Optimal distributed generation allocation in distribution system for power loss minimization and voltage stability improvement

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Abstract. Voltage instability and power loss are significant problems in distribution Systems (DS). However, these problems are usually mitigated by the optimal integration of distributed generation (DG) units in the DN. In this regard, the optimal location and size of the DGs are crucial. Otherwise, System performance will deteriorate. This study is conducted to place the DGs in the radial DS. Mayfly Algorithm (MA) is used to determine the optimal placement and size of the DGs to minimize power loss, increase voltage stability in radial DS. The simulation results showed a reduction in the percentage of power loss is 69.14% for three PV-type DG unit integration. The corresponding percentage of power loss reduction is 98.09 % for three WT-type DG units by installing DG units to the test System. Similarly, the minimum bus voltage stability improves to 0.959 per unit for three PV type DG unit integration. The VSI after DG allocation increases to 0.989 per unit for three WT type DG units by optimal installing DG units. Comparative studies have been conducted, and the results have shown the effectiveness of the proposed method in reducing the power loss and improving the voltage stability of the DS. The proposed algorithm is evaluated in the IEEE-69 bus radial DS using MATLAB.

1 Introduction

Meeting the growing load demand is a significant challenge for all energy companies. Combustion of fossil fuels provides 75% of the world's load demand. Increasing greenhouse gas emissions, global warming, declining fossil fuels, and rising fuel prices have required developing a potential energy strategy for renewable energy resources (RES) [1]. Providing renewable technologies such as photovoltaic (PV) and wind turbine (WT) for power generation has been a major challenge in many countries over the past decade. The main problem faced by electrical distribution companies concerns power losses and voltage instabilities that occur in their respective Systems [2]. For reliable operation of the DS and high-quality service to consumers, it is necessary to increase the efficiency of the DS and

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reduce its operating cost. One of the best ways to achieve this goal is to minimize active power loss and improve voltage stability in DS. Minimization of power loss and improved voltage stability can be achieved through a variety of methods, including distribution System reconfiguration (DSR), installation of capacitors, optimal placement, and sizing of distributed generation (DG) units [3]. Among these available techniques, the optimal DG unit's allocation is the most efficient technique for power distribution operators.

The main advantages of integrating DG units into power systems are the stability of the power supply and the increased reliability of the DS, and many operational and cost-effective benefits. However, the above benefits are only achieved when the DG units are optimally integrated into a suitable location and size. Otherwise, the incorrect size and place of the DG units could cause additional technical problems. Thus, optimizing the location and size of the DG units is a problem with many concerns [3]

Various methods have been proposed to solve the problem of DG allocation. In [4], a genetic algorithm (GA) has been presented to determine DG units' optimal size and location to reduce costs. In [5], presented GA to solve the allocation problem of DG units to reduce power losses. Likewise, [6]GA also proposes determining the size and location of the DG units in the smart grid. In [7], the Golden algorithm has been proposed to determine the optimal size and location of the DG unit in the DN. In [8], proposed the Bat Algorithm (BA) to reduce power loss by optimal allocate the DG units. In [9], proposed combined Particle Swarm Optimization (PSO) with GA to determine DG units' size and location to power loss minimization and improve voltage stability. In [10], a hybrid approach (HA) is presented to solve the allocation problem of DG units considering System reconfiguration.

Not only common approaches such as BA, GA, Hybrid and PSO are used to solve the DG allocation problem in DN, but many recently developed methods such as Whale Optimization Algorithm (WOA) [11], Chaotic Grasshopper Optimization Algorithm (CGOA) [12], Rider optimization algorithm (ROA) [13], Harmony Search Algorithm (HSA) [14], Atom Search Optimization Algorithm (ASO) [15], Adaptive Cuckoo Search Algorithm (ACSA) [16], Fireworks Optimization Algorithm (FOA) [17], Coyote Optimization Algorithm (COA)[18], Uniform Voltage Distribution Algorithm (UVDA) [19], Hypercubic Ant Colony Algorithm (HCACA) [20], Runner Root Algorithm (RRA)[21], and Modified Plant Growth Algorithm (MPGA) [22] are successfully applied.

In light of the previous, it is evident that to power loss minimization and improvement of voltage stability in a DS using the RES based most researchers in the mainstream literature mainly used DG units, heuristic and metaheuristic methods, and there is an increase in interest in nature-inspired algorithms for the optimal solution of the DG allocation problem. In this paper, the recently developed Mayfly Algorithm (MA) [23] is proposed to solve the problem of DG allocation, which is designed to reduce the active power loss and improve voltage stability of the system while fulfilling all the operational limitations of the system. The stability of the proposed MA is confirmed on the standard radial IEEE 69 bus system. Numerical results show that the proposed MA is accurate and efficient compared to the results available in the recently published literature.

This paper is organized as follows: Section 2 presents methods. Section 3 presents the numerical results and discussion. Section 4 presents the conclusions of this paper.

2 Methods

These parts are aimed at minimizing power loss and improve voltage stability through DG allocation. The objective function of this paper represents as follows:

$$\min(\mathrm{F}) = \Delta P_{loss}^{R} + \Delta VSI \tag{1}$$

where $\Delta \mathrm{P}_{loss}^{R}$ is the total power loss reduction and can be found as follows:

$$\Delta \mathrm{P}_{loss}^{R} = \frac{\sum_{i=1}^{N} P_{loss(i)}^{DG}}{\sum_{i=1}^{N} P_{loss(i)}^{before}} \tag{2}$$

where, $\mathrm{P}_{loss}^{before}$ and P_{loss}^{DG} are the total power losses before and after the DG installation to the system, N is the total branches number. ΔVSI is a deviation of the voltage stability index of the system and can be calculated as follows [2]:

$$\Delta VSI = \max\left(\frac{1 - VSI_k}{1}\right); \qquad k = 2, \ldots, N_{bus} \tag{3}$$

The voltage stability index is expressed as follows [2]:

$$VSI(j) = |V_i|^4 - 4(P_j X_i - Q_j R_i)^2 - 4(P_j R_i + Q_j X_i)|V_i|^2 \tag{4}$$

Ri and Xi are *i* branch's resistance and reactance, *Vi* is the voltage of *ith* bus, and *Pj* and *Qj* are the active and reactive power at the *jth* bus.

The following constraints must be met in optimization prosses:

a) Power balance constraints

The total power supplied from the system and generated by DG must balance the total demand of the load and the total power loss [2].

$$P_{system} + \sum_{l=1}^{N_{DG}} P_{DG}(l) = \sum_{l=1}^{N_{br}} P_{brloss}(l) + \sum_{j=1}^{M} P_d(j) \tag{5}$$

$$Q_{system} + \sum_{l=1}^{N_{DG}} Q_{DG}(l) = \sum_{l=1}^{N_{br}} Q_{brloss}(l) + \sum_{j=1}^{M} Q_d(j) \tag{6}$$

where, P_{system} and Q_{system} are injected active and reactive power, P_{brloss} and Q_{brloss} are active and reactive branch power losses, P_d and Q_d are active and reactive load, M is total bus numbers, N_{DG} is the DG number.

b) Bus voltage constraints

The operating voltage on all System buses must be within the specified minimum and maximum voltage limits [13].

$$V_{\min} \leq |V_i| \leq V_{\max} \tag{7}$$

c) Branch thermal constraints

All System branches must operate within their heat limits.

$$I_{Bi} \leq I_{Bi(rated)} \tag{8}$$

d) Power generation constraints

The power generation of DG must have the specified minimum and maximum limits [13].

$$P_{DG}^{\min} \le P_{DG}(i) \le P_{DG}^{\max} \tag{9}$$

$$Q_{DG}^{\min} \le Q_{DG}(i) \le Q_{DG}^{\max} \tag{10}$$

e) Power factor constraints

The power factor by DG must have the specified minimum and maximum limits [24].

$$PF_{DG,\min} \le PF_{DG,i} \le PF_{DG,\max} \tag{11}$$

The Mayfly Algorithm (MA) is a recently developed metaheuristic optimization technique [23]. This algorithm is inspired by mayflies' social behavior, especially their mating process. Once hatched, the mayflies become adults, and the strongest mayflies are expected to survive no matter how long they dwell. The location of each mayfly in the search space provides a candidate solution to the problem. The steps of the method are as follows:

1. The male and female mayflies' positions and velocity were primarily randomly generated.

$$\begin{aligned} x_i^0 &\quad U(x_{\min}, x_{\max}) \\ v_i^0 &\quad U(v_{\min}, v_{\max}) \end{aligned} \tag{12}$$

where, $x_{\min,j}, v_{\min,j}$ and $x_{\max,j}, v_{\max,j}$ are the lower and upper limits of the dimension j.

2. Find the personal best position (*pbest*) of two sets of mayflies, then the whole population's global best position (gbest).

$$fit(x_i) \tag{13}$$

3. *Male mayflies' movement*

The male mayfly's position changed in the search space considering its current position and velocity. It can be expressed as follows:

$$x_i^{t+1} = x_i^t + v_i^{t+1} \tag{14}$$

The velocity v_i^{t+1} of male mayflies will update their velocity according to their current fitness values $fit(x_i)$ and the historical best fitness values in trajectories $fit(x_{hi})$. If $fit(x_i)$ is bigger than $fit(x_{hi})$, the velocity is calculated as follows:

$$v_{ij}^{t+1} = v_{ij}^t + a_1 e^{-\beta r_p^2}(pbest_{ij} - x_{ij}^t) + a_2 e^{-\beta r_g^2}(gbest_{ij} - x_{ij}^t) \tag{15}$$

where v_{ij}^t and x_{ij}^t are the velocity and location of mayfly *i* in dimension *j* at a time step, *r*espectively. *a*1 and *a*2 are positive gravity constants. *rp and rg* are the cartesian distance and calculated as follows:

$$x_i - X_i = \sqrt{\sum_{j=1}^{n}(x_{ij} - X_{ij})^2} \qquad (16)$$

where x_{ij} is the location of *ith* mayfly in dimension j and X_i is the position of *pbesti* or *gbest.*

If $fit(x_i)$ is smaller than $fit(x_{hi})$, the velocity is calculated as follows:

$$v_{ij}^{t+1} = v_{ij}^{t} + d * r \qquad (17)$$

where *d* is the coefficient of mating dance, and *r* is a random number within [−1, 1].

4. Female mayflies' movements

The female mayfly's position changed in the search space considering its current position and velocity. It can be expressed as follows:

$$y_i^{t+1} = y_i^t + v_i^{t+1} \qquad (18)$$

The velocity of female mayflies is calculated as follows:

$$v_{ij}^{t+1} = \{\begin{matrix} v_{ij}^t + a_2 e^{-\beta r_{mf}^2}(x_{ij}^t - y_{ij}^t), if \quad f(y_i) > f(x_i) \\ v_{ij}^t + fl * r, if \quad f(y_i) \le f(x_i) \end{matrix} \qquad (19)$$

where, β is the coefficient of fixed visibility, rmf is the Cartesian distance, calculated using equation (16). *fl* is the coefficient of random walk.

5. The Mating process of mayflies

The mating process between two mayflies is as follows: one set of parents are selected from the male and female population. The selection of parents can be random or based on their fitness function. The two offspring children are generated as follows:

$$\begin{aligned} offspring1 &= L * male + (1 - L) * female \\ offspring2 &= L * female + (1 - L) * male \end{aligned} \qquad (20)$$

where, *male* is the male parent, *female* is the female parent, and *L* is a random number generated using Gaussian distribution. The initial velocity of the offspring is zero.

6. Update personal best position (*pbest*) and global position (*gbest*) of mayflies.

$$pbest_i = \{\begin{matrix} x_i^{t+1}, if \quad f(x_i^{t+1}) < f(pbest_i) \\ is \quad kept \quad the \quad same, otherwise \end{matrix} \qquad (21)$$

$$gbest \in \{pbest_1, pbest_2, ..., pbest_N\} = \min\{f(pbest_1), f(pbest_2), ..., f(pbest_N)\} \qquad (22)$$

Table 1 presents the used parameters of this study. Figure 1 illustrates the flowchart of the optimization process.

Table 1. Used parameters and operational constraints

Parameters	Value
Number of populations	40
Number of iterations	100
Random flight Mating Dance a1, a2, a3	1 5 1,1.5,1.5
β	2
Bus system voltage constraints	$0.9\, p.u. \le V_i \le 1.05\, p.u.$

3 Results and discussion

To evaluate and validate the effectiveness of the proposed method has been tested on the standard IEEE 69 - bus DS. To analyze the robustness of the presented method in comparison with other optimization techniques in the existing literature to achieve objective function. The IEEE 69 bus is a standard 12.66 kV medium-scale DS that consists of active and reactive power loads are 3801.5 kW and 2694.6 kVAr, respectively [25]. The base case (without DG allocation) System power loss calculated from the load flow is 224.98 kW, and the minimum VSI is 0.6842 p.u. The line diagram of 69 – bus DS is depicted in Figure 2, and the results obtained by the proposed MA for the test system are presented in Table 2. As can be seen from the results obtained in this table, after performing the proposed DG allocation task based on MA for the IEEE 69 - bus system, the System power losses are 83.22,71.67 and 69.42 kW for one, two, and three PV type DG unit integration.

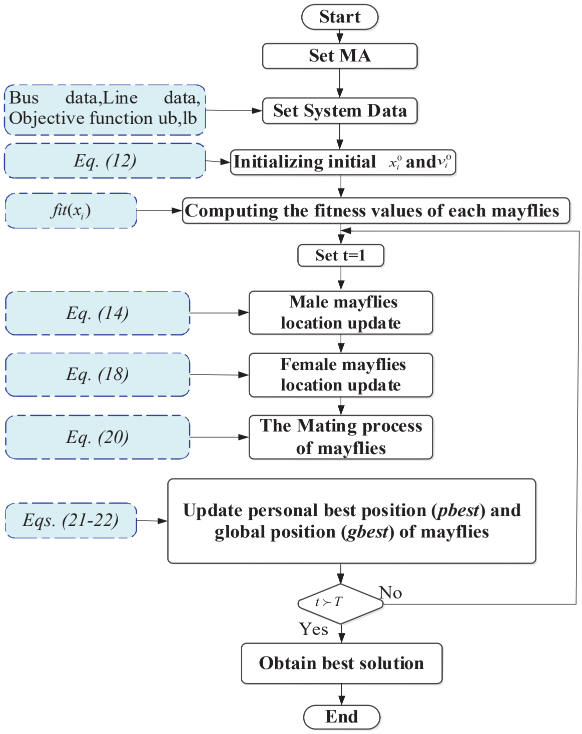

Fig. 1. Flowchart of the optimization process

The System power losses are 23.17, 7.819 and 4.275 kW for one, two, and three WT type DG unit integration. The corresponding power loss reduction percentage for normal load conditions is 63%, 68.14 %, and 69.14% for one, two, and three PV type DG unit integration. The corresponding percentage of power loss reduction is 89.7%, 96.52 %, and 98.09% for one, two, and three WT type DG unit integration. The VSI after DG allocation increases to 0.88, 0.94, and 0.959 pu for one, two, and three PV type DG unit integration. The VSI after DG allocation increases to 0.90, 0.975, and 0.989 pu for one, two, and three WT type DG unit integration. A comparison of the results obtained using the proposed method and other methods available in the existing literature are presented in Table 3-4. Comparative analysis shows that the proposed method is effective and efficient in reducing DS losses and improving the voltage stability of the system bus. The test system's voltage profiles and voltage stability before and after DG allocation are shown in Figures 3-4. The figure shows that the System voltage profile and voltage stability improve with DG allocation. In addition, the convergence curve for Two DG integration of the IEEE 69-bus system is illustrated in Fig. 5.

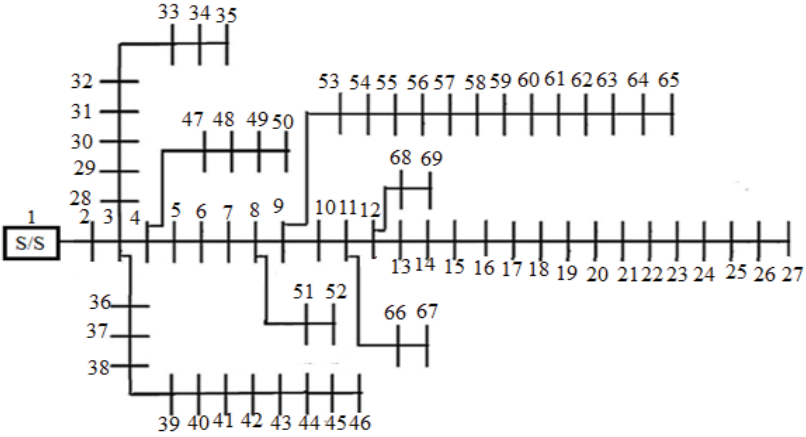

Fig. 2. Single line diagram of IEEE 69-bus DS

Table 2. The results obtained by the proposed MA for the 69-bus system

Items	Base case	With DG					
		One DG		Two DG		Three DG	
		PV-based	WT-based	PV-based	WT-based	PV-based	WT-based
Active power loss in KW	224.978	83.22	23.17	71.67	7.82	69.42	4.27
Reactive power loss in KVAR	102.187	40.56	14.41	35.94	8.28	34.96	6.75
Loss reduction percentage (%)	-	63.008	89.701	68.141	96.524	69.140	98.099
Minimum voltage in p.u	0.9092	0.96829	0.9724	0.978	0.9934	0.978	0.994
VSI	-	64.62	65.72	66.03	67.33	66.22	67.73

Table 3. Comparison of the results obtained using the proposed approach and other approaches for

69-bus system (PV based DG)

Items		Golden [7]	BA [8]	PSO [9]	MA
One PV-based	Node (Size in KW /PF)	61(1819.7/1)	61(1901/1)	61(1901/1)	61 (1872.8/1)
	Active power loss in KW	83.33	83.23	83.23	83.2
	Loss reduction percentage (%)	62.96	63.02	63.02	63.00
	Minimum VSI	0.880	0.879	0.879	0.881
Two PV-based	Node (Size in KW /PF)	6 (1719/1) 8 (840.2/1)	61 (2000/1) 17 (500/1)	61 (1900/1) 15 (400/1)	61 (1781.5/1) 17 (531.48/1)
	Active power loss in KW	96.5	73.3	73.1	71.674
	Loss reduction percentage (%)	57.11	67.42	67.51	68.14
	Minimum VSI	0.922	0.946	0.9305	0.94
Three PV-based	Node (Size in KW /PF)	13 (1013.4/1) 61 (990.1/1) 62 (1160.1/1)	61 (2000/1) 22 (300/1) 13 (400/1)	66 (700/1) 62 (1900/1) 18 (300/1)	18 (380.34/1) 11 (526.91/1) 61 (1718.8/1)
	Active power loss in KW	82.17	72.6	73.1	69.426
	Loss reduction percentage (%)	63.47	67.73	67.51	69.14
	Minimum VSI	0.938	0.950	0.947	0.959

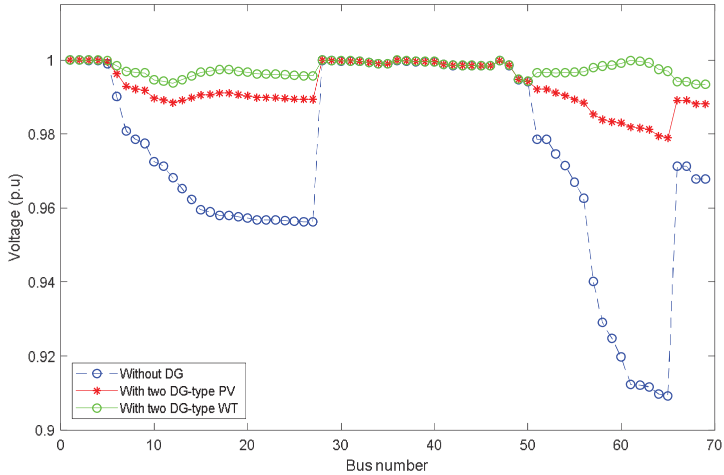

Fig. 3. The effect of installing Two DG units on voltages of the IEEE 69-bus

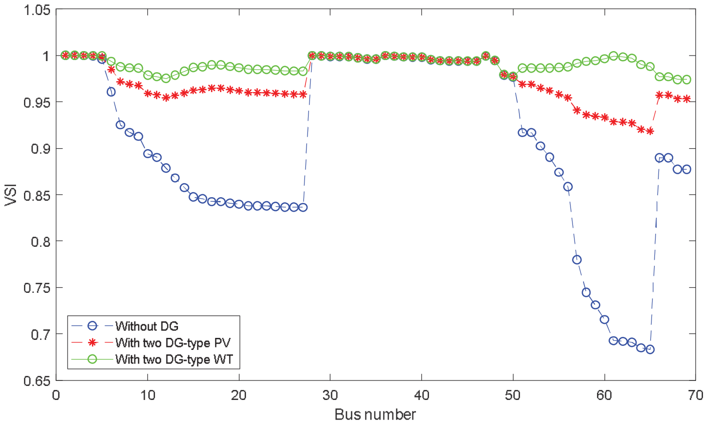

Fig. 4. The effect of installing Two DG units on VSI of the IEEE 69-bus

Table 4. Comparison of the results obtained using the proposed approach and other approaches for 69-bus system (WT based DG)

Items		HA [10]	BA [8]	PSO [9]	MA
One WT-based	Node (Size in KW /PF)	61 (2240/0.81)	61 (2100/0.98)	61 (2100/0.98)	61 (1828.4/ 0.81)
	Active power loss in KW	23.19	52.5	52.5	23.16
	Loss reduction percentage (%)	89.7	76.67	76.67	89.70
	Minimum VSI	0.9	0.8896	0.8896	0.901
Two WT-based	Node (Size in KW /PF)	61 (2121/0.81) 17 (630/0.82)	61 (2001/0.98) 17 (600/0.98)	61 (2202/0.98) 18 (600/0.98)	61 (1750.1/0.82) 17 (432.371/0.7)
	Active power loss in KW	7.21	38.7	41.1	7.82
	Loss reduction percentage (%)	96.8	82.8	81.73	96.52
	Minimum VSI	0.972	0.971	0.976	0.975
Three WT-based	Node (Size in KW /PF)	18 (480/ 0.77) 61 (2060/ 0.83) 66 (530/ 0.82)	61 (2000/0.98) 49 (800/0.98) 19 (600/0.98)	61 (1500/0.98) 59 (600/0.98) 16 (500/0.98)	18 (370.25/ 0.82) 11 (508.44/0.84) 61 (1670.84/0.81)
	Active power loss in KW	4.3	37.1	39.2	4.275
	Loss reduction percentage (%)	98.08	83.51	82.58	98.1
	Minimum VSI	0.98	0.97	0.96	0.99

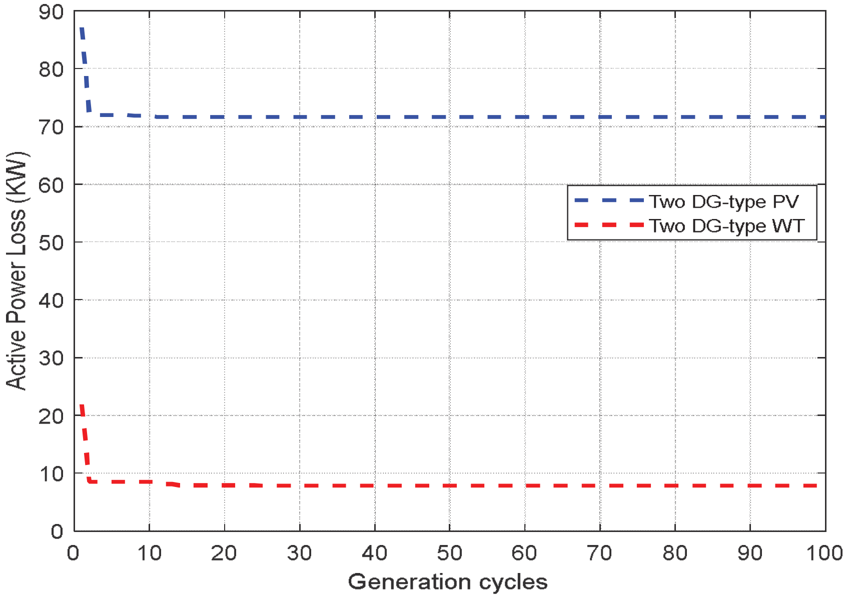

Fig. 5. The convergence curve for Two DG units of the IEEE 69-bus

4 Conclusions

This paper proposed recently developed Mayfly Algorithm (MA) for solving optimal distributed generation (DG) units' allocation problem for medium scale radial distribution System (DN). The proposed optimization algorithm establishes the optimal DG allocation, with the main objective being active power loss minimization and voltage stability improvement while considering operating constraints. The IEEE 69 – bus DN has been considered to validate the efficacy of the presented MA technique. Moreover, the results also signify that the proposed MA, in comparison with other available methods, provides a better quality of power loss reduction and enhancement of voltage stability. So, because of the above discussion, it can be concluded that the proposed MA method can be a very promising and powerful approach for dealing with the DG allocation problem.

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