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Research Article

Optimal Sizing and Placement of Series Capacitors in Distribution Networks Using Modified Elephant Herding Optimization Algorithm

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Abstract: The optimal size and location of series capacitors is a critical challenge in a distribution network. In this paper, a novel approach for enhancing voltage stability in distribution networks through the optimal sizing and placement of series capacitors is proposed. The study introduces a technique to determine the optimal lines for connecting series capacitors based on line reactance and current. A Modified Elephant Herding Optimization (MEHO) algorithm was used to determine the reactance sizes of the series capacitors and the best lines to place them for optimum system performance. To evaluate the effectiveness of the proposed method, three series capacitors are placed and sized in the standard IEEE 33-bus radial distribution system for stability enhancement. A comparison is conducted between the proposed MEHO algorithm-based approach, the original Elephant Herding Optimization (EHO) algorithm, and the IGWO-TS-based methods reported in the literature. The evaluation is performed by analyzing the system voltage profile, total system losses, and system voltage deviation index under varying loading conditions of 30%, 100%, and 120% of the system nominal loading. Results demonstrate that the proposed MEHO algorithm-based approach outperforms the other two methods significantly in all the scenarios, highlighting its effectiveness in voltage stability enhancement in distribution networks.

Keywords: Elephant herding optimization algorithm, series capacitors, metaheuristic, voltage profile, distribution network.

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1. INTRODUCTION

The growing demand for reliable and high-quality electric power supply has necessitated the enhancement of voltage stability in distribution networks [1], as well as maximizing the power carrying capacity of the distribution lines [2]. Shunt reactive compensators such as shunt capacitor banks are known to be viable in providing reactive power compensation to minimize losses and improve voltage profile [3]. Voltage stability issues can lead to undesirable voltage deviations, system inefficiencies, and even cascading failures [4]. Series reactive compensation has been established as an effective method of maximizing power flows and reducing reactive power losses [5]. However, oversizing of series capacitors in distribution lines can lead to resonance as established in [5] and [6]. Therefore, the optimization of series capacitor placement and sizing has emerged as a promising approach to improve system voltage stability by maximizing the power carrying capacity of distribution lines, and minimizing reactive power losses [7]. Unlike shunt capacitor banks that provide the reactive power at the demand end to reduce the reactive power flows on the distribution lines [8], series capacitors minimize the reactance of the distribution lines [9]. The placement and sizing of series capacitors in electrical power distribution networks have been widely investigated to alleviate voltage stability concerns. For instance, R. AL-Mula et al. [10] optimized the placement and sizing of series compensators to enhance voltage stability and reduce losses during increased power demand using PSO. Also, Mohammed Abd-EL-Hakeem et al proposed a method for optimal integration of series capacitors in distribution networks based on an Improved Grey Wolf Optimization (IGWO) algorithm and Tabu Search (TS) to improve the system voltage stability of a distribution network in Egypt [11]. Most of the proposed techniques used algorithms that tend to produce suboptimal solutions [12]. The challenge, therefore, lies in determining better optimal locations and series capacitor ratings to achieve maximum voltage stability improvement while considering network constraints such as network topology and operational limitations [13].

To address this challenge, this research proposes a modified Elephant Herding Optimization (EHO) algorithm for the optimal sizing and placement of series capacitors in distribution networks [14]. The EHO algorithm is a population-based metaheuristic optimization technique inspired by the herding behavior of elephants in nature [15]. By adopting a modified version [16] of this algorithm to the problem of series capacitor optimization, this work aims to effectively determine the most suitable locations and sizes of series capacitors to enhance system voltage stability under different loading conditions.

Therefore, this paper develops a comprehensive and efficient methodology for the placement and sizing of series capacitors in distribution networks. The proposed approach integrates power system analysis, optimization techniques, and simulation studies to identify the optimal line and optimal sizes of series capacitors. The effectiveness of the proposed methodology is validated through extensive simulations and comparisons with existing methods in the literature.

The remainder of this paper is organized as follows: Section 2 presents the methodology, including the modified EHO algorithm and the formulation of the optimization problem. Section 3 discusses the simulation studies and the test system. Section 4 discusses the simulation results. Finally, Section 5 concludes the paper and outlines potential avenues for future research.

2. Methodology

2.1. Problem Formulation

To formulate the problem, a distribution line with a series capacitor connected is presented in Fig. 1 to illustrate the capacitor modeling. In Fig. 1, the amount of power flow from bus *i* to bus *j* without the capacitor can be expressed according to the power equation presented in (1) [17, 18]. Under heavily loaded conditions, the amount of power flow can be increased without affecting system voltage quality by reducing the line reactance value, Xc [19].

$$P_{flow} = \frac{V_i V_j}{X_T} \sin \delta \tag{1}$$

where; δ is the angle difference between V_i and V_j, and X_T is the total reactance of the line. The presence of the series capacitor results in a new total reactance, X_{Tnew}, expressed in (2) below to achieve an effective reduction in the overall line reactance as expressed in [20].

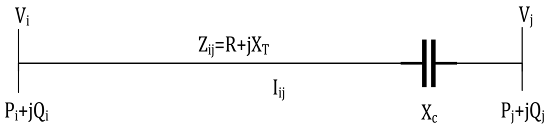

Fig. 1: Distribution Line with Series Capacitor.

$$X_{Tnew} = X_T - X_C \tag{2}$$

The X_{Tnew} is less than the X_T as a result of the presence of the capacitive reactance, X_c, of the series capacitor connected to the line. This increases the amount of maximum power the line can transmit safely within desired voltages [21].

However, within a given complex distribution network, the line to connect (location) and the amount of reactance sizing of the series capacitor plays a crucial role in its impact on the quality of power delivery [22]. Also, the oversizing of series capacitors can result in resonance [23]. To maximize the benefits and ensure stability, a two-step approach consisting of location determination and sizing is proposed as follows.

The proposed technique for determining the optimal lines to connect the series capacitors focuses on the loading level of the lines, and the reactance of the lines. This is on the basis that heavily loaded lines need series compensation the most, and series capacitors provide compensation by reducing the line reactance [24]. Hence the higher the line reactance, the more compensation a series capacitor can provide. The two conditions of the lines are combined to form an indicator of a priority list of distribution systems lines for series capacitor placement as presented in (3).

$$f_{ij} = \left| I_{ij} \times X_{ij} \right| \tag{3}$$

where I_{ij} represents the line current and X_{ij} represents the total line reactance. The value of *f* for all the lines in the distribution system is calculated from data from a backward-forward sweep load flow algorithm. The system lines are sorted in descending order according to the corresponding *f* values. This order of the system lines is considered the order for optimal placement of series capacitors in the distribution system for effective voltage profile enhancement. To enhance the system's voltage stability, the proposed objective function is developed based on the total system voltage deviation [25]. The system voltage profile is a good indicator of the system stability and the system losses [26]. The proposed MEHO algorithm [16] is then adopted to determine the optimal reactance values of the series capacitors to minimize the objective function expressed in (4), Just like in other areas of application where various metaheuristic algorithms have been adopted. For instance, the gravitation search algorithm in [26] has been used in optimal power flow for economic dispatch and emission.

$$\min\left(f_{obj}\right) = \sum_{i=1}^{N} \left| V_{ref} - V_i \right| \tag{4}$$

where the reference voltage, V_{ref}, is set to 1 p.u and V_i is the bus voltage.

2.2. Modified Elephant Herding Optimization (MEHO) Algorithm

The MEHO algorithm [16] is an improved version of the original EHO algorithm [15] that emulates the collective behavior of elephants in their natural habitat, specifically their herding and foraging patterns. It consists of two main phases: the clan updating operator and the separating updating operator. MEHO algorithm operates on the following assumptions:

1. The elephant population is composed of smaller groups known as clans, with a fixed number of members.
2. Male elephants tend to separate themselves from their clans and establish independent lives in each generation.
3. Within each clan, elephants coexist and are led by the strongest female member, known as the matriarch.

2.2.1. Initialization

To begin, the initial positions of N elephants in the population are generated randomly using (5). The population is then divided into smaller groups, referred to as clans, with an equal number of members.

$$x_j = x_{\min} + \alpha\left(x_{\max} - x_{\min} + 1\right) \times rand \quad (5)$$

where $x_{\min}$ and $x_{\max}$ are lower and upper bound of positions in the elephant population, and $rand \in [0,1]$ is a stochastic distribution.

2.2.2. Clan updating operator

In a given clan, C_i, the members coexist and are led by the matriarch. the matriarch's influence on the next generation determines the new position of each member, *j*, based on (6).

$$x_{ci,j}^{t+1} = x_{ci,j}^{t} + \alpha\left(x_{best,ci}^{t} - x_{ci,j}^{t}\right) \times r \quad (6)$$

where $x_{new,ci,j}$ and $x_{ci,j}$ represent the new and old positions of clan members respectively, $x_{best,ci}$ represents the position of the matriarch, $\alpha \in [0,1]$ is a factor that determines the level of the matriarch's influence on the clan members' new position, $r \in [0,1]$ and is a factor randomly generated using a uniform distribution.

The matriarch's new position is updated using equation (7).

$$x_{best,ci}^{t+1} = x_{best,ci}^{t} + \beta \times \left(x_{center,ci}^{t} - x_{best,ci}^{t}\right) \quad (7)$$

where $\beta \in [0,1]$ is a factor for determining the influence of $x_{center,ci}$ the matriarch's new position, while $x_{center,ci}$ represents the clan center calculated using (8).

$$x_{center,ci}^{t+1} = \frac{1}{n_{ci}} \times \sum_{j=1}^{n_c i} x_{ci,j,d}^{t} \quad (8)$$

where n_{ci} represents the number of elephants in the clan, and *d* is the dimension of the problem being solved in an interval $(1 \le d \le D)$.

2.2.3. Separating updating operator

The male elephant leaves the clan when it attains puberty. To ensure the elimination of the worst clan member, it is assumed that the weakest clan member implements the separation operator. The weakest member in each generation is replaced by a newly borne calf which is usually positioned close to the two strongest elephants in the clan. The weakest clan member is updated according to (9).

$$x_{worst,ci}^{t+1} = \frac{1}{2} \times \left(x_{best,ci}^{t} + x_{\sec-best,ci}^{t}\right) \times R \quad (9)$$

where $x_{best,ci}$ and $x_{\sec-best,ci}$ are the best two female members of the clan at the respective generation. R is a factor that gives the calf the freedom to roam within a certain range of the assigned position. It is randomly generated within the range $[0.5, 1.01]$. The following pseudo codes can be used to implement the operators. With the detailed description provided in the clan updating operator and the separating updating operator, Fig. 4 serves as a flowchart guide for implementing the Modified Elephant Herding Optimization (MEHO) algorithm.

```
for Ci =1 to nClan (for all clans in the population) do
    for j=1 to nCi (for all elephants in Ci) do
        Update x_ci,j and generate x_new,ci,j using (6)
      If x_ci,j = x_best,ci then
        Update x_ci,j and generate x_new,ci,j using (7)
      end if
    end for j
end for Ci
```

Fig. 2: Pseudocode of clan updating operator.

```
for Ci =1 to nClan (all the clans in the elephant
    population) do
      Replace the worst elephant in clan Ci using (9).
end for Ci
```

Fig. 3: Pseudocode of separating updating operator.

The steps below outline the implementation of the Modified Elephant Herding Optimization (MEHO) algorithm.

Step 1: Initialization.

Set generation counter t=1, Initialize population, and maximum generation (MaxGen).

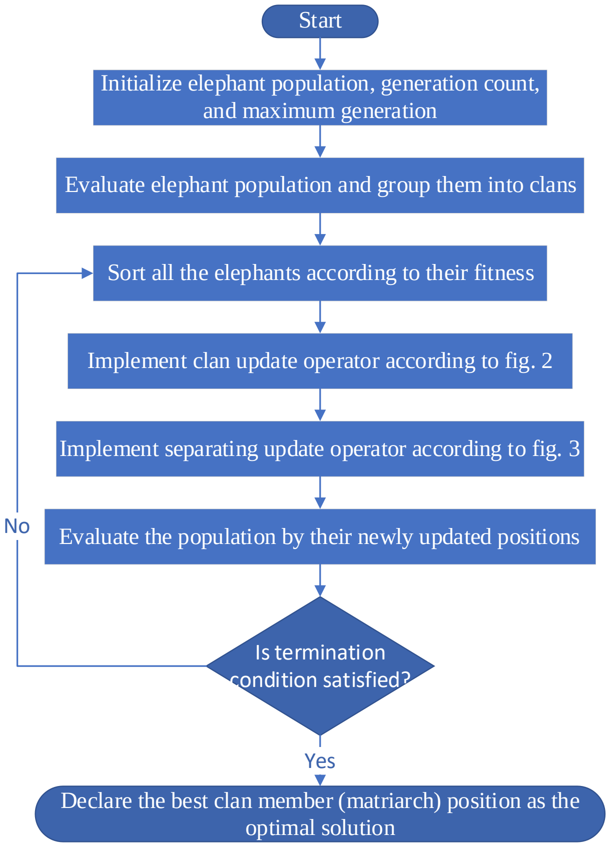

Fig. 4: Implementation of MEHO.

Step 2: While $t < MaxGen$, **Do**

Sort all the elephants according to their fitness.

Implement the clan updating operator according to Fig. 2.

Implement the separating operator according to Fig. 3.

Evaluate the population by the newly updated positions.

$t = t+1$

Step 3: end while

2.3. Implementation

The following steps elaborate on the procedure to follow to implement the proposed method on a given electrical power distribution network.

1. Run a backward-forward sweep load flow algorithm (or any appropriate load flow method for distribution systems) on the system to determine the system data.
2. Calculate the values of f for all system lines using (8), sort the lines in descending order according to the values of f, and select the optimal lines to place capacitors starting from the top downwards till the number of capacitors wishes to be placed.
3. Integrate the capacitors at the various selected lines according to (7) to be sized by the MEHO algorithm.
4. Set the number of elephant clans to be equal to the number of series capacitors to be sized. The matriarch value of each clan will represent the size of a series capacitor.
5. Set all initial parameters of the MEHO algorithm, and run the algorithm to determine the sizes of the series capacitors.
6. Save the sizes of the matriarch elephants of all clans as the optimal sizes produced by the proposed MEHO algorithm-based method.

3. Test Simulation

To establish the effectiveness of the performance of the proposed method, it was implemented in a MATLAB environment (MATLAB R2019a) and tested on the standard IEEE 33-bus radial distribution test system under varying load conditions. The simulation was carried out using an HP Pavilion laptop with a 64-bit AMD processor, 4.0 GB RAM, and 2.0GHz clock speed. The parameter settings used in simulating the Modified Elephant Herding Optimization (MEHO) algorithm to determine the series capacitor sizes are presented in Table 1.

3.1. IEEE 33-bus Radial Distribution Test System

The IEEE 33-bus radial distribution test system is one of the standard power distribution network systems developed for simulation tests in research works [27]. It has 33 buses and 32 lines, a total active and reactive power loading of 3.72MW and 2.3MVAr respectively, and total active power losses and reactive power losses of 202.67KW and 135.14KVAr respectively.

Table. 1: Parameter settings for MEHO simulation.

Parameter	Value
Population size	30
Number of clans	3
Maximum Iterations	100
A	0.1
B	0.5

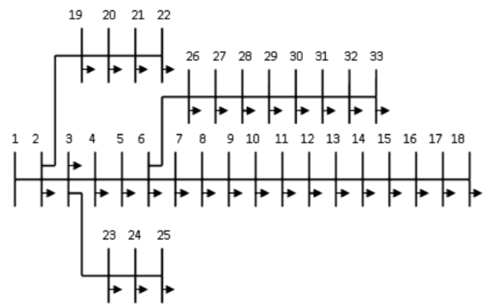

Fig. 5: Single line diagram of IEEE 33-bus system.

The proposed MEHO algorithm-based approach was used to place and size three (3) series capacitors in the IEEE 33-bus system to assess the performance in improving the system voltage stability. The outcome of this test is presented in the next section.

4. Results and Discussion

The simulation results of the proposed method to integrate three series capacitors in the standard IEEE 33-bus radial distribution system are presented in this section. To establish the effectiveness of the proposed method, other methods reported in the literature and the original EHO algorithm were implemented as well to serve as benchmarks for comparison. The optimal locations and sizes produced by the methods are presented in Table 2. The impact of the various outcomes on the IEEE 33-bus system for the various methods is presented under three (3) cases of different system loading conditions. It is important to mention that series capacitors for distribution networks are available in varying sizes produced by manufacturers such as ABB, Schneider, siemens, and so on [29]. Special requests can be made to meet certain requirements.

4.1. Case 1: System Performance Under Lightly Loaded Condition (30% of Nominal Load)

The performance of the system under lightly loaded conditions of 30% of the nominal loading condition is presented in Table 3. It covered the base system without compensation and with the compensation by all the methods considered.

Table 2: Simulation results on IEEE 33-bus system.

Method	Location (Size)
EHO	Line 5 (0.30p.u), Line 2 (0.19p.u), Line 27 (0.75p.u)
IGWO-TS	Line 2 (0.21p.u), Line 5 (0.50p.u), Line 3 (0.16p.u)
MEHO	Line 5 (0.70p.u), Line 2 (0.25p.u), Line 27 (0.90p.u)

Table 3: System Performance of IEEE 33-bus (30% loading).

IEEE 33-bus	Base Case	EHO	IGWO-TS [11]	MEHO
P Losses (KW)	16.49	16.43	16.41	16.38
% P Loss Reduction	-	0.36%	0.48%	0.67%
Q Losses (KVar)	10.98	7.53	6.54	5.38
% Q Loss Reduction	-	31.42%	40.44%	51.00%
Min. Voltage	0.97533	0.97697	0.97811	0.97836

The original EHO successfully reduced the total system active power losses to 16.43KW representing 0.36%, and that of the system total reactive power losses to 7.53KVar representing 31.42%. The IGWO-TS approach reported in [11] effectively reduced the total system active power losses to 16.41KW representing a 0.48% reduction, and the system total reactive power losses were reduced to 6.54KVar representing a 40.44% reduction. Finally, the proposed MEHO approach effectively reduced the total active power losses from 16.49KW to 16.38KW, representing the most marginal reduction of 0.67%, and the total reactive power losses to 5.38KVar representing 51.00%. Also, the MEHO produced the best voltage profile improvement with a minimum voltage of 0.97836p.u as shown in Fig. 6. The system voltage deviation index of the test system for various compensation conditions is presented in Fig 7. The base case scenario has a voltage deviation index of 0.014681, while the IGWO-TS [11], EHO, and MEHO methods produced voltage deviation indexes of 0.012734, 0.013268, and 0.012297 respectively. The proposed MEHO produced the best minimum index value of 0.012297.

4.2. Case 2: System Performance Under Nominal Load Condition (100% of Nominal Load)

Under nominal loading conditions, the performance of the system with the compensations for the various methods is presented in Table 4.

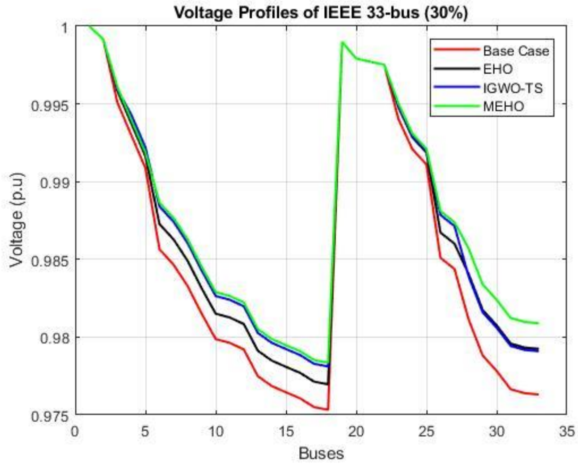

Fig 6: Voltage profiles of IEEE 33-bus (30% loading).

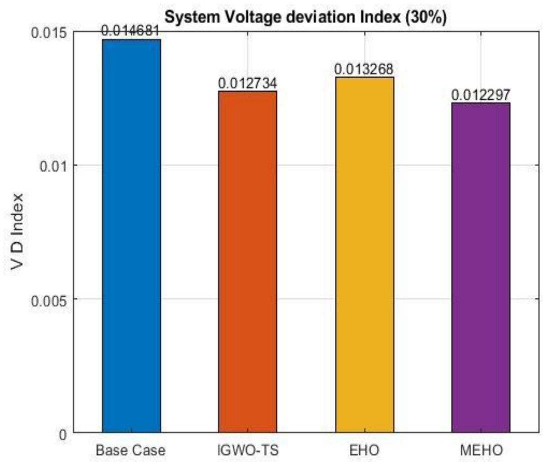

Fig. 7: System voltage deviation index (30% loading).

From Table 4, the original EHO successfully reduced the total system active power losses to 199.61KW representing 1.51%, and that of the system total reactive power losses to 91.75KVAr representing 32.11%. The IGWO-TS approach reported in [11] effectively reduced the total system active power losses to 198.87 representing a 1.88% reduction, and the system total reactive power losses were reduced to 79.48 representing a 41.18% reduction. Finally, the proposed MEHO approach effectively reduced the total active power losses from 202.68KW to 197.68KW, representing the most marginal reduction of 51.92%. Also, the MEHO produced the best voltage profile improvement with a minimum voltage of 0.92432p.u as shown in Fig. 8.

Table 4: System Performance of IEEE 33-bus (100% loading).

IEEE 33-bus	Base Case	EHO	IGWO-TS [11]	MEHO
P Losses (KW)	202.68	199.61	198.87	197.68
% P Loss Reduction	-	1.51%	1.88%	2.47%
Q Losses (KVar)	135.14	91.75	79.48	64.97
% Q Loss Reduction	-	32.11%	41.18%	51.92%
Min. Voltage	0.91309	0.91924	0.9234	0.92432

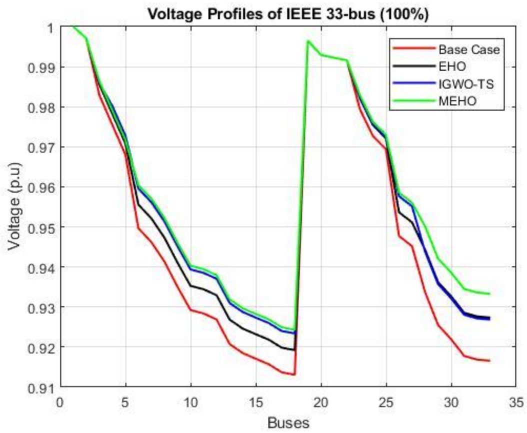

Fig 8: Voltage profiles of IEEE 33-bus (100% loading).

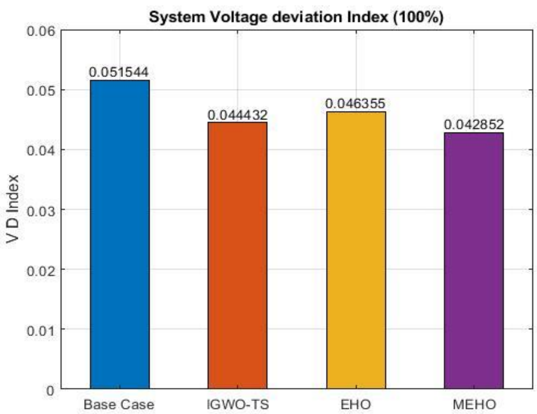

Fig 9: System voltage deviation index (100% lading).

To further assess the impact of the capacitors on the system voltage stability, the system voltage deviation index is presented in Fig 9. The base case scenario has a voltage deviation index of 0.051544, while the IGWO-TS, EHO, and MEHO methods produced voltage deviation indexes of 0.044432, 0.046355, and 0.042852 respectively. The proposed MEHO produced the best minimum index value of 0.042852.

4.3. Case 3: System Performance Under Heavily Loaded Condition (120% of Nominal Load)

The performance has also been assessed under a heavily loaded condition of 120% and the performance is presented in Table 5 below. Under a heavy loading condition of 120%, the total system active power losses and reactive power losses are 301.45KW and 201.10KVar respectively. The EHO technique successfully reduced them to 295.70KW (1.91%) and 136.00KVar (32.37%) respectively. Also, the IGWO-TS method reduced the total active power losses to 294.31KW representing 2.37%, and the total reactive power losses to 117.71KVAr representing 41.47%. Again, the proposed MEHO approach produced the best reduction of the total active power losses to 292.11KW and total reactive power losses to 96.02KVAr representing 3.10% and 52.25% reductions respectively. It also achieved the best voltage profile improvement as shown in Fig. 10 with a minimum voltage of 0.90781p.u.

Table 5: System performance of IEEE 33-bus (120% loading).

IEEE 33-bus	Base Case	EHO	IGWO-TS [11]	MEHO
P Losses (KW)	301.45	295.70	294.31	292.11
% P Loss Reduction	-	1.91%	2.37%	3.10%
Q Losses (KVar)	201.10	136.00	117.71	96.02
% Q Loss Reduction	-	32.37%	41.47%	52.25%
Min. Voltage	0.89384	0.90152	0.90666	0.90781

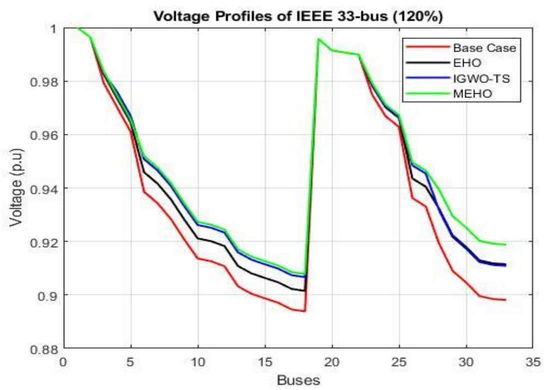

Fig 10: Voltage profiles of IEEE 33-bus (120% loading).

Fig. 11 presents the system voltage stability level of the test system with an illustration of the system voltage deviation index for the various placement methods. The lower the index value shows the more stable the system voltage. From Fig. 11, the base case situation has a system voltage deviation index value of 0.062893, the IGWO-TS produced 0.054095, EHO produced 0.056462, and the proposed MEHO produced the lowest index value of 0.052146. The proposed MEHO algorithm-based method produced the most stable system. From the results, the proposed method outperformed the other methods proposed in the literature by producing the lowest active power losses and the lowest reactive power losses. Also, the MEHO algorithm method produced the lowest system voltage deviation index, indicating the most stable system relative to the other methods. Again, the MEHO algorithm method exhibited a relatively better voltage profile. These performances are reflected in all the loading scenarios considered.

5. Conclusion and Recommendation

A new approach has been proposed in this work to optimally place and size series capacitors in electrical power distribution networks to improve system voltage stability based on a Modified Elephant Herding Optimization (MEHO) algorithm. It has been tested on the standard IEEE 33-bus radial distribution test system by optimally placing and sizing three series capacitors, and the system performance under different loading conditions has been presented. The proposed method effectively enhanced the system voltage stability with minimum voltages of 0.97836p.u, 0.92432p.u, and 0.90781p.u under light loading, nominal loading, and heavy loading conditions respectively. It also resulted in a system voltage deviation index of 0.012297, 0.042852, and 0.052146 respectively under the three loading conditions. There were significant reductions in total reactive power losses of the system and slight reductions in the total active power losses in the various scenarios considered. These performances were superior to those of the other methods in the literature considered. Based on the performance of this work, the MEHO algorithm is recommended for application in determining the placement and sizing of series capacitors in distribution networks. Also, the proposed method is suitable for optimizing TSCS location and sizing. Future works should focus on exploring the potential of metaheuristic algorithms such as the MEHO algorithm for optimal joint integration of series and shunt capacitors for efficient power delivery.

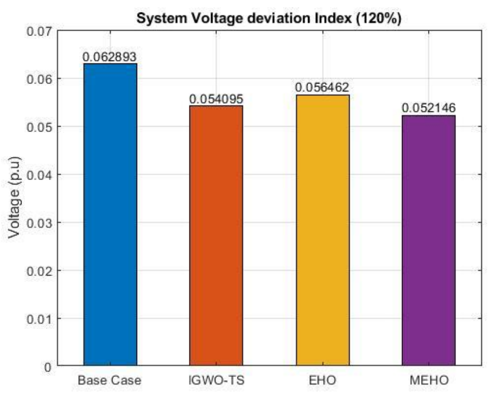

Fig 11: System voltage deviation index (120% loading).

CRediT Authorship Contribution Statement

Elvis Twumasi: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Supervision, Validation, Roles/Writing - original draft, Writing review & editing. **Abdul-Fatawu Seini Yussif:** Data curation, Investigation, Methodology, Software, Validation, Visualization, Roles/Writing - original draft, Writing - review & editing. **Emmanuel Asuming Frimpong:** Investigation, Methodology, Project administration, Supervision, Visualization, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues; including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy has been completely observed by the authors.

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