Self-adaptive firefly algorithm-based capacitor banks and distributed generation allocation in hybrid networks

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ABSTRACT

Power system deregulation has made significant changes to the power grid through various technologies, privatization of entities, and improved efficiency and reliability. This work mainly focuses on different combinations of distributed generation (DG) and capacitor banks (CBs) integration to cater to multiple technical, economic, environmental, and reliable concerns. A new optimal planning framework is proposed for optimally allocating the DG units and CBs to achieve multiple objectives. In this work, an augmented objective function is formulated by considering active power losses, voltage deviation, and voltage stability index objectives. This objective function is solved considering various equality and inequality constraints. This work proposes a novel approach for allocation of DGs and CBs in the radial distribution systems (RDSs) using an evolutionary-based self-adaptive firefly algorithm (SAFA). The effectiveness of the developed planning approach is demonstrated on IEEE 33 bus RDS in MATLAB software. The obtained results indicate that proposed planning approach resulted in reduced power losses, voltage deviations, and improved voltage stability.

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1. INTRODUCTION

In recent years, environmentally friendly and pollution-free non-conventional usage of energy in radial distribution systems (RDSs) has an advantage over conventional energy. Distributed generation (DG) in recent years has grown rapidly and it is very important to meet the excess power demand. Generally, power loss minimization has mainly concentrated on network reconfiguration and capacitor bank allocation (CBA) for reactive power support [1]. However, due to the penetration of DG, the passive RDSs are changed to active. Although DG allocation limits the distribution network (DN) operators and inventors due to various planning issues, the administrative system, and resource availability, governments are encouraging low carbon emissions as a means of environmental protection, growing energy needs, and security [2]. The ON load tap changers (OLTCs) of the main transformer, switched substation, and feeder capacitor banks (CBs) are used as controls for reactive voltage control of RDS.

CBA is considered to be a viable solution in HV-based RDSs. CBs act as reactive power a source that minimizes the inductive reactance (X_L) of radial line loading, and they can reduce the reactive power losses by CBA. CBA can be used for voltage control and for the minimization of power losses. Various challenges in the CBA are the selection of the appropriate number of CBs, allocation of CBs for achieving minimum power loss, power factor (PF) control, good voltage profile (VP) and regulation [3], [4]. The emerging advances in power generation technologies and large-scale penetration of DG units are shifting conventional power model away from centralized generation (CG) system to the decentralized generation system. DGs are encouraged to get availed in RDSs widely. The optimal placement of DG units can impact various factors such as technical, economic as well as environmental. Optimal allocation of DG units has several advantages including reduced line losses, improved bus voltages, and environmental benefits [5]. The allocation of DGs is more approved for foremost objective since pollution-free green energy is the only future of the earth. The economic benefits include maintaining the critical load during peak demand periods, reduced costs for operation and maintenance [6]. The environmental benefits include the addition of green energy resources will reduce the emission of carbon which will reduce health hazards.

Several researchers attempted various conventional and meta-heuristic-based approaches to achieve optimal planning of DG units [7]. However, meta-heuristic approaches are used for optimal planning of DGs and CBs for getting optimal results. An improved coordinated allocation approach for real and reactive power sources is developed in [8] for radial and meshed systems. Application of firefly and backtracking search algorithms for solving the allocation of DGs and fixed CBs to reduce losses and VP enhancement of RDS is proposed in [9]. Simultaneous allocation of DG units and CBs in RDSs with voltage and frequency-based voltage models is presented in [10]. The objective of this work is to enhance the grid performance by considering multiple objectives.

2. MODELING OF CAPACITOR BANK AND DISTRIBUTED GENERATION

DNs provide a reliable, economical, and environmentally friendly power supply to consumers while satisfying operational and geographic constraints. In this paper, a direct method is used to solve the load flow (LF) in the radial and weekly meshed DNs and this method was proposed by Teng [11]. Figure 1 depicts an RDS with a CB and a DG unit in the system.

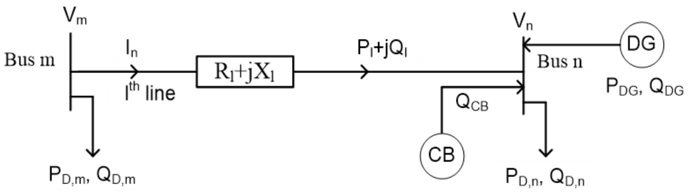

Figure 1. RDS with CB and DG unit

LF developed in this work uses the multiplication of BIBC and BCBV matrices. The development procedure of this method is described below:
The complex power at bus i (S_i) can be formulated as [12],

$$S_i = P_i + jQ_i \quad i = 1,2,\dots,N_B \tag{1}$$

the current injected at bus i in k^{th} iteration can be expressed by,

$$I_i^k = \frac{P_i + jQ_i}{V_i^{k-1}} \quad i = 2,3,\dots,N_{Br} \tag{2}$$

the BIBC matrix is formulated by using the branch current (I_{branch}) and it is expressed by [13],

$$[I_{branch}] = [BIBC][I_{node}] \tag{3}$$

relationship between node voltages and I_{branch} can be represented by,

$$[\Delta V] = [BCBV][I_{branch}] \tag{4}$$

here the receiving end voltage at $(k+1)^{th}$ iteration is given by,

$$[V]^{k+1} = [V]^0 + [\Delta V]^{k+1} \tag{5}$$

by substituting (3) in (4), we can obtain the distribution load matrix (DL) and it can be expressed by,

$$[\Delta V] = [BCBV][BIBC][I_{node}] \tag{6}$$

$$[\Delta V] = [DLF][I_{node}] \tag{7}$$

where $[DLF] = [BCBV][BIBC]$. The convergence criteria for this approach in terms of receiving end voltages is given by [14],

$$max\left[\left|V_i^k\right| - \left|V_i^{k-1}\right|\right] < \in \tag{8}$$

where ∈ is the tolerance value. The total power demand after the installation of DG units (P_D^{new}) is given by,

$$P_D^{new} = P_D - P_{DG} \tag{9}$$

the net reactive power after the installation of CB at bus n (Q_n^{net}) is given by,

$$Q_n^{net} = Q_n - Q_{CB} \tag{10}$$

3. PROBLEM FORMULATION

Optimal allocation problem of DGs in RDS is a MINLP as size of DG can be discrete or continuous in range whereas DG location is discrete in nature [15]. CBA helps with power flow control, PF correction, voltage stability enhancement, minimum loss, and improved VP. In this paper, 3 objectives are formulated as below.

3.1. Loss minimization (F_1)

The RDS has higher power losses when compared to the transmission network due to higher R/X ratio and also the radial structure of network [16]. These losses are given by,

$$P_{loss} = \left(\frac{P^2+Q^2}{|V_R|^2}\right) R \tag{11}$$

$$Q_{loss} = \left(\frac{P^2+Q^2}{|V_R|^2}\right) X \tag{12}$$

this objective function (F_1), i.e., total power loss can be expressed by [17],

$$F_1 = \sum_{i=1}^{N_{Br}} P_{loss,i} \tag{13}$$

3.2. Voltage deviation minimization (F_2)

The second objective, i.e., VD minimization (F_2) helps to minimize the deviation in the voltages which in turn results in improvement in voltages in the RDS [18]. This objective can be expressed by (14).

$$F_2 = \sum_{i=1}^{N_B} \left|V_i - V_i^{ref}\right| \tag{14}$$

3.3. Overall voltage stability index (OVSI)

The VSI value indicates how vulnerable the bus in the RDS is to voltage stability [19], [20]. VSI at any node in the RDS is given by,

$$VSI_i = |V_i^4| - 4\left(P_i X_{ij} - Q_i R_{ij}\right)^2 - 4\left(P_i X_{ij} - Q_i R_{ij}\right)|V_i|^2 \tag{15}$$

the third objective, i.e., the minimization of OVSI (F_3) can be formulated as (16).

$$F_3 = OVSI = \sum_{i=2}^{N_B} VSI_i \tag{16}$$

3.4. Formulation of augmented objective function

In this work, the three objectives (i.e., F_1, F_2, and F_3) are converted into an augmented/single objective (F_{aug}) by using the weighted sum of individual three objectives [21]. The augmented objective function (F_{aug}) can be expressed by,

$$F_{aug} = min[\omega_1 F_1 + \omega_2 F_2 + \omega_3 (1/F_3)] \tag{17}$$

where ω_1, ω_2 and ω_3 are weight factors, and $\omega_1 + \omega_2 + \omega_3 = 1$.

3.5. Constraints

The above-formulated objective function can be optimized and subjected to various constraints for secure operation of the entire RDS.

3.5.1. Power balance constraint

This constraint is stated as follows:

$$P_{loss}^{T} + P_D + \sum_{i=1}^{N_{EVCS}} P_{D,i}^{EVCS} = \sum_{i=1}^{N_{DG}} P_{DG,i} + P_G^{Grid} \tag{18}$$

$$Q_{loss}^{T} + Q_D = \sum_{i=1}^{N_{DG}} Q_{DG,i} + Q_G^{Grid} + \sum_{i=1}^{N_{CB}} Q_{CB} \tag{19}$$

3.5.2. DG location constraints

This constraint can be expressed by,

$$LOC_{DG}^{min} \leq LOC_{DG} \leq LOC_{DG}^{max} \tag{20}$$

where LOC_{DG}^{min} and LOC_{DG}^{max} are lower and upper location limits of DG units.

3.5.3. DG power limits

The power output from DG (P_{DG} and Q_{DG}) units are limited by,

$$P_{DG,i}^{min} \leq P_{DG,i} \leq P_{DG,i}^{max} \tag{21}$$

$$Q_{DG,i}^{min} \leq Q_{DG,i} \leq Q_{DG,i}^{max} \tag{22}$$

3.5.4. DG power factor (PF) constraint

This constraint is required to reduce losses in RDS and this operating PF of DGs is given by,

$$0.8 \leq PF \leq 1 \tag{23}$$

3.5.5. Constraint on reactive power demand (Q_D)

Reactive power obtained from CBs (Q_{CB}) must be less than total reactive demand in RDS (Q_D), and it is expressed by [22],

$$Q_{CB} < Q_D \tag{24}$$

3.5.6. Voltage Constraint

The voltage at bus k (V_b) must be within the allowed lower (V_b^{min}) and upper (V_b^{max}) values.

$$V_b^{min} \leq V_b \leq V_b^{max} \tag{25}$$

3.5.7. VSI constraint

For stable operation, the VSI is limited by,

$$VSI_i \geq 0 \qquad \text{i} = 2,3, \dots, N_B \tag{26}$$

3.5.8. Current constraint

Current flowing through any branch ‘mn’ in the RDS is limited by,

$$I_{mn} < I_{mn}^{max} \tag{27}$$

3.5.9. Radiality constraint

To check the radial nature of the DN, the following constraint has been considered in this work, and it is expressed by using,

$$N_{Br} + N_{tie} = N_B - 1 \tag{28}$$

where N_{tie} is a number of tie-lines in RDS.

4. SELF-ADAPTIVE FIREFLY ALGORITHM (SAFA)

The firefly algorithm (FA) is an evolutionary-based technique and its behavior is inspired by the behavior of fireflies [23]. To enhance the performance of the original FA, it is improved and extended for self-adaptation (SA) of control variables which balances the exploitation and exploration for optimizing the search process of fireflies [24]. Readers may refer to [25]-[27] for detailed implementation of SAFA. The implementation of the proposed planning methodology using SAFA is presented in Figure 2. Various steps involved in solving the proposed planning problem by using the SAFA are presented below:

- Step 1: generate the initial population of fireflies (X) considering the minimum and maximum bounds of control variables.

$$X = \begin{bmatrix} x_1^1, x_2^1, & \cdots, & x_n^1 \\ \vdots \ \vdots & \ddots & \vdots \\ x_1^p, x_2^p, & \cdots, & x_n^p \end{bmatrix} \quad (29)$$

- Step 2: determine light intensity (fitness) for every individual firefly, i.e., $I = [I_1, I_2, \dots, I_n]$.
- Step 3: determine the best location by using best value of fitness which is the highest value light intensity among the fireflies.
- Step 4: update random movement factor and absorption coefficient.
- Step 5: each element of present fireflies are moved toward brighter one.
- Step 6: apply mutation operator to the existing population to generate a new population.
- Step 7: update population for next generation/iteration by the population obtained in step 6.
- Step 8: repeat the steps 2 to 7 till the termination criterion (i.e., iter $< iter^{max}$) is satisfied.
- Step 9: output the optimal solution (i.e., position with best fitness among the existing fireflies).

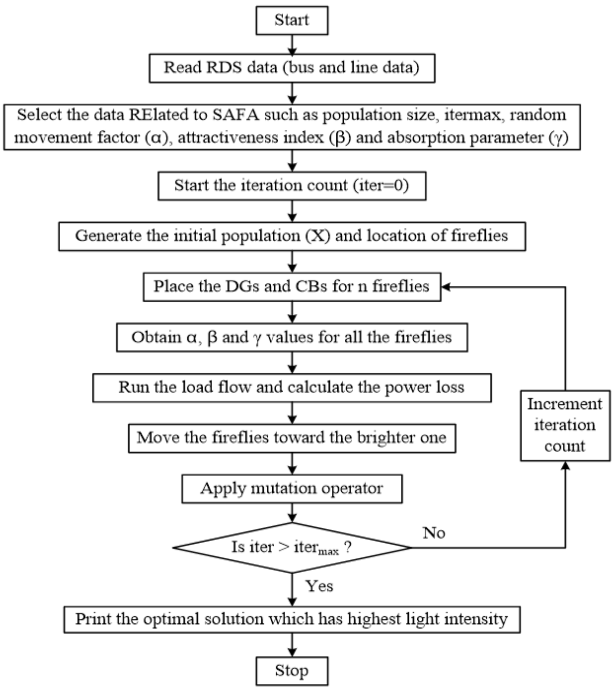

Figure 2. Proposed optimal allocation methodology using SAFA

5. RESULTS AND DISCUSSION

In this paper, 33 bus RDS is selected to solve the developed allocation method, and the topology of this RDS is depicted in Figure 3. Real and reactive power loads of this RDS are 3,715 kW and 2,300 kVAr [28]. The base voltage of this system is 12.3 kV and a power rating of 100 MVA. The maximum size of each DG is considered as 2,000 kW. The maximum size of each CB is considered as 1,000 kVAr. For the SAFA algorithm, the population size is 50, and maximum iterations are 200. Here, 5 simulation cases are performed and they are presented below.

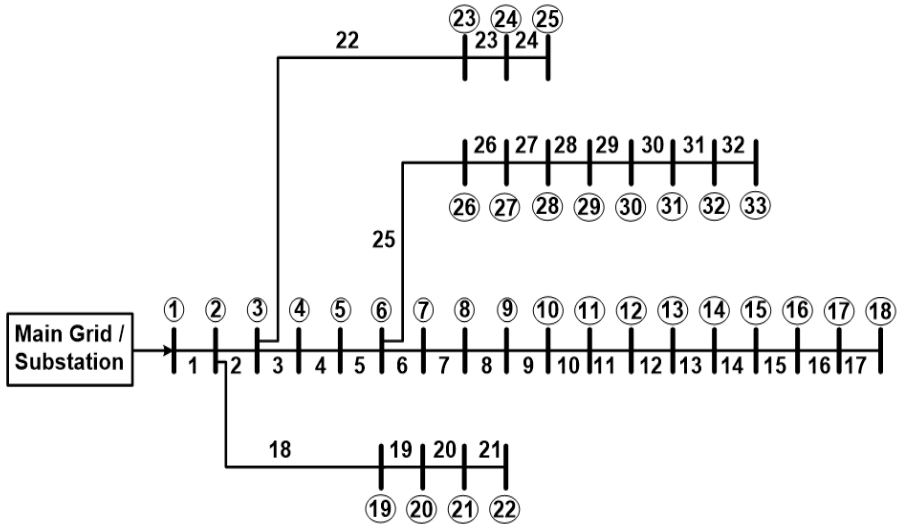

Figure 3. IEEE 33 bus RDS

5.1. Case 1: base case (optimal planning without DGs and CBs)

As it is a base case, the simulation is performed without placing the DGs and CBs. Therefore, resulting real power loss of 202.67 kW and the minimum voltage is occurred is 0.9131 p.u. at bus 18. These results are reported in Table 1.

5.2. Case 2: optimal planning with allocation of one DG

Here, the allocation problem is solved by optimally allocating one DG unit. This problem is implemented by using the meta-heuristic-based SAFA and it results in installing the DG unit at bus 8 with a capacity of 1,836.4 kW (presented in Table 1). This has resulted in a reduced power of 106.92 kW and an improved VP in RDS with a minimum voltage of 0.9432 p.u. at bus 18. This power loss incurred here is 47.24% less when compared to case 1. However, it can be concluded from the literature that by installing optimum number of DGs, the power loss could be reduced further. Therefore, in this work, 3 DG units are considered the 3 DG units simultaneously.

Table 1. Simulation results for cases 1, 2, and 3

	Case 1	Case 2	Case 3
DG size in kW (bus)	---	1,836.4(8)	1,089.6(13), 1,205.2(23), 1,095.5(29)
Total size of DGs (in kW)	---	1,836.4	3390.3
Minimum voltage (bus)	0.9131 p.u. (18)	0.9432p.u. (18)	0.9681p.u. (32)
Active power loss (in kW)	202.67	106.92	70.08
Active power loss reduction (in %)	---	47.24	65.24

5.3. Case 3: optimal planning with the allocation of three DGs

As mentioned, here 3 DGs are allocated simultaneously and solved by using the SAFA and results are shown in Table 1. The optimum results have the capacities of DG with 1,089.6 kW, 1,205.2 kW, and 1,095.5 kW at buses 13, 23, and 29, respectively. Therefore, total size of DGs is 339.2 kW. This DG allocation has a reduced power loss of 70.08 kW, which is 65.24% less than case 1. The minimum voltage incurred in this case 3 is 0.9681 p.u. at bus 32.

5.4. Case 4: optimal planning with the allocation of three CBs

In this case, only 3 CBs are considered without DGs and obtained results are shown in Table 2. The resulting optimum CB values are 600 kVAr, 450 kVAr, and 1,000 kVAr, respectively. This optimal allocation has reduced power loss of 131.24 kW which is 35.24% lesser than case 1. The minimum voltage in RDS after the allocation of 3 CBs is 0.9526 p.u. at bus 18.

Table 2. Simulation results for cases 1, 4, and 5

	Case 1	Case 4	Case 5
DG size in kW (bus)	---	---	1,089.2(13), 1,080(23), 1,050.6(29)
Total size of DGs (in kW)	---	---	3,219.8
CB size in kVAr (bus)		600(18), 450(23), 1,000(30)	600(18), 600(23), 1,000(30)
Minimum voltage (bus)	0.9131 p.u. (18)	0.9526 p.u. (18)	0.9903 p.u. (25)
Active power loss (in kW)	202.67	131.24	27.92
Active power loss reduction (in %)	---	35.24	86.22

5.5. Case 5: optimal planning with the allocation of three CBs and three DG units

In this case, 3 CBs and 3 DG units are installed simultaneously and augmented objective function (F_{aug}) is solved by using SAFA. Here the 3 DGs are located at buses 13, 23, and 29 with capacities of 1,089.2 kW, 1,080 kW, and 1,050.6 kW, respectively. Also, 3 CBs are located at buses 18, 23, and 30 has capacities of 600 kVAr, 600 kVAr, and 1,000 kVAr. The minimum power loss incurred in case 5 is 27.92 kW which is 86.22% lesser than the case 1. Minimum voltage resulted here is 0.9903 p.u. at bus 25. The comparison of power loss resulting in all 5 case studies is depicted in Figure 4 and the percentage reduction in power loss is depicted in Figure 5. From all these studies it can be concluded that simultaneously allocating the CBs and DG units has resulted in reduced power losses and enhanced VP in RDS.

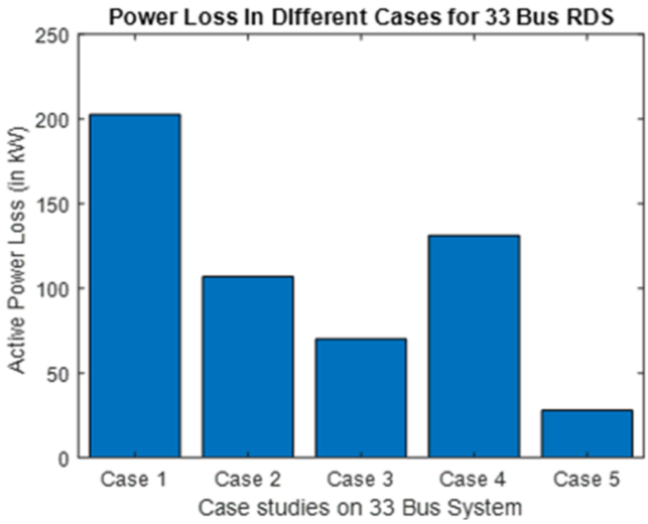

Figure 4. Comparison of active power losses obtained in all the cases

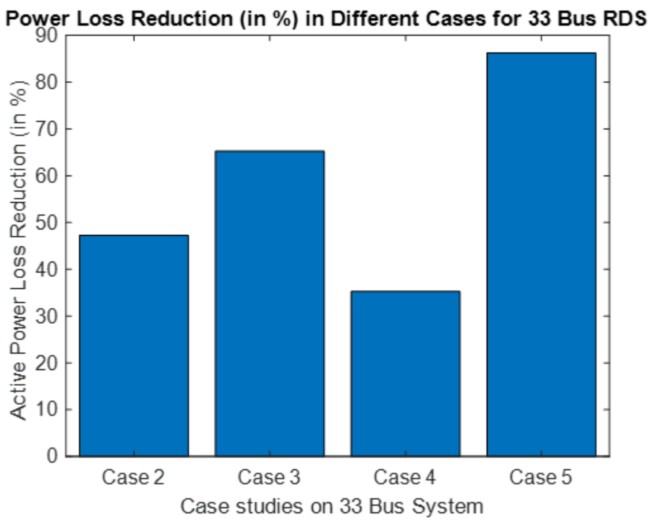

Figure 5. Comparison of reduction in active power losses in percentage obtained in all the cases

6. CONCLUSION

This paper proposed an optimal approach for the allocation of CBs and DG in hybrid networks. A LF is modeled by incorporating CBs and DG at a bus in the RDS. Three objective functions are formulated by selecting power loss, voltage deviation, and voltage stability index. The augmented objective function is formulated by considering the weighted sum of each objective. The proposed planning problem is solved by an evolutionary-based SAFA and it is implemented on IEEE 33 bus RDS considering various case studies. The obtained results revealed that simultaneously allocating the CBs and DG units resulted in reduced power losses, voltage deviations, and improved voltage stability and VP in RDS.

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AUTHOR CONTRIBUTIONS STATEMENT

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Seong-Cheol Kim	✓	✓	✓	✓		✓		✓	✓	✓	✓		✓	
Sravanthi Pagidipala		✓	✓	✓	✓	✓		✓	✓	✓	✓	✓		✓
Surender Reddy Salkuti	✓		✓	✓	✓		✓		✓	✓	✓		✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

This article does not contain any studies with human participants or animal studies performed by any of the authors.

DATA AVAILABILITY

The datasets used and/or analyzed during the current study available from the corresponding author [SRS], on reasonable requests.

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