Moth Flame Optimization for Optimal Sizing and Placement of Distributed Energy Systems

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ABSTRACT

This paper proposed the application of moth flame optimization algorithm (MFO) for optimal sizing and allocation of multiple distributed generation (DG) units in electrical networks. Recently, there is significant increased penetration level of DGs in electrical networks in order to reduce power losses, improve voltage profile, security and stability of the power system. However, the optimal sizing and siting of the distributed generations are the most challenging task for most utilities. The advent of soft computing techniques has paved a way for optimal sizing and sitting of DGs in electrical networks. A lot of soft computing techniques have been proposed for sizing and sitting of multiple DGs in a distribution network, each with its merit, demerits and optimal solutions. Computational resources, objectives functions, constraints, DGs and transmission line capacities, and optimal solutions are some of the important factors considered by most researchers for selecting a particular soft computing technique. This research utilises the MFO algorithms for sizing and siting of multiple DGs in an electrical network. Active, reactive power and power factors are used in formulating the objective functions taking into cognisant power loss, DGs and transmission lines capacities. The proposed technique is applied on the IEEE 33-bus system for validation. The test results show that, the proposed (MFO) method produced an optimal solution, with less computational effort as compared to particle swamp optimization (PSO), harmony search algorithm, chaotic sine cosine algorithm, multi-objective Taguchi method and Bat Algorithm based techniques.

1. INTRODUCTION

The continuous rise in load demand by customers connected to the distribution network is one of the primary factors causing systems to operate near their voltage stability limits, resulting in increased financial losses and decreased efficiency [1]. In the distribution system, the Distributed Energy System (DES) has expanded due to the evolution of power markets, concerns over fuel cost uncertainties and technological advancements [2]. The DES comprises various Distributed Generation (DG) units connected at the distribution voltage level, which provide benefits such as environmental sustainability, loss reduction, deferral of transmission system upgrades, voltage enhancement and improved reliability [3]. However, achieving these benefits requires the appropriate placement and sizing of Distributed Generation units. Incorrect placement and sizing can lead to poor power quality, voltage instability, high line losses and degradation of protection systems [4],[5].

Among the significant challenges system designers face is the optimal placement of DG units, with several methods employed to determine the best locations [6][7]. Techniques such as the sensitivity analysis, two-degree gradient method and Lagrange method have been utilized for placement of DGs.

Researchers have applied various techniques to ensure the proper placement and sizing of DG units in a distribution network, which can be categorized into four groups [8][9][10]: Analytical Expressions (AEs), Metaheuristic Methods (MMs), Numerical Methods (NMs) and Metaheuristic Methods combined with Analytical Expressions.

The AE approach involves using analytical expressions to identify either the size or optimal DG location, followed with a search technique to determine the corresponding size or location. From the equation of network losses, Ref [8] proposed an AE in terms of injected phasor feeder current to minimize power loss. However, this method assumes uniform, centrally, or increasingly distributed loads, which is not practical. Other AE-based methods include active power loss sensitivity factor (LSF) [11], the sensitivity of line loss [12], power stability index (PSI) [13] and sensitivity of combined power loss [14].

Numerical methods, such as the continuation power flow (CPF) [15], identify the most delicate bus to voltage collapse, where DG is then integrated to minimize real power loss. Dynamic programming methods have also been used to determine optimal DG locations to maximize profit while considering DG costs and benefits [16].

Meta-heuristic methods, including symbiotic organisms search (SOS) algorithm [17] and particle swarm optimization (PSO) [18] and have been used to minimize network power loss. The Stud Krill Herd Algorithm (SKHA) [19] and Ant Lion Optimization Algorithm (ALOA) [20] are other examples, focusing on optimal DG placement and sizing in radial distribution systems and various distribution systems, respectively.

Finally, combining AE and meta-heuristic methods yields optimal solutions and reduces computational time [21]. For example, combining LSF with a genetic algorithm (GA) involves using GA to determine optimal DG sizes and LSF to find optimal DG locations [22].

This research proposes a new approach that integrates an analytical method with Moth flame optimization algorithm for optimal DG allocation. The analytical approach sizes the individual DGs for each bus, while the Moth flame optimization algorithm searches randomly for their optimal locations. The algorithm is implemented on the MATLAB R2023a platform and tested on a standard IEEE 33-bus distribution test system.

The following contribution is made in this work;

i. A hybrid method that utilizes an improved Moth Flame Optimization (MFO) technique to explore a wide range of combinations of locations and power factors for Distributed Generations (DGs).
ii. A technique that employs an enhanced analytical approach to compute the capacities of DGs for each location.

This paper is organized as follows: Section 2 explains the problem formulation. Section 3 portrays the methodology. Section 4 shows the results and discussion test distribution systems and numerical results for multiple DG placement. Finally, the major contributions and conclusions are summarized in Section 5.

2. PROBLEM FORMULATION

2.1 Objective Function

In order to improve the voltage profiles and minimize power losses across the distribution network's line length, the following sections shows the objective function formulated.

2.1.1 Power Loss Reduction

$$Losses_{with\ DG} \leq Losses_{without\ DG} \quad (1)$$

$$f = maxLLR\% = \frac{LL_{WODG} - LL_{WDG}}{LL_{WODG}} X\ 100 \quad (2)$$

Where;

$$LL_{WDG} = \sum_{l=1}^{N} I_{l,WDG}^2 R_i D_i \quad (3)$$

$$LL_{WODG} = \sum_{l=1}^{N} I_{l,WODG}^2 R_i D_i \quad (4)$$

Where:

f is the objective function

LL_{WODG} is the loss on the line without DG consideration

LL_{WDG} is the loss on the line with DG consideration

D_i is the line length in km;

R_i is the resistance of the line in pu/km;

$I_{l,WODG}$ is the value of current in pu before installation of DG.

$I_{l,WDG}$ is the value of current in pu after DG installation;

2.1.2 Bus Voltage Limit

The voltage magnitude at each bus must be maintained within acceptable boundaries as shown in (5).

$$V_{min,n} \leq V_n \leq V_{max,n} \quad (5)$$

Where $V_{min,n}$ and $V_{max,n}$ represent the minimum voltage and maximum voltage respectively at bus n and V_n is the voltage magnitude at bus n.

2.2 Operational Constraint

The optimisation problem considers the following:

The power injection constraints;

$$\sum_{i=l}^{n} P_{DG} < P_{load} + P_{losses} \quad (6)$$

Total Power Balanced Constraint;

$$\sum_{i=l}^{n} P_{DG} + P_{substation} = P_{load} + P_{losses} \quad (7)$$

Where;

$P_{substation}$ is the substation power supply

P_{DG} represents the power supplied by DG

P_{losses} is the losses in power on the network

P_{load} represents the supplied power to connected loads on the network.

N represents the number of connected distributed generators

2.2.1 Total Number of DG

Number of DG (N_{DG}) must be equal or less than the maximum number of DG ($N_{DG/MAX}$)

$$N_{DG} \leq N_{\frac{DG}{MAX}} \quad (8)$$

2.2.2 Constraint On Capacity of DG Generation

Each DG's active power (P_{ga}) is restricted by its lower and upper limits.

$$P_{ga}^{min} \leq P_{ga} \leq P_{ga}^{max} \quad (9)$$

2.2.3. Voltage Profile

The current magnitude of a feeder and the Voltage magnitude at each bus must satisfy permissible limit as shown in (10)

$$V_{min} \leq |V_i| \leq V_{max} \quad (10)$$

Where;

V_{max} represents the maximum voltage limits

V_{min} represents the minimum voltage limits

$|V_i|$ represents the magnitude of voltage magnitude at node i

2.2.4. Line Flow Limit

In the overhead line, the current flowing should not over reach the limit shown in (12)

$$|I_j| \leq I_{jmax} \quad (11)$$

I_{jmax} is the maximum current limit of j and $|I_j|$ is the current magnitude of each line j

3. METHODOLOGY

3.1 Implementation of moth flame optimization for DG allocation

The MFO is a metaheuristic optimization technique which is bio-inspired and was developed by [23]. It draws its main inspiration from the navigation behavior of moths, specifically their transverse orientation mechanism. This unique moth behavior is translated into a mathematical framework for optimization purposes.

Interestingly, moths, despite their ability to travel in a transverse path, often exhibit a behavior of spiraling around light sources. This behavior is observed when moths become disoriented by indoor lighting. The reason behind this preference for spiraling is linked to the limitations of the transverse orientation behavior. While effective for certain situations, it proves inefficient for motion in a straight line except for when the light source is considerably distant.

When moths encounter a man-made artificial light source, they instinctively strive to maintain a consistent angle relative to the light. However, due to the proximity of artificial lights compared to the moon, this behavior results in a spiraling flight path that can be fatal for the moths.

The representation of this behaviour is shown in Figure 1. In this algorithm, candidate solutions are represented as moths while the variables correspond to the positions of these moths in space. These moths have the ability to adjust their positions and move within one or more dimensional spaces. The structure of the moth matrix, as described by [23], is presented as follows:

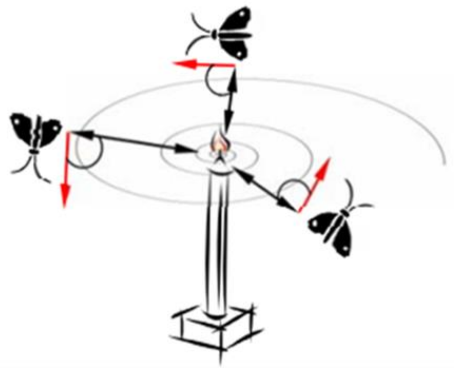

Figure 1: Spiral path of MFA [13]

$$A = \begin{bmatrix} A_{1,1} & A_{1,2} & . & . & . & A_{1,d} \\ A_{2,1} & A_{2,2} & . & . & . & A_{2,d} \\ \vdots & \ddots & & & & \vdots \\ A_{n,1} & A_{n,1} & . & . & . & A_{n,1} \end{bmatrix} \quad (12)$$

Where n represents the number of moths and d represents the number of variables or dimensions. The fitness value of every moth is shown in (13):

$$OA = \begin{bmatrix} OA_1 \\ OA_2 \\ \vdots \\ OA_n \end{bmatrix} \quad (13)$$

Flame matrix represents the population of flames:

$$B = \begin{bmatrix} b_{1,1} & b_{1,2} & . & . & . & b_{1,d} \\ b_{2,1} & b_{2,2} & . & . & . & b_{2,d} \\ \vdots & \ddots & & & & \vdots \\ b_{n,1} & b_{n,1} & & & & b_{n,1} \end{bmatrix} \quad (14)$$

And the fitness value of flames is given as:

$$OB = \begin{bmatrix} OB_1 \\ OB_2 \\ \vdots \\ OB_n \end{bmatrix} \quad (15)$$

Position of a moth with respect to a flame is represented by (16)

$$A_i = S(A_i, B_j) \quad (16)$$

where S is the spiral/helical function, B_j for jth flame and A_i denotes the ith moth. The path of flight [23] is represented in (17):

$$S(A_i, B_j) = L_i e^{bt} Cos(2\pi t) + B_j \qquad (17)$$

Where t is a random number within the range [-1, 1], b is the logarithmic shape constant and L_i represents the distance between the jth flame and the ith moth.

This elliptical region serves as the area within which the moth is positioned. The use of a spiral equation allows the moth to effectively exploit and explore the search area by circling around the flame instead of moving in the space between them. MFO flowchart is shown in Figure 2.

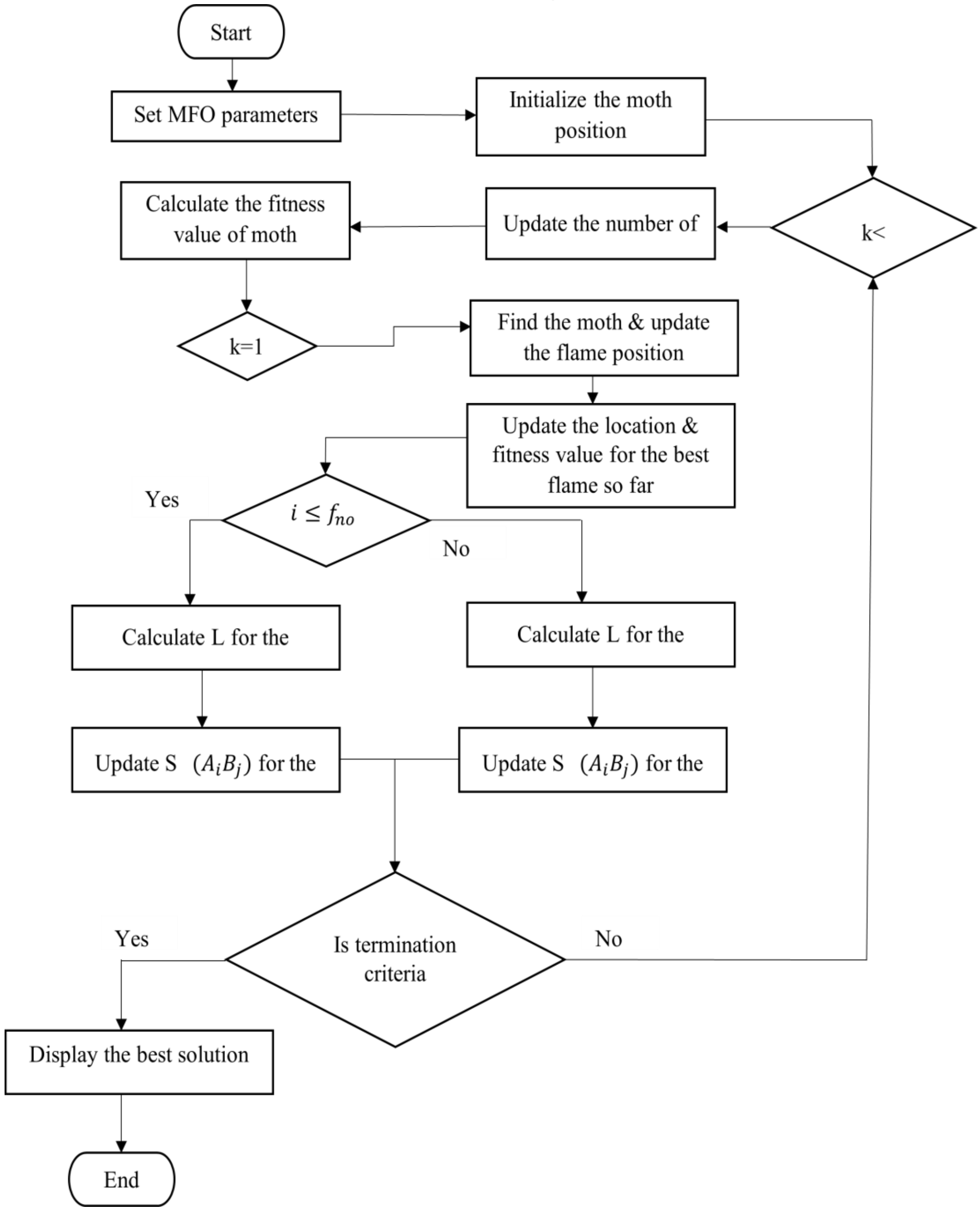

Figure 2: MFO Flowchart [13]

In Figure 3, the area around the flame, the values of t on the curve and the logarithmic spiral is shown. The calculation of L, which denotes the distance between moths and flames, is determined as follows:

$$|L_i = |B_j - A_i| \quad (18)$$

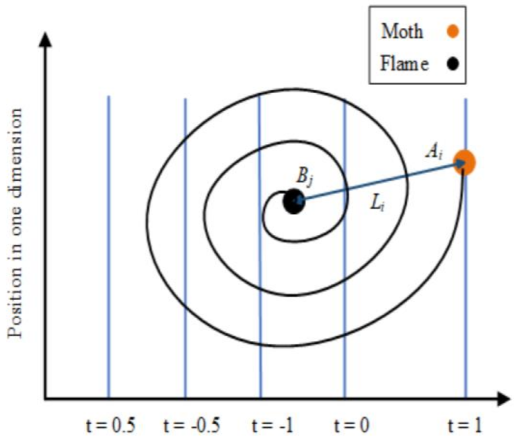

Figure 3: MFO logarithmic spiral [13]

An adaptive approach [23] is used for determining the number of flames f_{no} which reduces as the number of iterations increases.

$$f_{no} = Round\left(N - K \times \frac{N-1}{K_{max}}\right) \quad (19)$$

where N for the maximum number of flames, k_{max} denotes the maximum number of iterations and k is the current number of iterations.

3.2 Standard IEEE 33-Bus System Test Case

This is a widely used medium scale distribution system with 33 buses and 32 branches. The line voltage, real and reactive power loads of the radial distribution networks are 12.66kV, 3715kW and 2300kVar, respectively[11]. The standard IEEE-33 bus system distribution as shown in Figure 4.

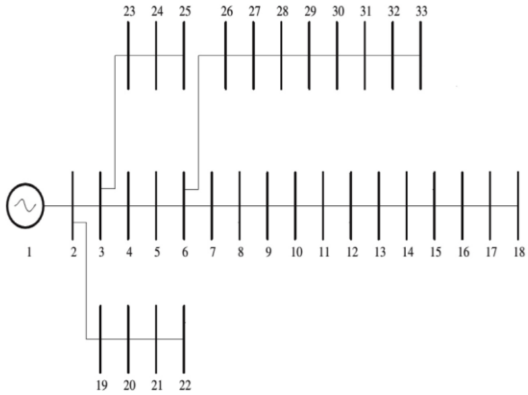

Figure 4: IEEE 33-bus distribution network

4. RESULTS AND DISCUSSION

After the implementation of the moth flame algorithm-based technique to the IEEE 33-bus system, the results in Table 1 were obtained. From the results in Table 1, the connection of four DG unit gave the minimum power loss and best voltage profile. The results of four scenarios were presented for DG placement on IEEE 33-bus radial distribution system; the first, second, third and fourth scenarios considered one, two, three and four DG placements respectively.

Figure 5 to Figure 12 shows the power loss and voltage profile with and without DG placement on the IEEE 33-bus test network system. From the illustrations in the figures, one to four DG units were installed on the IEEE 33-bus radial distribution network.

Table 1. IEEE 33-Bus System Comparative Analysis

No. of DG	Method	Optimal Bus Location	DG Power (kW)	Power Factor	Power Loss (kW)
1	MFO	6	2664	1	103
2	MFO	30, 13	1212, 873	1	83
3	MFO	14, 24, 30	780, 1075, 1120	1	69
4	MFO	31, 14, 24, 7	761, 622, 965, 863	1	65

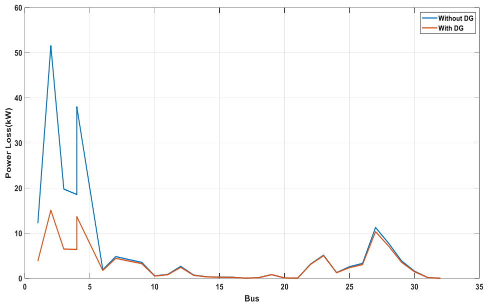

Figure 5: Power loss with single DG placement

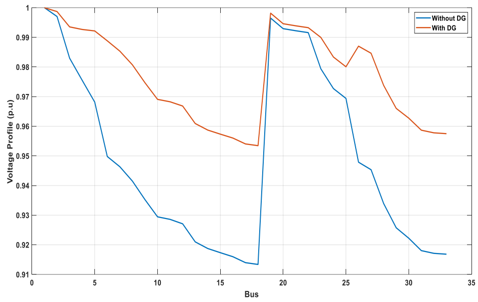

Figure 6: Voltage Profile with single DG placement

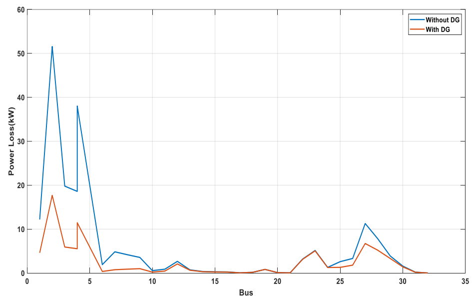

Figure 7: Power loss with two DG placement

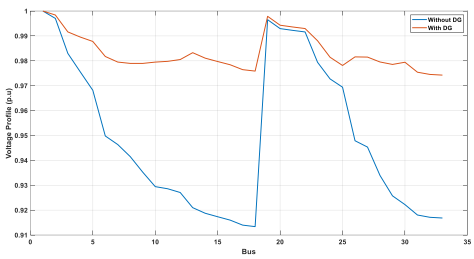

Figure 8: Voltage Profile with two DG placement

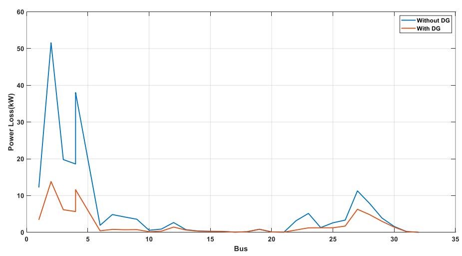

Figure 9: Power loss with three DG placement

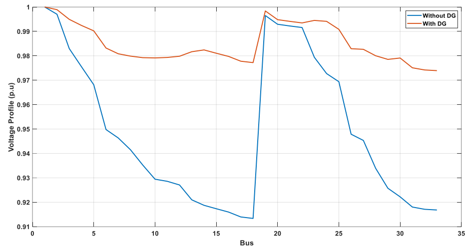

Figure 10: Voltage Profile with three DG placement

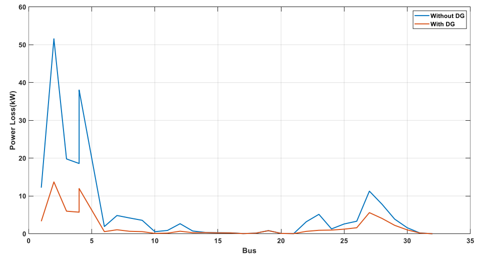

Figure 11: Power loss with four DG placement

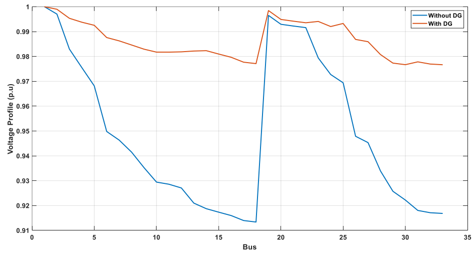

Figure 12: Voltage Profile with four DG placement

From Figures 5 to 12, it can clearly be seen that there was significant improvement when DG was placed on the network.

The proposed MFO method was compared with particle swamp optimization, harmony search algorithm, chaotic sine cosine algorithm, multi-objective Taguchi method and Bat Algorithm based techniques as shown in Table 2. From Table 2, it can be seen that the MFO method outperforms the other techniques.

Table 2: IEEE 33-bus system Percentage improvement in power loss reduction

S/N	Method	Percentage Improvement in Power Loss (%)
1	Particle Swamp Optimization [24]	65
2	Chaotic Sine Cosine Algorithm (CSCA) [25]	64.5
3	Taguchi Method (TM) [26]	49.52
4	Multi-objective Taguchi Algorithm [26]	52.40
5	Bat Algorithm [27]	64.42
6	Harmony Search Algorithm [28]	52.26
7	**Proposed Method**	**67.30**

5. CONCLUSION

This paper introduced the moth flame optimization (MFO) technique for the optimal placement of Distributed Generation (DG) units in power systems. The effectiveness and robustness of the proposed MFO method were demonstrated through its application on the IEEE 33-bus system. The performance of MFO was evaluated and compared against other established methods documented in the literature. The results indicated that MFO significantly outperforms these methods in terms of reducing power losses and improving voltage profiles. The superior performance of MFO highlights its potential as a highly effective tool for enhancing the efficiency and stability of power distribution networks.

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