

Optimal Placement And Sizing of Capacitors using Binary Firefly Algorithm To Reduce Power Losses

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Abstract. Optimal capacitor placement in radial distribution systems plays a vital role in minimizing real power losses and enhancing voltage profiles, thereby improving the overall performance and reliability of power networks. This paper presents an efficient approach using Binary Firefly Algorithm (BFA) to determine the optimal locations and sizes of shunt capacitors. The method focuses on reducing active power losses and maintaining voltage levels within acceptable limits, while adhering to operational constraints such as bus voltage bounds and capacitor sizing limits. The proposed method is tested on standard IEEE radial distribution systems, and the results show significant improvements in power loss reduction and voltage profile enhancement when compared to conventional techniques. Based on the analysis and simulation results, BFA demonstrated the most optimal performance in reducing power losses in the distribution system. Compared to other algorithms used in this study, BFA consistently identified the best combination of capacitor placement and sizing that resulted in the lowest total power loss. The effectiveness of BFA lies in its balanced exploration and exploitation capabilities within the solution space, enabling it to find optimal solutions that not only significantly reduce power losses but also improve voltage profiles throughout the system. Furthermore, from an economic perspective, BFA outperforms other methods in terms of net savings, defined as the difference between the energy cost savings due to loss reduction and the investment cost of the installed capacitors. Overall, BFA has proven to be the most efficient and effective approach for optimizing capacitor placement and sizing, delivering superior performance in both technical and economic aspects

Keywords: Capacitor, Firefly, Algorithm, Power Loss, Profil Voltage

1. Introduction

The optimization of capacitor placement and sizing in electrical distribution networks plays a crucial role in enhancing system efficiency. By strategically installing capacitors, reactive power can be better managed, leading to a significant reduction in power losses. Minimizing these losses not only improves voltage profiles but also increases the overall reliability of the power system. Advanced optimization techniques are essential to determine the optimal locations and capacities of capacitors for maximum effectiveness. This study focuses on developing an effective approach to capacitor allocation aimed at reducing power losses in distribution networks [1].

Tamiselvan introduces the Flower Pollination Algorithm (FPA) to address the optimal capacitor placement (OCP) issue in radial distribution systems. The main goal is to minimize power losses and installation costs while enhancing voltage levels across the network. FPA, inspired by natural pollination processes, effectively determines both capacitor locations and

sizes without relying on predefined indices. The approach is tested on multiple systems, including 33-, 34-, 69-, and 85-bus networks, and shows superior performance compared to traditional methods. Results demonstrate significant improvements in efficiency, voltage stability, and economic savings [2].

The Whale Optimization Algorithm (WOA), inspired by the bubble-net hunting behavior of humpback whales, is applied to optimize the placement and sizing of capacitors in radial distribution systems. This method effectively reduces real and reactive power losses, enhances voltage profiles, and minimizes operating costs compared to traditional algorithms like PSO, BFOA, and MINLP. WOA stands out due to its ability to avoid local minima and handle multi-objective constraints efficiently. Simulation results on IEEE 34-bus and 85-bus test systems demonstrate significant improvements in system performance and annual cost savings. Through its iterative and intelligent search mechanism, WOA shows great promise for practical application in power distribution optimization [3].

Devabalaji introduces a method to determine the best locations and sizes for capacitors in radial distribution networks using the Cuckoo Search Algorithm (CSA). By combining voltage stability indexing and a metaheuristic approach, the technique aims to cut down on power losses and enhance voltage profiles. The CSA simulates how cuckoo birds lay eggs in host nests, using random search patterns to find better solutions over time. Tested on IEEE 34-bus and 69-bus systems, the method outperformed traditional approaches in both loss reduction and economic savings. Thanks to its simplicity and fewer tuning requirements, CSA proves to be a practical and efficient tool for optimizing power distribution networks [4].

Nguyen proposes the DUTA algorithm to identify the best placement and sizing of capacitors in radial distribution networks. It combines diffusion and update phases to search for optimal solutions efficiently. Tested on 15-bus and 33-bus systems, DUTA consistently reduced power losses and improved voltage profiles across various loading conditions. Compared to other techniques, it achieved similar or better results with fewer computational resources. The findings confirm DUTA's potential as a robust and cost-effective approach for capacitor placement in power distribution systems [5].

Adeleke explores the use of Constriction-Factor Particle Swarm Optimization (CF-PSO) to find the best locations and sizes for shunt capacitors in radial power distribution networks. The method leverages a voltage stability index to pre-select promising bus locations, reducing the computational effort. Tests on IEEE 33-bus and 69-bus systems showed significant reductions in power losses, especially with the installation of up to four capacitors. However, the improvement in both technical and economic performance tends to level off beyond two or three capacitors. Overall, CF-PSO outperforms several other optimization methods in efficiency, precision, and cost-benefit results [6].

Pegado presents an enhanced optimization technique called Improved Selective Binary Particle Swarm Optimization (IS-BPSO) for reconfiguring radial distribution networks. The method introduces a modified sigmoid transfer function that helps better control particle behavior and speeds up convergence to optimal solutions. It was tested on IEEE 33-bus and 94-node systems, showing notable reductions in power losses and improved voltage profiles. Compared to other PSO-based methods, IS-BPSO achieved higher efficiency and greater consistency across simulations. By adjusting a tuning parameter β , the algorithm balances between exploration and exploitation, making it highly adaptable for various network configurations [7].

Díaz introduces the Locust Search (LS) algorithm as a new approach to solve the Optimal Capacitor Placement (OCP) problem in radial distribution networks. Inspired by the collective foraging behavior of locusts, LS avoids premature convergence by preventing individuals from

clustering too closely around the best solution [8]. This method was adapted to handle discrete capacitor sizes and tested on IEEE 10-, 33-, and 69-bus systems. Across all cases, LS demonstrated superior performance in reducing power losses and improving voltage profiles compared to other algorithms like FPA, CSA, and GSA. The results confirm LS as a reliable and efficient tool for enhancing power distribution network operations [9].

This study introduces an approach to reduce power losses and improve voltage profiles at each bus in a distribution network. The Firefly Algorithm is employed to determine the optimal placement and sizing of capacitors within the system. The proposed method is tested on the IEEE 33-bus distribution network to evaluate its performance. Optimization results obtained using the Binary Particle Swarm Optimization (BPSO) method are compared with those from other algorithms, including NSGA-II, MOWCA, MOGWO, and the ABC algorithm. This comparative analysis aims to highlight the effectiveness and efficiency of each technique in solving the capacitor placement.

2. Method

This research utilizes the IEEE 33-bus radial distribution system as the test network to evaluate the effectiveness of the proposed optimization approach. The system operates at a nominal voltage level of 12.66 kV and consists of 33 buses and 32 branches. Figure 1 shows the one-line diagram of the IEEE 33-bus distribution system. The total active power load is 3715 kW, and the total reactive power load is 2300 kVar.

2.1 Capacitor

The combination of capacitor locations and their corresponding sizes serves as the input for the Binary Firefly Algorithm. Both location and size variables are encoded in binary format. The binary input data for capacitor placement is detailed in Table 1, where the length of the binary string depends on the total number of buses in the distribution network. Meanwhile, Table 2 provides the binary representation of the capacitor size inputs [10].

Table 1. Binary Data Input for Capacitor Placement

Bus	Binary					
2	0	0	0	0	0	1
3	0	0	0	0	1	0
4	0	0	0	0	1	1
5	0	0	0	1	0	0
6	0	0	0	1	0	1
7	0	0	0	1	1	0
8	0	0	0	1	1	1
9	0	0	1	0	0	0
10	0	0	1	0	0	1
11	0	0	1	0	1	0
12	0	0	1	0	1	1
13	0	0	1	1	0	0
14	0	0	1	1	0	1
15	0	0	1	1	1	0
16	0	0	1	1	1	1
17	0	1	0	0	0	0
18	0	1	0	0	0	1
19	0	1	0	0	1	0
20	0	1	0	0	1	1

Bus	Binary					
21	0	1	0	1	0	0
22	0	1	0	1	0	1
23	0	1	0	1	1	0
24	0	1	0	1	1	1
25	0	1	1	0	0	0
26	0	1	1	0	0	1
27	0	1	1	0	1	0
28	0	1	1	0	1	1
29	0	1	1	1	0	0
30	0	1	1	1	0	1
31	0	1	1	1	1	0
32	0	1	1	1	1	1
33	1	0	0	0	0	0

This study focuses on optimizing both the placement and sizing of capacitors within the distribution network. The capacitor placement is determined based on the number of buses in the system. The capacitor sizes considered range from 150 kVAR to 2100 kVAR, as presented in Table 2 [11].

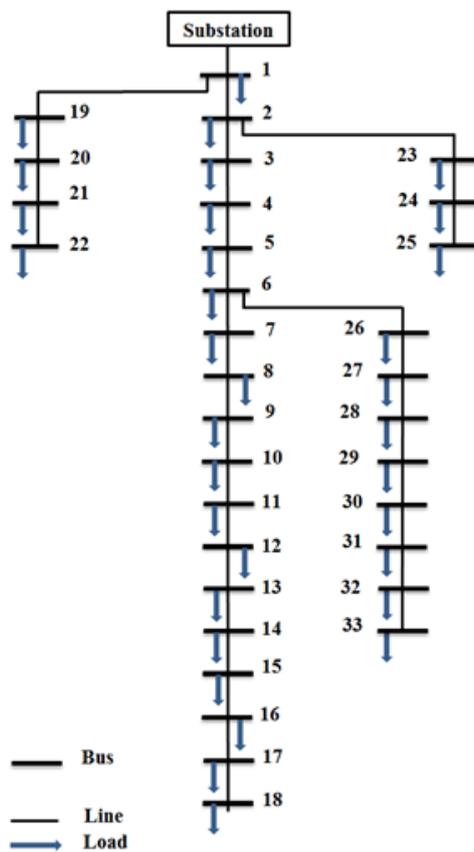


Fig. 1. One Line Diagram IEEE 33 Bus

Table 2. Binary Input Data for Capacitor Rating

Daya (kVAR)	Binary					
150	0	0	0	0	0	1
350	0	0	0	0	1	0
450	0	0	0	0	1	1
600	0	0	0	1	0	0
800	0	0	0	1	0	1
900	0	0	0	1	1	0
1050	0	0	0	1	1	1
1200	0	0	1	0	0	0
1350	0	0	1	0	0	1
1500	0	0	1	0	1	0
1650	0	0	1	0	1	1
1800	0	0	1	1	0	0
1950	0	0	1	1	0	1
2100	0	0	1	1	1	0

The capacitor installation cost for the 12,66 kV distribution system in this study is based on the reference provided in paper [12]. The total cost is calculated using the following formula, as shown in equation (1):

$$total\ cost = (P_{loss} \times K_p) + (K_c \times Q_c) \quad (1)$$

Where P_{loss} is the total power loss in kilowatts (kW), K_p is the cost coefficient for power loss (typically in currency per kW), K_c is the cost coefficient of capacitor installation (currency per kVAR) and Q_c is the total installed reactive power capacity of the capacitors (in kVAR). This cost function is used to constrain the number of capacitors installed in the distribution system, ensuring that the optimization process does not exceed reasonable installation costs. The detailed cost data for capacitor installation in a 20 kV distribution network is provided in Table 3.

Table 3. Capacitor Installation Cost

Capacitor Capacity (kVAR)	Capacitor Cost (\$/kVAR)
150	0,5
350	0,35
450	0,253
600	0,22
800	0,276
900	0,183
1050	0,228
1200	0,17
1350	0,207
1500	0,201
1650	0,193
1800	0,87
1950	0,211
2100	0,176

2.2 Binary Firefly Algorithm

The Binary Firefly Algorithm (BFA) is an extension of the original Firefly Algorithm (FA), which is based on the flashing behavior of fireflies observed in nature. In BFA, the algorithm is adapted to work in binary search spaces, making it suitable for discrete optimization problems. The development carried out in this study involves input and output data represented in binary form, namely “0” and “1”. The output generated by the Binary Firefly Algorithm is also in binary format therefore, an additional function, the sigmoid function is required. The sigmoid function is defined as follows [13] :

$$S(x_i) = \frac{1}{1 + \exp(-x_i)} \quad (2)$$

$$x_i = \begin{cases} 1, & \text{if } S(x_i) > r \\ 0, & \text{—} \end{cases} \quad (3)$$

2.3. Objective Function

The objective function is used to obtain the optimal result in a power flow optimization process. In this study, the objective function aims to minimize the total power loss in the distribution network. The mathematical formulation of the objective function is expressed in equation (4):

$$\text{Min } F = \min (P_{loss} + (\lambda_V \times S_{CV})) \quad (4)$$

Where, P_{loss} is the total power loss, calculated, λ_V is the penalty factor and S_{CV} represents the sum of voltage violations (i.e., the total amount of voltages outside their permissible limits).

The value of the penalty factor λ_V is determined as follows:

$$\lambda_V = \begin{cases} 0, & \text{if no voltage limits are violated} \\ 1, & \text{if there is any voltage limit violation} \end{cases}$$

2.4. Constraint

Constraints are requirements that must not be violated in the process of power flow optimization. These limitations are essential for guiding the algorithm toward producing the most optimal solution. If any of the constraints are breached, the resulting solution cannot be considered optimal. In this study, the following constraints are applied [14].

- Voltage Constraint

The voltage constraint ensures that the bus voltages remain within allowable limits. This constraint is based on the reference [10] and is defined as [15]:

$$0,95\text{pu} \leq V \leq 1,05 \text{ pu} \quad (5)$$

Where 0.95 pu and 1.05 pu represent the lower and upper voltage limits, respectively. This means that the voltage in the distribution system must remain within $\pm 5\%$ of the nominal voltage [16].

- Total Capacity Constraint

This constraint limits the maximum total reactive power capacity of the capacitors installed in the distribution system. Based on reference [17], the constraint is formulated as:

$$\sum_{q \in S_B} Q_q^C \leq 1 \times \sum_{q \in S_B} Q_q^L \quad (6)$$

Where, Q_q^C is the reactive power supplied by the capacitor at bus qq, Q_q^L is the reactive load at bus q, S_b is the set of all buses in the system. This constraint ensures that the total installed capacitor capacity does not exceed the total reactive load demand.

- Power Factor Constraint

This constraint ensures that the overall power factor of the system remains above a certain threshold. According to reference [18], the power factor of the IEEE 33-bus distribution system must satisfy:

$$\text{Cos phi IEEE 33 bus} > 0,9 \quad (7)$$

This constraint guarantees that the power factor remains within acceptable operational limits, improving system efficiency and reducing reactive power loss.

3. Result and Discussion

The BFA algorithm will be tested on the IEEE 33-bus distribution system to determine the optimal placement and sizing of capacitors in order to minimize power losses in the network. In this study, the BFA algorithm will be compared with several methods, namely NSGA-II, MOWCA, and MOGWO. The optimal placement and sizing of capacitors are expected to reduce power losses and improve the voltage profile of the network [19].

Table 4. Comparison For 33 Bus Before and After Placement Capacitor

Item	Base Case	NSGA-II [20]	MOWCA [19]	MOWGO [19]	BPSO (Proposed Method)
Capacitor Location	-	6, 8, 30, 13	30, 13, 10	30, 13, 10	14, 17, 30
Capacitor Sies (kVAR)	-	137, 359, 1035, 430	1211, 396, 480	1199, 362, 474	450, 150, 1200
Total kVAR	-	1961	2087	2088	1800
Vmin (p.u)	0,9136	0,9412	0,9472	0,9456	0,951
Power Loss (kW)	202,7	142,70	150,62	148,79	139,50
Reactive Power Loss (kVAR)	135,15	97,56	103,42	102,03	93,3
Reduction Power Losses (%)	-	29,60	25,69	26,59	31,18
Reduction Reactive Power Losses (%)	-	27,81	23,48	24,31	30,97
(A) Cost of Power Loss (\$)	34.053,6	23.973,6	25.304,16	24996,72	23436
(B) Cost of capacitor (\$/kVAR-year)	-	580,63	465,97	450,45	392,85
Total Cost (C = A + B)	34.053,6	24.554,23	25.770,13	25.447,17	23828,85
Net Savings (\$) (34.053,6 - C)	0	9.499,37	8.283,47	8.606,43	10224,75
% Saving	0 %	27,89%	24,32%	25,27%	30,02%

Table 4 presents a comparative analysis of several optimization methods—NSGA-II, MOWCA, MOWGO, and the proposed BPSO method—for capacitor placement and sizing in a power distribution system, using the base case as a reference. In the base case, no capacitors are installed, resulting in a low minimum voltage of 0.9136 p.u., a high power loss of 202.7 kW, and a reactive power loss of 135.15 kVAR. All optimization methods improve system performance by enhancing the voltage profile and reducing both active and reactive power losses. Among these, the BPSO (Proposed Method) shows the most effective results. It achieves the highest

reduction in power loss (31.18%) and reactive power loss (30.97%), lowering the losses to 139.50 kW and 93.30 kVAR, respectively. Additionally, it improves the minimum voltage to 0.951 p.u., the highest among all methods. Notably, BPSO achieves this performance using a total capacitor size of 1800 kVAR, which is more efficient compared to the higher total capacities used by other methods. This indicates that BPSO not only optimizes capacitor placement effectively but also does so with better resource efficiency. In summary, the BPSO method outperforms the other techniques in all key performance metrics, making it the most advantageous approach for enhancing distribution system performance.

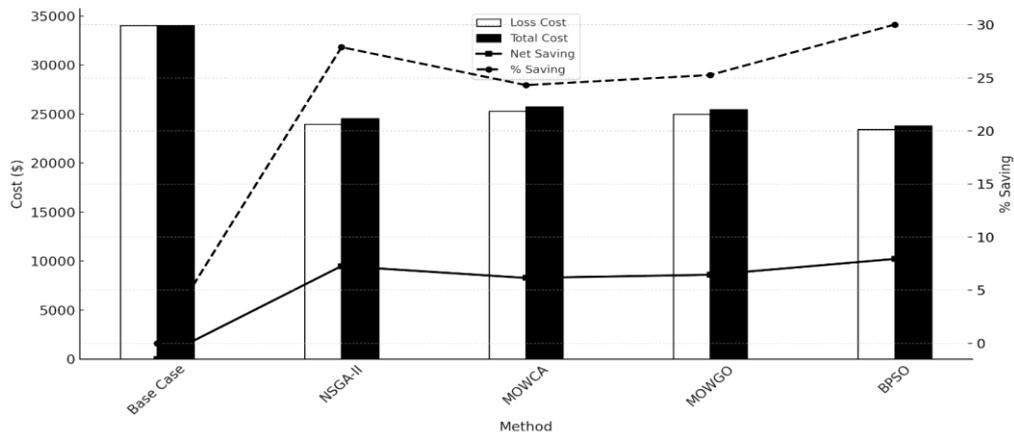


Fig. 2. Comparison Total Cost and Net Saving After and Before Placement Capacitor

Fig. 2 provides a comparison of annual costs for several scenarios involving power loss reduction and capacitor installation. Each scenario presents a different combination of power loss cost and capacitor cost, leading to varied total expenditures. In the base case, with no optimization applied, the total cost is \$34,053.60, and there is no savings achieved. Scenario 1 shows a significant improvement, with a reduced total cost of \$24,554.23 and savings of \$9,499.37, equal to 27.89%. Scenario 2 yields a total cost of \$25,770.13, resulting in a 24.32% savings. Scenario 3 further reduces costs to \$25,447.17, providing a 25.27% decrease compared to the base. Scenario 4 offers the best performance, with the lowest total cost of \$23,828.85 and the highest net savings of \$10,224.75. This represents a 30.02% cost reduction, making it the most efficient scenario. The consistent decline in total cost across the scenarios reflects the effectiveness of applying optimization strategies. Overall, Scenario 4 stands out as the most economical and optimal solution among all tested configurations.

Fig. 3 illustrates the voltage profile of a distribution network before and after the placement of capacitors. The horizontal axis represents the bus numbers, while the vertical axis shows the voltage magnitude in per unit (p.u.). Before capacitor installation, the voltage progressively decreases along the buses, reaching a minimum value of approximately 0.9136 p.u.. This low voltage level indicates significant voltage drops due to the lack of reactive power support in the system. Such conditions can lead to reduced efficiency and potential voltage instability, especially at buses farther from the source. After capacitors are installed at selected buses, the voltage profile shows a noticeable improvement. The overall voltage levels across the network are higher, and the minimum voltage rises to about 0.951 p.u.. This enhancement demonstrates that capacitor placement effectively supports the voltage levels by supplying local reactive power, reducing voltage drops, and improving power quality throughout the network. In

conclusion, the graph clearly demonstrates that the strategic placement of capacitors significantly improves the voltage profile, especially by increasing the minimum voltage from 0.9136 p.u. to 0.951 p.u., thereby ensuring a more stable and efficient operation of the distribution system.

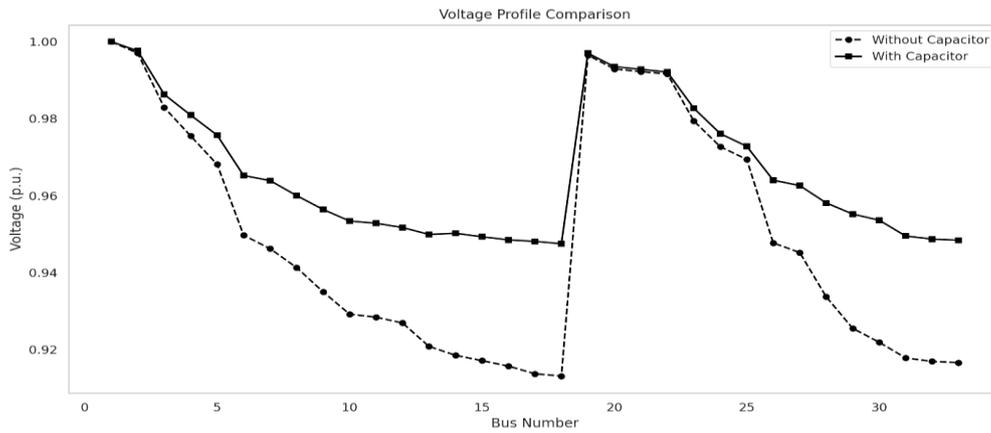


Fig. 3. Voltage Profile Before and After Placement Capacitor

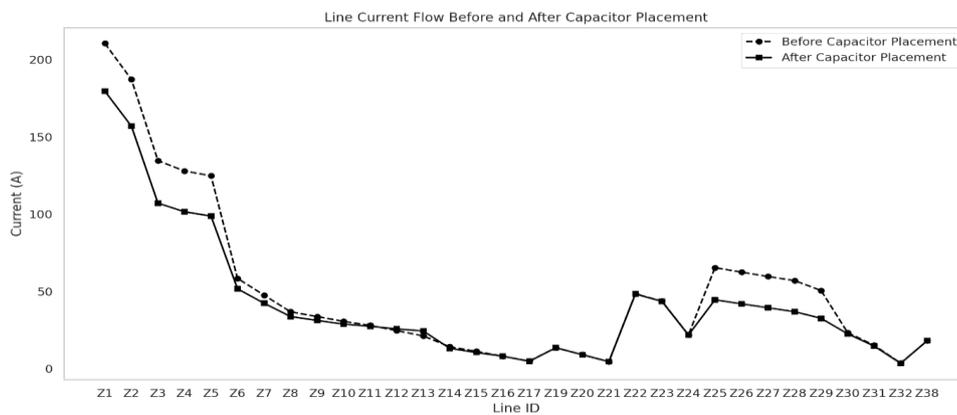


Fig. 4. Line Current Flow Before and After Capacitor Placement

Fig. 4 displays the comparison of line current flow (in Amperes) before and after the placement of capacitors in a power distribution network. The x-axis represents the line ID, while the y-axis indicates the current magnitude in Amperes. This is due to the increased reactive power demand, which raises the total current in the lines. After capacitors are strategically placed within the system, a visible reduction in line current is observed across nearly all line segments. This indicates that the capacitors are supplying local reactive power, thereby reducing the burden on the network to transmit reactive power over long distances.

The reduction in current not only improves the efficiency of the system by lowering I²R losses (resistive losses) but also helps in relieving the stress on the conductors and improving overall voltage regulation. The graph clearly demonstrates that capacitor placement contributes to a more balanced and efficient network operation. In conclusion, the chart highlights a significant drop in line current after capacitor installation, confirming the effectiveness of reactive power compensation in reducing current flow and enhancing the performance of the distribution system.

4. Conclusion

This journal presents a comparative study of several optimization techniques for capacitor placement in distribution systems, focusing on their impact on power loss reduction and voltage profile improvement. The analysis includes five scenarios: the Base Case (no optimization), NSGA-II, MOWCA, MOWGO, and the Proposed Method based on BPSO. The Base Case exhibits the poorest performance, with the highest power loss of 202.7 kW and the lowest minimum voltage of 0.9136 p.u. In contrast, all optimization methods significantly reduce losses and improve voltage levels. NSGA-II reduces losses to 142.7 kW and increases the minimum voltage to 0.9412 p.u. MOWCA achieves a slightly higher loss at 150.62 kW but produces a better voltage minimum of 0.9472 p.u. MOWGO offers a balanced outcome with 148.79 kW losses and 0.9456 p.u. voltage. The best results are obtained by the Proposed Method using BPSO, which minimizes losses to 139.50 kW and raises the minimum voltage to 0.951 p.u. These findings confirm the effectiveness of optimization algorithms in enhancing distribution network performance. Among all, the BPSO-based approach demonstrates the most promising solution in terms of both energy efficiency and voltage stability.

This journal compares the economic performance of five different approaches Base Case, NSGA-II, MOWCA, MOWGO, and the Proposed Method using BPSO—based on the cost of power loss, capacitor cost, total cost, net savings, and percentage savings. The Base Case, which does not include any optimization, shows the highest total cost of \$34,053.60, as it does not reduce power loss or apply capacitors. The NSGA-II method improves the system significantly by lowering the power loss cost to \$23,973.60, adding a capacitor cost of \$580.63, and resulting in a total cost of \$24,554.23. This leads to a net saving of \$9,499.37 or about 27.89%. The MOWCA method results in a slightly higher total cost of \$25,770.13 due to a higher power loss cost of \$25,304.16 and a capacitor cost of \$465.97, achieving a 24.32% saving. MOWGO provides a more balanced result, with a power loss cost of \$24,996.72 and capacitor cost of \$450.45, leading to a total cost of \$25,447.17 and a 25.27% savings. The Proposed BPSO Method demonstrates the best performance by minimizing the power loss cost to \$23,436.00 and the capacitor investment to \$392.85. This results in the lowest total cost of \$23,828.85 and the highest percentage savings of 30.02%. Overall, while all optimization techniques offer economic advantages compared to the base scenario, the BPSO method proves to be the most cost-efficient and effective in minimizing both power loss and capacitor costs.

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