	2	0.123	0.413	540	160
2	3	2.055	1.164	150	60
3	4	0.905	0.798	780	210
2	5	0.746	1.205	590	446
5	6	1.795	1.716	980	330
3	7	0.698	0.608	298	140
7	8	0.343	0.026	580	120

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