Transactions on Machine Intelligence 5(4) (2022) 265-276

ISSN Online: 2821-1693

Transactions on Machine Intelligence

Journal Homepage: https://tmachineintelligence.ir/index.php/TMI

# Optimization of Capacitor Placement and Sizing in Radial Distribution Systems Using Enhanced Harmony Search Algorithm, PSO, and TLBO with Power Loss Index (PLI)

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**ARTICLE INFO**

Article History:
Received 20 July 2022
Received in revised form 14 October 2022
Accepted 25 December 2022
Available online 26 December 2022

Keywords:
Enhanced Harmony Search Algorithm (IHA), Radial Distribution Systems, Power Loss Index (PLI), Optimal Capacitor Placement and Sizing, Particle Swarm Optimization (PSO), TLBO

**ABSTRACT**

Given the significant contribution of the distribution network to the total system losses, it is essential to implement fundamental measures to reduce losses in the distribution network. The placement and optimal sizing of parallel capacitors to reduce power losses and improve voltage profiles is a common issue in power system design and control, which has been extensively studied. In this paper, the Enhanced Harmony Search Algorithm (IHA) is proposed to determine the optimal capacitor placement and sizing, utilizing the Power Loss Index (PLI) in radial distribution systems. The procedure begins by using the PLI to select the buses for optimal capacitor installation, followed by the development of the IHA to determine the optimal location and size of capacitors using PLI. The proposed method has been applied to the IEEE 33-bus and 69-bus radial distribution systems. The results of this algorithm are compared with those of the Particle Swarm Optimization (PSO) algorithm and the Teaching-Learning-Based Optimization (TLBO) algorithm to demonstrate its superiority. Additionally, the IHA is tested under different loading conditions, and the impact of this method on the results has been proven.

## 1. INTRODUCTION

The flow of reactive power in the distribution network increases power losses and reduces the capacity of the lines. Proper installation of capacitors, by compensating part of the consumed reactive current, not only reduces energy losses but also helps in freeing up the capacity of installed equipment in the distribution system, improving the power factor, and enhancing the voltage profile. Therefore, finding the optimal size and location of capacitors in the distribution network is crucial. Various optimization methods have been employed for capacitor placement.

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http://dx.doi.org/10.47176/TMI.2022.265

In reference [1], a simulated annealing algorithm was used for optimal capacitor placement; however, this algorithm does not guarantee cost optimization and may select a local optimum. The tabu search algorithm in [2] was introduced to address the capacitor placement problem. While it is an effective method for design issues, its quality decreases due to the use of complex objective functions and many optimization parameters, and it is also time-consuming. The genetic algorithm in reference [3] was used for the optimal sizing and placement of capacitors, but it requires a long execution time due to the size of the studied system. The direct search algorithm in reference [4] was introduced but does not consider installation and maintenance costs. In reference [5], a bacterial search algorithm combined with PSO was used for capacitor placement and sizing in the distribution network, aiming to reduce losses and improve the system's voltage profile. The capacitor placement and sizing in the distribution system based on a multi-objective method was presented in [6]. Capacitor placement and sizing in the distribution system to increase energy storage and improve the system's voltage profile was conducted in [7]. In this reference, a fuzzy genetic algorithm and loss sensitivity coefficient were used to solve the optimization problem.

From the above-mentioned methods, the diversity of approaches proposed for solving the capacitor placement and optimal sizing problem in distribution networks becomes evident. In this study, the Enhanced Harmony Search Algorithm (IHA) along with the Power Loss Index (PLI) is employed. The proposed method proceeds as follows: first, the PLI selects the best candidate buses for capacitor installation using the back-and-forth load flow [8], and then the IHA algorithm uses the selected buses to determine the optimal location and sizing of capacitors.

Section two of this paper briefly introduces the Enhanced Harmony Search Algorithm, section three formulates the presented problem, and section four presents the simulation results and discussion.

## 2. INTRODUCTION TO THE INTELLIGENT ALGORITHMS USED IN THE PAPER

### 2.1. Traditional Harmony Search Algorithm

The Harmony Search Algorithm is a metaheuristic algorithm developed in 2001. It is used as a successful metaheuristic for routing in wireless sensor networks and for extending the lifespan of such networks. One of the simplest and most recent metaheuristic methods, it is inspired by the process of simultaneous playing in a music orchestra during the optimization process of problem-solving. In other words, there is a similarity between finding an optimal solution to a complex problem and the process of executing music. This solution method was first introduced by Geem in 2001. The Harmony Search Algorithm, due to its applicability to both discrete and continuous optimization problems, low mathematical computation requirements, simple concept, minimal parameters, and ease of execution, has become one of the most widely used optimization algorithms in recent years for various problems. Compared to other metaheuristic methods, it requires fewer mathematical constraints and can be adapted to different engineering problems by changing parameters and operators. This algorithm utilizes all the solutions in its memory, which increases its flexibility in searching for better solution spaces. Another feature of the Harmony Search Algorithm is that it identifies solution spaces with better performance within a suitable time, but this feature causes a problem when the problem under study has a local optimum; it may get stuck at a local optimum and fail to reach the global optimum. The reason for this problem is the algorithm's inefficiency in executing local searches in discrete optimization problems. This algorithm consists of five steps:

1. Initializing the optimization problem and initial parameters:

The optimization process is defined by minimizing J(x), where $x_i \in X_i$ for $i = 1,2,\dots,n$. In this context, J(x) represents the objective function, and $x_{il} \leq X_i \leq x_{iu}$ denotes the set of response matrices, with $x_{il}$ and $x_{iu}$ representing the minimum and maximum constraints for each variable, respectively. The parameter n indicates the number of variables. At this stage, key parameters, including the harmony memory size (HMS), the harmony memory consideration rate (HMCR), the pitch adjustment rate (PAR), the bandwidth (BW), and the maximum number of iterations, are specified.

2. **Initializing the Harmony Memory (HM)**: This is populated with random values according to **hms**.

3. **Creating a New Improved Harmony**: A new harmony is generated based on considering the memory and selecting randomly. The response variable is updated according to the probability **par** (heuristic step). The modified rule is as follows:

$$x_i = x_i \pm r.bw \tag{1}$$

4. **Updating the Harmony Memory (HM):** If a new harmony is better than an existing one, replace it.
5. Repeat steps 3 and 4 until the stopping criterion is satisfied or the iterations are completed.

### 2.2. Improved Harmony Search Algorithm

The Improved Harmony Search (IHS) algorithm suggests modifying the pitch adjustment rate (par) and bandwidth (bw) in the heuristic step (step 3) instead of using fixed values for them. The modified parameters are as follows [9,10]:

$$par(k) = par_{\min} + \left(\frac{par_{\max} - par_{\min}}{k}\right)k \tag{2}$$

$$bw\,(k) = bw_{\max} \exp\left[\left(\frac{\ln\left(\frac{bw_{\min}}{bw_{\max}}\right)}{k}\right)k\,\right] \tag{3}$$

where we have:

$$bw_{\max} = 0.5, bw_{\min} = 0.2, par_{\max} = 0.9, par_{\min} = 0.3$$

IHA has been used as a new optimization method in many articles, as mentioned in [11, 12].

A complete introduction to the TLBO algorithm can be found in references [13, 14], and the PSO algorithm is discussed in reference [19].

## 3. FORMULATION OF THE PROBLEM

### 3.1. PLI Index

In this study, the PLI index is introduced to select the best candidate buses for capacitor installation. In fact, the IHA algorithm is developed using this index, which results in a significant reduction in the search area and the optimization time by the IHA algorithm [15, 16].

$$PLI(i) = \frac{lr(i) - lr_{min}}{lrmin_{max}} \tag{1}$$

Where $lr_i$ represents the reduction in active power losses at bus i, $lr_{max}$denotes the maximum reduction in active power losses, and $lr_{min}$ indicates the minimum reduction in active power losses. It is important to note that buses with higher PLI values are given priority for inclusion in the search space of the IHA algorithm for capacitor installation.

### 3.2. Objective Function

The objective function used in this study is defined as follows:

$$Cos\,t = K_p * P_{LOSS} * T + D(K_1 * CB * K_C * \textstyle\sum_i^{CB} Q_{ci}) + K_0 CB \tag{5}$$

The constants are according to reference [17]. Equation (5) is minimized while considering the equality and inequality constraints below.

### 3.2.1. Problem Constraints

**Load Flow Constraint**: Traditional load flow methods, such as Newton-Raphson and Gauss-Seidel, cannot be used in distribution systems due to their specific conditions. In distribution systems, due to their conditions, [18] the back-and-forth sweeping method is introduced. The back-and-forth sweeping load flow is one of the most suitable load flow methods for distribution networks. In this method, it does not matter how the load is modeled, and its advantage lies in ensuring high convergence speed.

$$P_{Swing} = \sum_{i=1}^{L} P_{Lineloss}(i) + \sum_{q=1}^{N} Pd(q) \tag{2}$$

$$Q_{Swing} + \sum_{b=1}^{CB} Q_C(b) = \sum_{i=1}^{L} Q_{Lineloss}(i) + \sum_{q=1}^{N} Qd(q) \tag{3}$$

**Voltage Constraint**: The voltage range at each bus must be constrained according to the following equation:

$$V_{\min} \le |V_i| \le V_{\max} \tag{4}$$

$V_{min}$ and $V_{max}$ are 0.9 and 1.1, respectively [19].

**Reactive Power Constraint**: The total reactive power of the system must be constrained according to the following equation, and the system must always operate with a lagging power factor:

$$\sum_{b=1}^{CB} Q_C(b) \le \sum_{q}^{N} Qd(q) \tag{5}$$

**Capacitor Constraint**: The reactive power injected by each capacitor is considered in discrete values with a step of 50 kVAr.

$$Q_{c\min} \le Q_c \le Q_{c\max} \tag{6}$$

## 4. DISCUSSION AND SIMULATION RESULTS

This section presents the simulation results using three algorithms: PSO, TLBO, and IHA, on IEEE 33-bus and 69-bus systems. The minimum total cost, which is the sum of the loss cost and the annual capacitor installation cost, as well as the minimum system losses, have been calculated and discussed. It should be noted that the voltage range constraint must always be adhered to during the calculations. The parameters used are shown in Table 1.

**Table 1.** Parameters Used

| Parameter | Value |
|---|---|
| $K_0$ | 300 USD/Year/location |
| $K_P$ | 0.06 USD/kWh |
| $K_I$ | 1600 USD |
| T | 8760 h |
| 50 kVAr≤Qc≤1500 kVAr50 | - |
| D | 0.2 |
| $K_C$ | 25 USD/kVAr |

The results indicate the superiority of the Improved Harmony Search (IHA) algorithm over PSO and TLBO algorithms when combined with the PLI index. To demonstrate the effectiveness of the IHA algorithm, developed using the PLI, both systems were tested under light load, nominal load, and peak load conditions. The light load was considered as 65% of the nominal load, and the peak load as 140% of the nominal load. Simulations were carried out using MATLAB software. For consistency, the results were obtained after 40 runs of the program for each algorithm. The number of optimization iterations for all three algorithms was set to 500.

## 4.1. IEEE 33-Bus Test System

### *4.1.1. Uncompensated System*

The IEEE 33-bus system has a total active power of 3715 kW and a reactive power of 2300 kVAr. In this case, the total system losses are 132.2032 kW, and one of our goals is to minimize these losses at the lowest possible cost. The minimum voltage and annual cost are 0.9365 per unit and 67,108.818 USD/year, respectively.

### *4.1.2. Compensated System*

In this case, candidate buses for capacitor installation are first selected using the PLI index. Then, the IHA algorithm uses these buses to determine the optimal locations and sizes of the capacitors. The priority of candidate buses for capacitor installation, according to the PLI values, is shown in Figure 1 as: 29, 14, 4, 5, etc. In IHA, only three buses were selected for capacitor installation, with a reactive power capacity of 1500 kVAr. The active losses were reduced to 90.2825 kW, which corresponds to a 31.71% reduction in losses. Additionally, the minimum voltage increased to 0.9509, which is higher than the minimum voltage obtained with other algorithms. The annual cost, according to the proposed cost function, was 52,432.2 USD/year, which represents a net annual saving of 21.78%, the highest increase compared to other algorithms. The improvement in the voltage profile of the system due to the installed capacitors is shown in Figure 2. The convergence rate of the cost function is shown in Figure 3. The computation time for compensation and obtaining the output with the IHA algorithm was 8 seconds.

Table 2 shows the results of the PSO, IHA, and TLBO algorithms after 40 iterations. Finally, Table 3 presents the optimal locations and capacities of the capacitors determined by the IHA algorithm under light, nominal, and peak load conditions. Table 2 also provides the minimum voltage, annual losses, total system power factor, annual cost, net annual savings, and the reactive power injected into the grid with and without compensation. By examining the results, we see that some of the best candidate buses for capacitor installation, selected by the PLI index, have been successfully compensated under different loads, indicating the effectiveness of the algorithm and the proposed method of simultaneously using IHA and the PLI index. As shown in Table 3, the proposed method uses the least number of buses for capacitor installation even under peak load, leading to a reduction in annual cost.

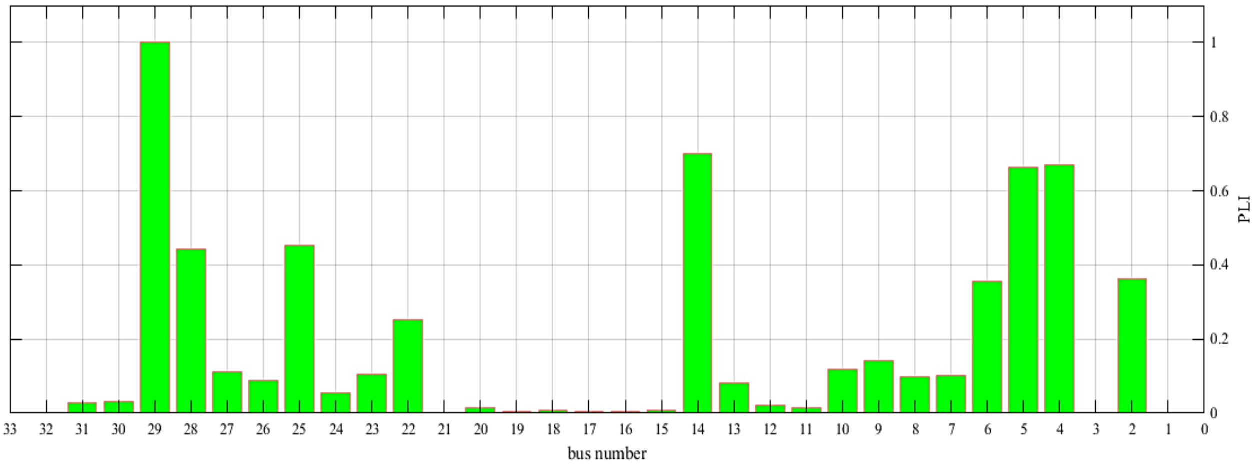

**Fig. 1.** PLI of a 33-Bus System

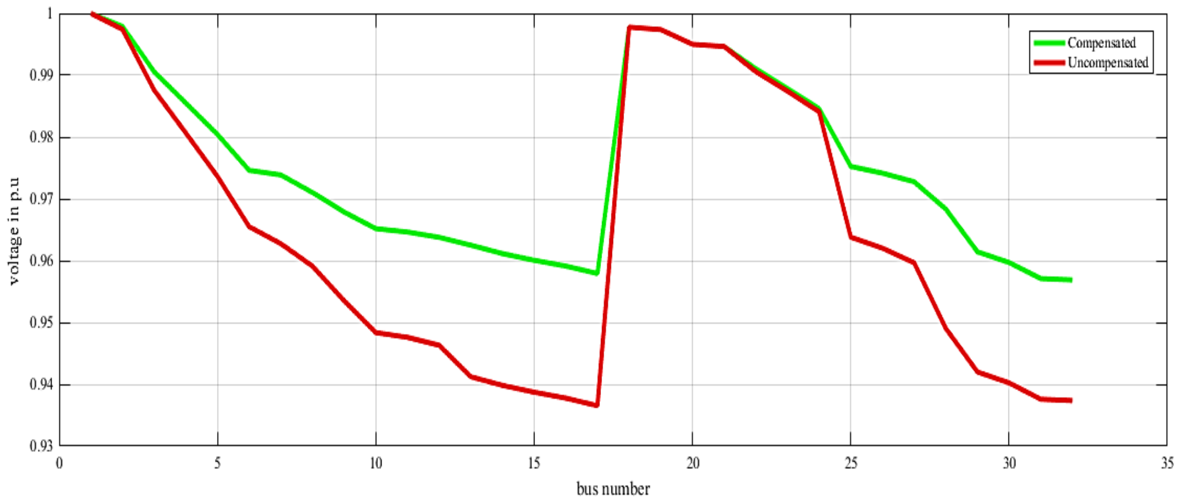

**Fig. 2.** Effect of Compensation on the Voltages of the 33-Bus System

**Table 2.** Results for the 33-Bus System under Nominal Load

| **Method** | **Execution Time (seconds)** | **Total Losses (KW)** | **Percentage Loss Reduction (%)** | **Minimum Voltage (P.U.)** | **Optimal Capacitor Installation Location and Capacity (Kvar-location)** | **Reactive Power Injected (Kvar)** | **Annual Cost (USD/year)** | **Annual Savings (USD/year)** | **Percentage Annual Savings (%)** |
|---|---|---|---|---|---|---|---|---|---|
| Without Compensation | ---- | 132.23 | ---- | 0.9365 | ---- | ---- | 67,108 | ---- | ---- |
| Compensation with: | | | | | | | | | |
| PSO | 8 | 93.52 | 29.26 | 0.95 | (150-16)<br>(300-12)<br>(100-32)<br>(900-30) | 1450 | 54,228.23 | 12,880.58 | 19.20 |
| TLBO | 13 | 92.1 | 30.33 | 0.9502 | (300-14)<br>(50-7)<br>(950-30)<br>(100-25) | 1400 | 53,942.76 | 13,166.06 | 19.62 |
| IHA | 12 | 90.2825 | 31.71 | 0.9509 | (250-14)<br>(400-6)<br>(850-29) | 1500 | 52,432.20 | 14,676.62 | 21.87 |

This table compares the results of different algorithms for the 33-bus system under nominal load. The IHA algorithm shows the best performance in terms of loss reduction, voltage improvement, annual savings, and the effectiveness of capacitor placement.

**Table 3.** Results for the 33-Bus System under Different Load Conditions

| Method | Load Level | Minimum Voltage (P.U.) | Annual Active Losses (KW) | Annual Reactive Losses (Kvar) | Power Factor (Lagging) | Annual Cost (USD/year) | Optimal Capacitor Installation Location and Capacity (Kvar-location) |
|---|---|---|---|---|---|---|---|
| **Without Compensation** | 65% Load | 0.959 | 53.94 | 36.44 | 0.849 | 34,203.8 | ---- |
| | 100% Load | 0.9365 | 132.23 | 89.24 | 0.86 | 67,108 | ---- |
| | 140% Load | 0.9092 | 269.87 | 182.03 | 0.84 | 124,995.5 | ---- |
| **Compensation with IHA** | 65% Load | 0.9619 | 41.06 | 28.21 | 0.926 | 32,221 | (519-29) |
| | 100% Load | 0.9509 | 90.2825 | 63.53 | 0.975 | 52,432.2 | (850-29) (250-14) (400-6) |
| | 140% Load | 0.9324 | 189.53 | 130.1 | 0.965 | 99,943.5 | (1000-29) (460-14) (432-6) |

This table shows the performance of the system under different load levels (65%, 100%, and 140%) for both with and without compensation using IHA. It includes key parameters such as voltage, active and reactive losses, power factor, annual cost, and optimal capacitor placement.

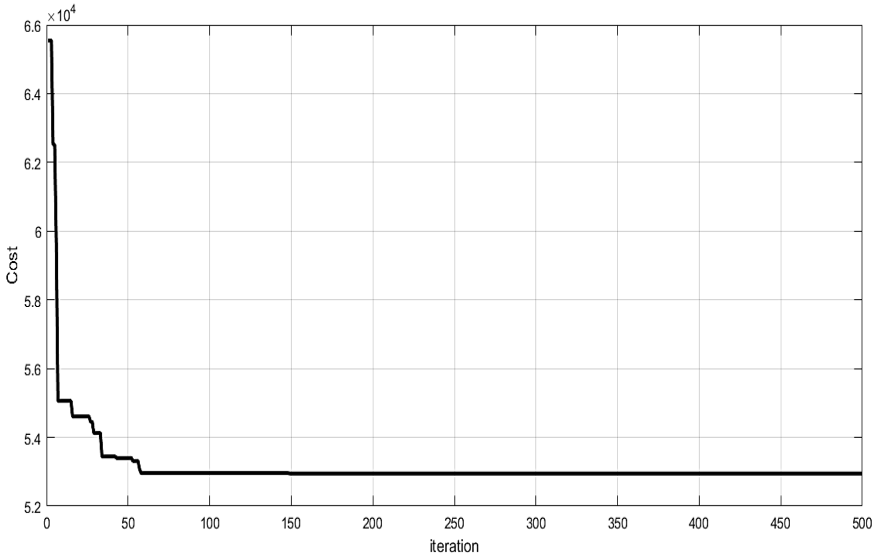

**Fig. 3.** Convergence of the Cost Function

## 4.2. 69-Bus Test System

### *4.2.1. Uncompensated System*

The IEEE 69-bus system has a total active power of 3785.89 kW and a total reactive power of 2683.6 kVAR. In this case, the total losses of the system amount to 224.38 kW. The minimum voltage is 0.9102 per unit, and the annual cost is $121,550.7. Our goal is to reduce losses and annual costs while increasing the minimum voltage of the buses.

### *4.2.2. Compensated System*

Following the previous explanation, the best candidate buses for capacitor placement are initially selected based on the PLI index. The priority of capacitor placement, as shown in Figure 4, is as follows: 56, 5, 6, 57, 58, 59.

According to the results, the IHA algorithm uses 1700 kVAR of reactive power for capacitor placement, distributed across three buses. In contrast, the PSO and TLBO algorithms use buses 4 and 5 for capacitor placement, leading to higher costs. The buses selected for compensation using IHA are the same buses that were prioritized for capacitor placement based on the PLI index.

With compensation, we have achieved a reduction of 65.54 kW in losses. Additionally, the minimum voltage has increased to 0.9308 per unit, which is higher than the minimum voltage obtained by other algorithms. The most significant reduction in the annual cost is achieved with IHA, which amounts to $46,668.85 per year. Table 4 compares the compensation results for the 69-bus system using all three algorithms, highlighting the superiority of the IHA algorithm over the others.

The voltage improvement and convergence rate of the cost function are shown in Figures 5 and 6. The execution time for the IHA algorithm is 25 seconds, which is shorter than that of the other algorithms.

Finally, to demonstrate the robustness and effectiveness of the proposed method, the 69-bus system is compensated using the IHA algorithm and PLI index under light, nominal, and peak load conditions, with the results presented in Table 5.

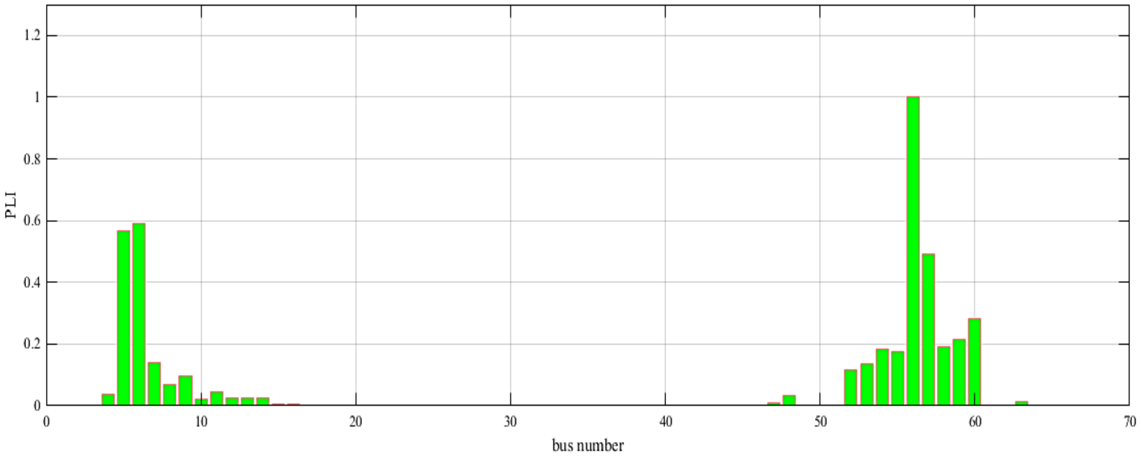

**Fig. 4.** PLI of a 69-Bus System

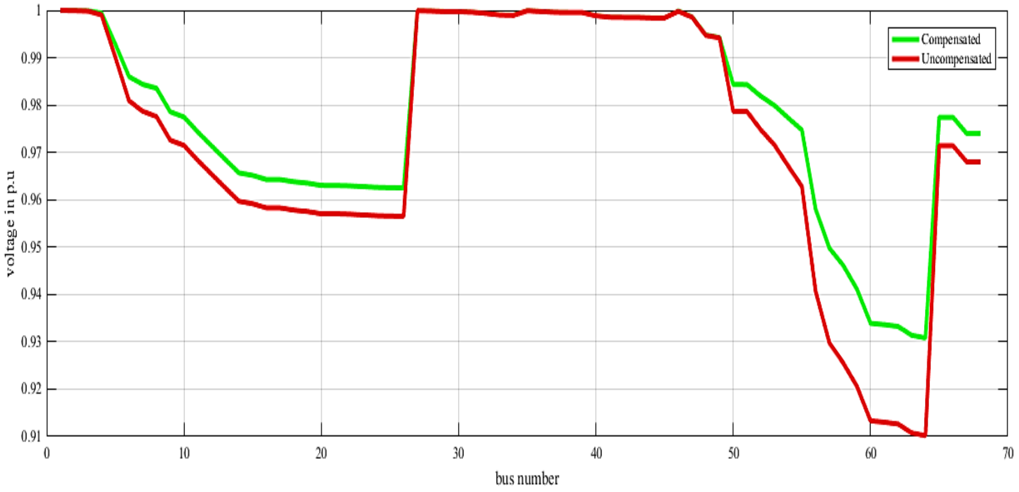

**Fig. 5.** Impact of Compensation on the Voltages of a 69-Bus System

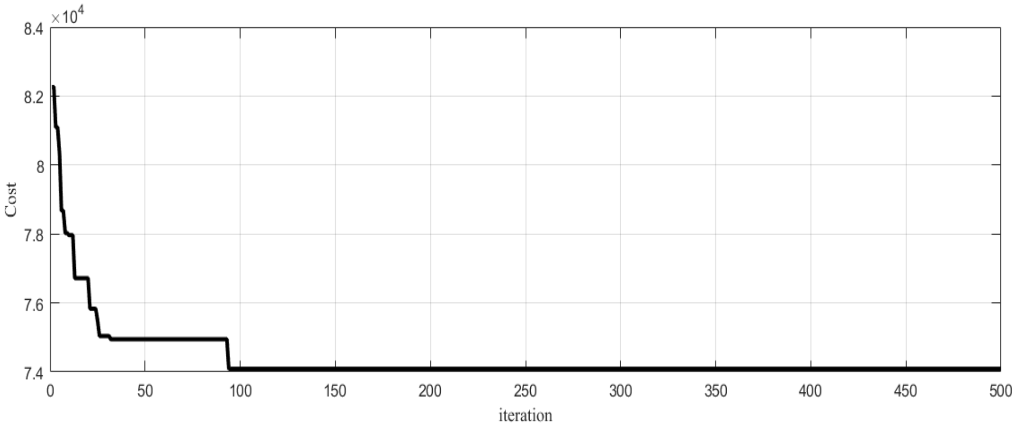

**Figure 6.** Convergence of the Cost Function

**Table 4.** Results for the 69-bus System Under Nominal Load

| Method | Execution Time (sec) | Total Loss (KW) | Loss Reduction (%) | Min Voltage (P.U) | Optimal Capacitor Locations and Sizes (Kvar - Location) | Injected Reactive Power (Kvar) | Annual Cost (Year/$) | Annual Savings ($) | Annual Savings (%) |
|---|---|---|---|---|---|---|---|---|---|
| **No Compensation** | ---- | 224.38 | ---- | 0.91 | ---- | ---- | 121550.7 | ---- | ---- |
| **PSO** | 34 | 165.24 | 26.3 | 0.93 | (700-61),<br>(150-49),<br>(200-22),<br>(300-65),<br>(4500-63) | 1800 | 79753.75 | 41796.9 | 34 |
| **TLBO** | 32 | 162.1 | 27.7 | 0.93 | (450-59),<br>(100-46),<br>(150-67),<br>(700-65) | 1700 | 76342.1 | 45208.6 | 37.1 |
| **IHA** | 25 | 158.45 | 29.38 | 0.93 | (800-59),<br>(550-58),<br>(350-56) | 1700 | 74881.9 | 46668.8 | 38.4 |

## Observations:

- **IHA** demonstrates the highest reduction in total losses (29.38%) and the greatest annual savings (38.4%).
- **PSO** and **TLBO** show notable improvements, but **IHA** outperforms them both in terms of loss reduction and savings.
- **IHA** achieves the highest efficiency with the lowest execution time (25 seconds), while **PSO** and **TLBO** require more time (34 and 32 seconds, respectively).

This demonstrates the effectiveness of the IHA algorithm in reducing both losses and costs, and its efficiency in the overall optimization process.

## 5. CONCLUSION

This paper presents a powerful and novel approach to the reactive power optimization problem with optimal capacitor placement. It introduces the development of the IHA algorithm using the PLI index, along with the PSO algorithm and the TLBO intelligent algorithm for determining the optimal location and capacity of capacitors. Additionally, the paper compares the three algorithms for two test systems: the 33-bus and 69-bus systems.

In this study, an objective function consisting of capacitor installation and maintenance costs, as well as the cost of power losses, is minimized using the developed IHA algorithm, while ensuring that voltage constraints are met. It is observed that, unlike the other algorithms, the IHA algorithm uses discrete reactive power values and fewer buses for capacitor installation.

The simulation results demonstrate the effectiveness of this method compared to other techniques mentioned in the paper, including PSO and TLBO. The proposed IHA approach yields superior results in terms of power loss reduction, cost savings, and voltage improvement.

**Table 5.** Results for the 69-bus System under Different Load Conditions

| Method | Load Level | Minimum Voltage (P.U) | Annual Active Losses (KW) | Annual Reactive Losses (Kvar) | Power Factor (Lagging) | Annual Cost (Year/$) | Location and Optimal Capacitor Size (Kvar-Location) |
|---|---|---|---|---|---|---|---|
| **Without Compensation** | 65% Load | 0.9433 | 89.3 | 40.7 | 0.819 | 64750.8 | ---- |
| | 100% Load | 0.9102 | 224.38 | 101.9 | 0.82 | 121550.7 | ---- |
| | 140% Load | 0.87 | 475.37 | 214.9 | 0.824 | 227055.2 | ---- |
| **Compensation with IHA** | 65% Load | 0.954 | 66.5 | 30.7 | 0.966 | 33531.9 | (600-59), (500-57) |
| | 100% Load | 0.9308 | 158.45 | 73 | 0.97 | 74881.9 | (800-59), (550-58), (350-56) |
| | 140% Load | 0.9324 | 327 | 149.9 | 0.98 | 147670 | (800-59), (550-58), (100-57), (550-6) |

## Transparency Statement

The data supporting this study are available upon reasonable request to the corresponding author, subject to ethical and confidentiality considerations.

## Acknowledgments

We would like to express our gratitude to all individuals who contributed to this project.

## Declaration of Interest

The authors declare that they have no competing interests.

## Funding

This research received no specific grant from any funding agency, commercial, or not-for-profit sectors.

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