

Application of Different Soft Computing Techniques for Optimal Capacitor Placement and Sizing in Distribution Networks

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ABSTRACT: This paper presents a unified study on reactive power compensation in distribution and transmission systems using advanced metaheuristic optimization methods. Three complementary approaches are integrated: teaching-learning-based optimization for capacitor placement, loss sensitivity index (LSI) combined with constriction-factor-based particle swarm optimization (CFBPSO) for capacitor sizing and placement, and cuckoo search optimization algorithm (CSOA) for optimal allocation of Thyristor Controlled Series Capacitors (TCSCs). The combined framework addresses key issues of power loss minimization, voltage stability enhancement, cost reduction, and reliability improvement. Case studies on radial distribution systems, industrial networks, and the 30-bus system validate the effectiveness of the proposed methodologies. Results show significant improvements in loss reduction, voltage profile enhancement, system stability, and economic savings, highlighting the value of metaheuristic optimization in modern power system planning and operation.

KEYWORDS: Optimal capacitor placement; capacitor sizing; loss sensitivity index (LSI); teaching-learning-based optimization (TLBO); constriction-factor-based particle swarm optimization (CFBPSO); reactive power compensation; distribution networks; industrial power systems; Thyristor Controlled Series Capacitor (TCSC); Flexible AC Transmission Systems (FACTS); Cuckoo Search Optimization Algorithm (CSOA); voltage stability; reliability; MATLAB/MATPOWER.

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I. INTRODUCTION

The growth of industrial demand and increasing population have created significant challenges in power system operation, including increased active power losses, degraded voltage profiles, and rising operational costs. Reactive power compensation has emerged as a vital solution for improving system efficiency, enhancing stability, and ensuring economic operation. Among compensation devices, shunt capacitors and series controllers like TCSCs are widely adopted due to their effectiveness and cost efficiency. However, identifying their optimal placement and sizing remains a nonlinear, complex optimization problem.

To address these challenges, researchers have applied metaheuristic optimization techniques that can efficiently handle nonlinear constraints and large search spaces. Capacitor placement in distribution and industrial networks is commonly approached using indices such as the Loss Sensitivity Index (LSI) to identify candidate buses, followed by optimization techniques such as Teaching-Learning-Based Optimization (TLBO) and Constriction-Factor-Based Particle Swarm Optimization (CFBPSO). These methods effectively minimize losses, improve voltage profiles, and reduce installation costs.

For transmission systems, FACTS devices like Thyristor Controlled Series Capacitors (TCSCs) provide dynamic compensation by controlling line reactance. Optimizing their placement enhances voltage stability, improves reliability, and reduces system losses. Recent studies have applied the Cuckoo Search Optimization Algorithm (CSOA) to identify optimal TCSC configurations, demonstrating significant improvements in both technical and economic performance.

This combined study highlights the effectiveness of metaheuristic optimization methods for both capacitor and TCSC allocation, providing a unified framework for enhancing system efficiency, stability, and cost savings.

1.1 Problem Statement

With the continuous growth of electrical demand and increasing network complexity, modern power systems face serious challenges in maintaining voltage stability, reducing real and reactive power losses, and ensuring cost-effective operation. Conventional compensation techniques using shunt capacitors and series compensators (such as TCSC) often fail to achieve global optimization due to the nonlinear, multi-objective, and highly constrained nature of the problem.

In distribution systems, inappropriate capacitor placement or incorrect sizing can lead to overcompensation, poor voltage profiles, and increased system losses. Similarly, in transmission networks, improper allocation of Thyristor Controlled Series Capacitors (TCSCs) can result in inefficient power flow, reduced reliability, and high investment costs.

Hence, there is a strong need for an integrated optimization framework that simultaneously determines the optimal location and size of capacitors and TCSCs using advanced metaheuristic algorithms to minimize losses, enhance voltage stability, and improve overall system performance.

1.2 Objectives

The main objectives of this research are as follows:

- To develop an integrated optimization framework that combines optimal capacitor placement, capacitor sizing, and TCSC allocation for comprehensive reactive power compensation and power system enhancement.
- To apply advanced metaheuristic algorithms specifically the Constriction-Factor-Based Particle Swarm Optimization (CFBPSO) and the Cuckoo Search Optimization Algorithm (CSOA) for solving the nonlinear multi-objective optimization problems in distribution and transmission networks.
- To minimize total real and reactive power losses while maintaining system voltages within permissible limits and improving the overall power factor.
- To enhance voltage stability and system reliability through coordinated use of capacitors in distribution systems and TCSCs in transmission systems.
- To validate the proposed optimization techniques using MATLAB/Matpower simulation on standard IEEE test systems (85-bus radial distribution and 30-bus transmission networks).
- To compare the performance of the proposed methods against conventional optimization techniques in terms of power loss reduction, voltage improvement, and economic savings.

II. Scope of the Work

The scope of this research encompasses the development, implementation, and performance evaluation of an integrated optimization strategy that combines capacitor placement, capacitor sizing, and TCSC allocation within both distribution and transmission networks.

- The study covers radial distribution systems (for capacitor placement and sizing) and meshed transmission networks (for TCSC installation).
- The optimization techniques employed include Loss Sensitivity Index (LSI) for preliminary bus selection, Constriction-Factor-Based Particle Swarm Optimization (CFBPSO) for determining optimal capacitor ratings, and Cuckoo Search Optimization Algorithm (CSOA) for identifying optimal TCSC locations and parameters.
- The algorithms are implemented in MATLAB/Matpower, ensuring compatibility with standard IEEE test systems.

- Performance is assessed in terms of power loss reduction, voltage profile enhancement, power factor correction, voltage stability improvement, and annual cost savings.
- Comparative analysis is carried out against conventional and existing metaheuristic methods such as standard PSO, PGSA, and MINLP to establish the superiority of the proposed integrated framework.

This research is limited to steady-state analysis under normal loading conditions, assuming balanced systems and neglecting the impact of system contingencies or dynamic transients.

2.1 Significance of the Study

The significance of this study lies in its holistic approach to reactive power compensation, bridging the gap between distribution level and transmission level optimization.

- *Comprehensive System Enhancement:* By integrating capacitor placement and TCSC allocation, the proposed framework improves both voltage regulation in distribution systems and stability margins in transmission networks.
- *Advanced Optimization Efficiency:* The hybrid use of CFBPSO and CSOA leverages the strengths of both algorithms—CFBPSO's convergence stability and CSOA's exploratory capability—to achieve global optimal solutions in nonlinear, multi-variable systems.
- *Economic and Operational Benefits:* The approach demonstrates substantial energy cost reduction (up to 50.83% loss reduction in the 85-bus system) and improved reliability (up to 0.9486 reliability index in the 30-bus system), making it highly practical for utility companies.
- *Scalability and Applicability:* The proposed methodology can be extended to larger or real-world power systems, offering a scalable solution adaptable to evolving smart grid environments with renewable energy integration.
- *Contribution to Smart Grid Research:* The study provides a foundation for future research in coordinated reactive power management, FACTS device optimization, and hybrid algorithm design for smart, resilient, and cost-efficient grid operation.

2.2 System Description

The integrated study considers two primary systems:

- 85-Bus Radial Distribution System for capacitor placement and sizing optimization.
- 30-Bus Transmission System for TCSC allocation and generator rescheduling.

Distribution Network: The 85-bus system operates within 0.9–1.1 p.u. voltage limits. Maximum allowable capacitor installations are 15, and each capacitor has cost coefficients $K_p = 168 \text{ €/}(kW \cdot \text{year})$ and $K_c = 5 \text{ €/}(kVAr)$.

Transmission Network: The 30-bus transmission system includes six generators and employs two TCSC devices optimally placed at bus 16 and bus 36. The devices are modeled in MATLAB/Matpower to simulate impedance compensation and power flow improvements.

III. Methodology

The proposed methodology integrates three layers of optimization

3.1 Loss Sensitivity Index (LSI) Analysis

The LSI identifies buses with the highest power loss sensitivity to voltage variations, narrowing the candidate set for capacitor installation

$$LSI = -2R_k \left(\frac{P_{load,j}^2 + Q_{load,j}^2}{V_j^3} \right) \quad (1)$$

Buses with the largest $|LSI|$ values are considered optimal for capacitor placement.

Explanation of the TLBO Algorithm

The presented flowchart outlines the procedural steps of the Teaching–Learning-Based Optimization (TLBO) algorithm. TLBO operates in two main phases are the Teacher Phase and the Learner Phase where candidate solutions represent students, and the best solution acts as the teacher who guides others toward improvement.

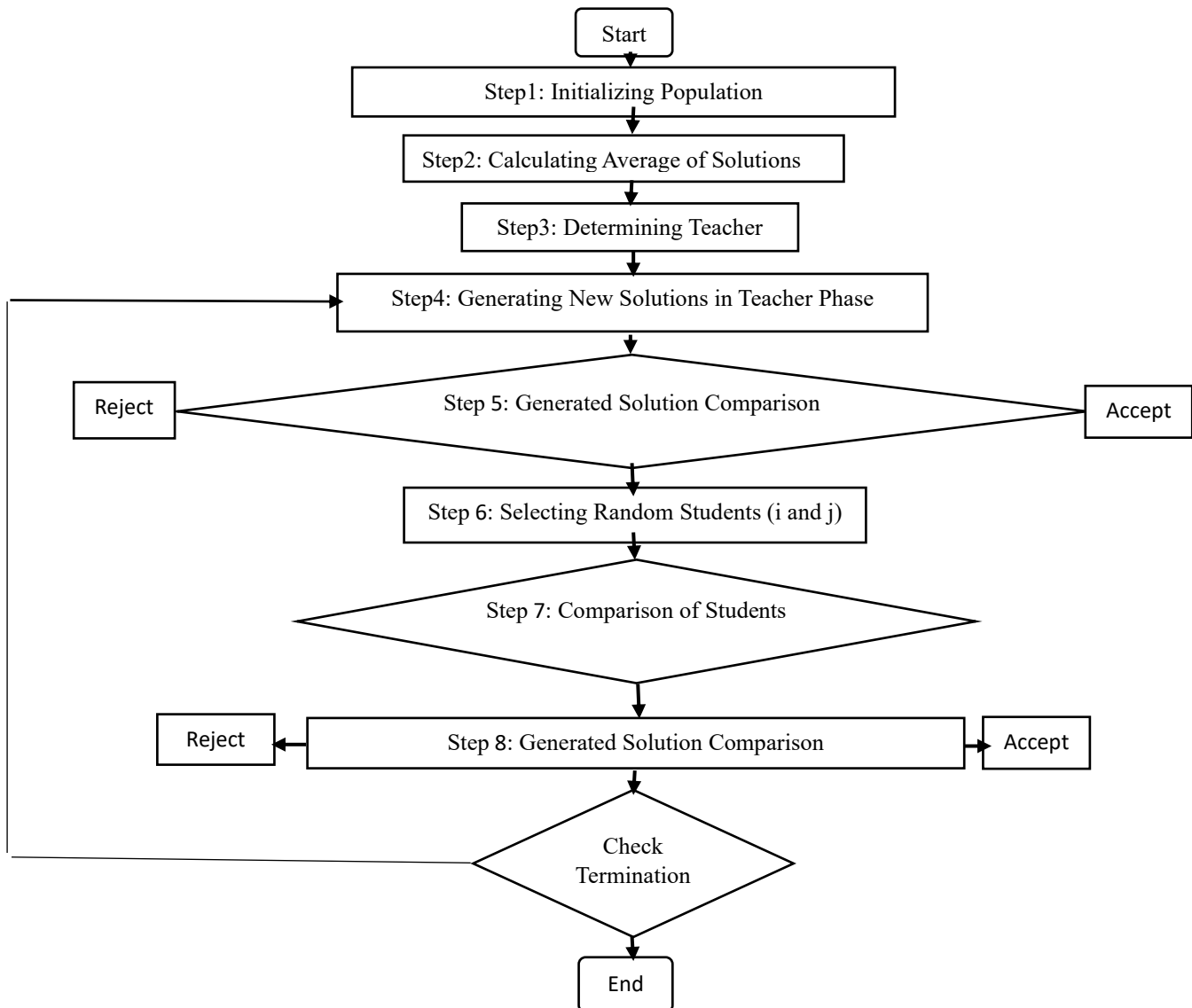


Figure1: Flowchart of TLBO algorithm

Step-by-Step Description:

- 1) Start: The algorithm begins its execution.
- 2) Initializing Population: An initial population of solutions (students) is randomly generated within the defined search space. Each solution represents a possible answer to the optimization problem.
- 3) Calculating Average of Solutions: The mean performance (knowledge level) of all solutions in the population is computed. This mean serves as a reference for evaluating improvement in subsequent steps.
- 4) Determining Teacher: The best-performing solution in the current population is selected as the teacher. This teacher is considered the most knowledgeable student in the group and will guide others toward better solutions.
- 5) Generating New Solutions in Teacher Phase: In the teacher phase, each student attempts to improve their performance by learning from the teacher. A new solution is generated based on the difference between the teacher's knowledge and the mean knowledge of the population.
- 6) Generated Solution Comparison: The newly generated solution is compared with the old one.

- a. If the new solution shows improvement, it is accepted.
- b. Otherwise, it is rejected, and the previous solution is retained.
- c. Selecting Random Students (i and j): In the learner phase, each student interacts with another randomly chosen student to exchange knowledge and learn from each other.
- 7) Comparison of Students: The performance of student i is compared with that of student j.
 - a. If student i performs better, the learning update is computed using Equation
 - b. Otherwise, Equation is used to guide the learning process.
- 8) Generated Solution Comparison (Learner Phase): The updated solution obtained through the learner phase is compared with the previous one.
 - a. If the new solution yields a better objective value, it is accepted;
 - b. Otherwise, it is rejected.
- 9) Checking Termination Criteria: The algorithm checks whether the termination condition (e.g., maximum iterations or acceptable error threshold) has been satisfied.
 - a. If yes, the process stops.
 - b. If No, it returns to the teacher phase for further improvement.
- 10) End: The algorithm terminates, and the best-obtained solution is reported as the final optimized result.

This flowchart effectively represents the iterative nature of the TLBO algorithm, where the population evolves through teaching (global guidance by the best solution) and learning (peer-to-peer knowledge sharing). The process continues until convergence or a predefined stopping condition is reached.

3.2 Constriction-Factor-Based PSO (CFBPSO)

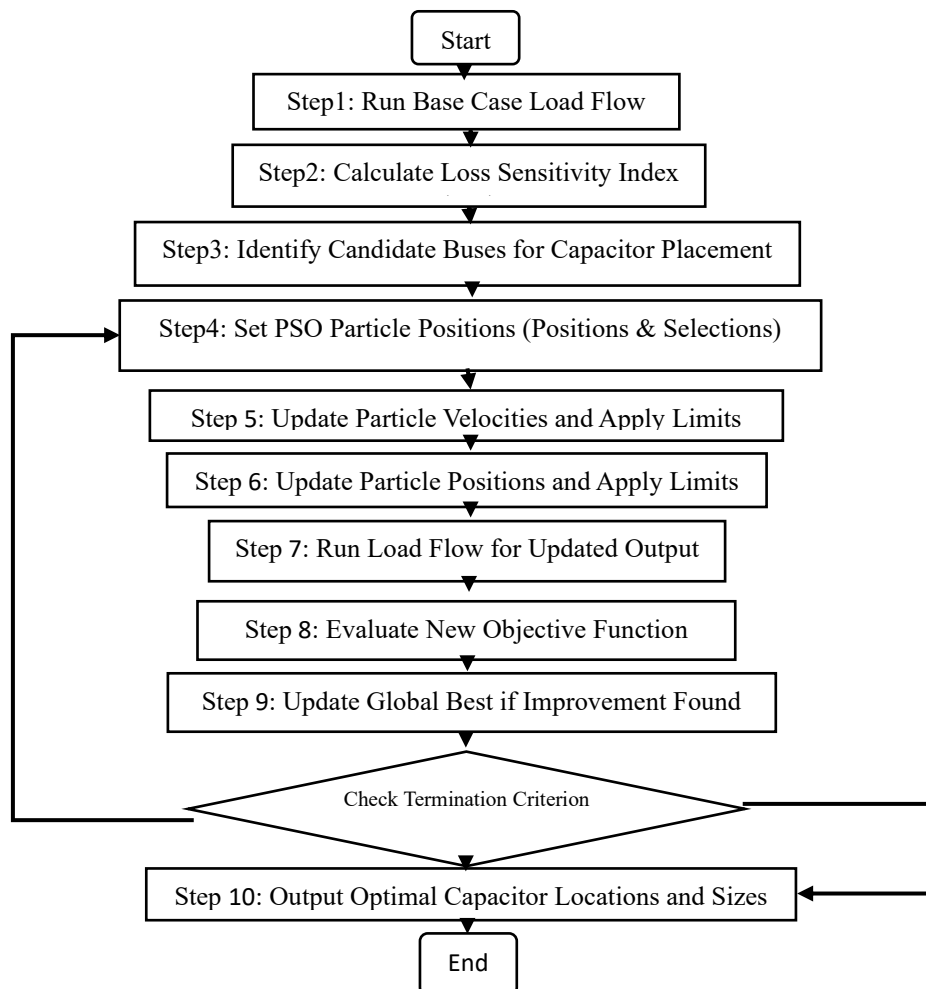


Figure2: Flowchart of CFBPSO algorithm

Explanation of the Capacitor Placement Optimization

The flowchart presents a systematic procedure for optimizing capacitor placement and sizing using the PSO (Particle Swarm Optimization) technique. Each step describes a stage in the iterative optimization process aimed at enhancing system performance.

CFBPSO optimizes capacitor sizes with stable convergence. Particle velocity and position updates are defined as:

$$v_i^{n+1} = K[v_i^n + c_1 r_1 (P_{best,i} - p_i^n) + c_2 r_2 (G_{best} - p_i^n)] + p_i^{n+1} = p_i^n + v_i^{n+1} \quad (2)$$

$$\text{where } K = \frac{1}{|2 - \phi - \sqrt{\phi^2 - 4\phi}|} \text{ and } \phi = c_1 + c_2. \quad (3)$$

This flowchart represents the Particle Swarm Optimization (PSO)-based methodology for optimal capacitor placement and sizing in a power distribution system. The algorithm iteratively updates potential solutions through swarm intelligence principles, evaluating system performance after each update until the best configuration is found. The method effectively minimizes power losses, improves voltage stability, and enhances overall network efficiency.

3.3 Cuckoo Search Optimization Algorithm (CSOA)

CSOA mimics the brood parasitic behavior of cuckoos, using Lévy flights to explore solution spaces

$$X_{new} = X_{old} + \alpha \times Levy(\lambda)(4)$$

where α is the stepsize and $Levy(\lambda)$ represents Lévy-distributed random steps. Each “nest” corresponds to a candidate TCSC placement and compensation level. Fitness is evaluated using the total system loss and voltage deviation.

Explanation of the Cuckoo Search Algorithm

The flowchart presents the main steps involved in the Cuckoo Search (CS) algorithm, which imitates the behavior of cuckoos laying their eggs in the nests of host birds. The algorithm uses Lévy flight for random walks and maintains a population of potential solutions (nests) that evolve toward an optimal solution through iterative improvement.

Step-by-Step Description:

1. Start: The algorithm begins by initializing the process for capacitor placement and sizing optimization.
2. Step 1: Run Base Case Load Flow: A base load flow analysis is conducted on the system without any capacitors to determine the initial voltage profile, power losses, and reactive power distribution. This provides a reference for comparison with improved configurations.
3. Step 2: Calculate Loss Sensitivity Index (LSI): The Loss Sensitivity Index (LSI) or Index of Active Power Loss Sensitivity (IAI) is computed to identify buses that are more sensitive to reactive power compensation. This helps determine the most effective locations for capacitor placement.
4. Step 3: Identify Candidate Buses for Capacitor Placement: Based on the computed LSI values, buses with high sensitivity are selected as candidate buses where capacitors can potentially be placed.
5. Step 4: Set PSO Particle Positions (Positions & Selections): The initial positions of the PSO particles are defined. Each particle represents a possible solution that includes both capacitor locations and their corresponding sizes.
6. Step 5: Update Particle Velocities and Apply Limits: The velocities of particles are updated according to the PSO velocity update equation, ensuring they stay within permissible search limits. This step governs how solutions move through the search space.
7. Step 6: Update Particle Positions and Apply Limits: Based on the new velocities, particle positions are updated, representing new candidate solutions

8. Step 7: Run Load Flow for Updated Output: A new load flow analysis is executed for each updated solution to evaluate its performance in terms of power loss, voltage deviation, and overall system efficiency.
9. Step 8: Evaluate New Objective Function: The objective function (often minimizing total power losses or improving voltage stability) is calculated for each particle. This step quantifies the performance of each solution.
10. Step 9: Update Global Best if Improvement Found: If the current solution offers a better objective value than the previous global best, it replaces the global best
11. Check Termination Criterion: The algorithm checks whether the stopping condition is met typically based on a maximum number of iterations or convergence threshold.
 - If No, the process loops back to update particle velocities and positions for another iteration.
 - If Yes, the algorithm proceeds to the final step.
12. Step 10: Output Optimal Capacitor Locations and Sizes
13. End: The optimization process terminates, and the final solution is reported.

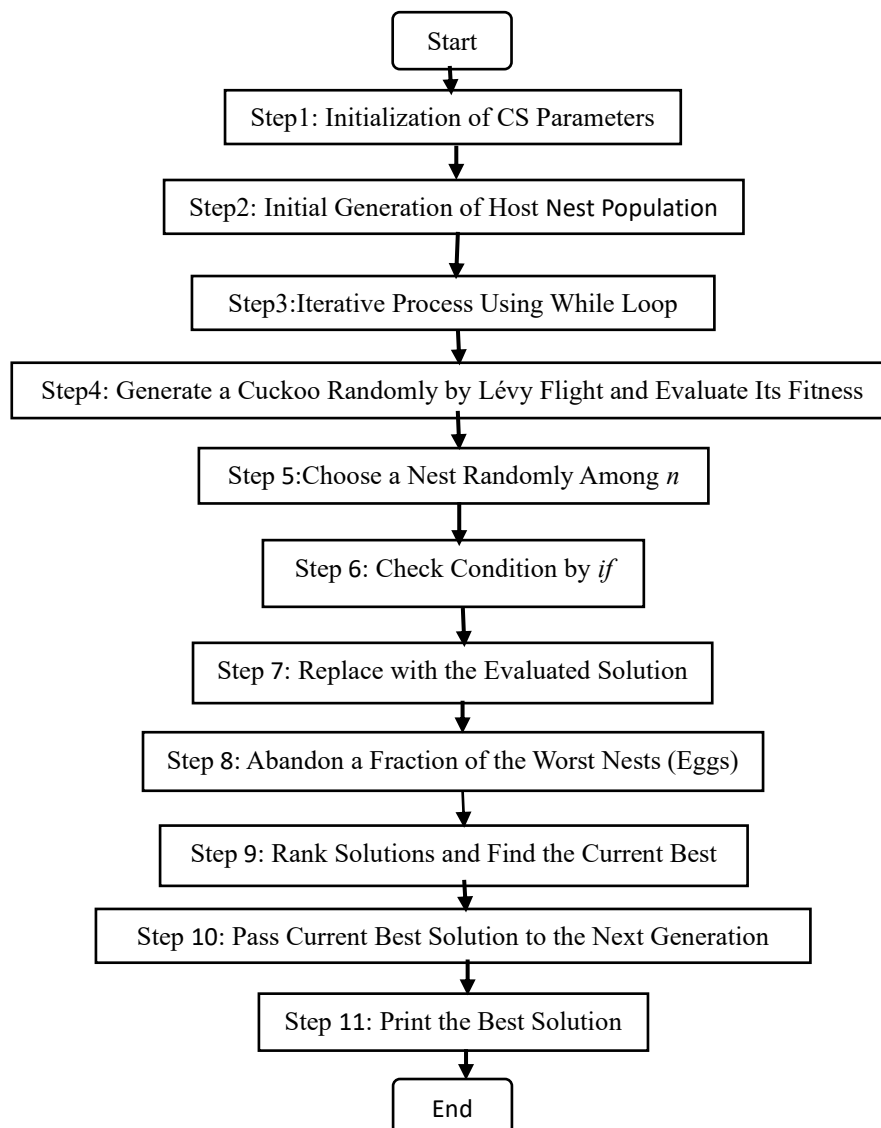


Figure3: Flowchart of CFBPSO algorithm

The Cuckoo Search algorithm efficiently balances exploration (via Lévy flights) and exploitation (via replacement and ranking of solutions) to locate the global optimum. The process involves generating new candidate solutions, evaluating their fitness, and replacing poor solutions iteratively until convergence. This approach is widely applied in engineering design, power systems, image processing, and machine learning optimization tasks due to its simplicity and strong global search capability.

IV. Problem Formulation

The integrated optimization aims to minimize the total annual energy cost:

$$F = K_p \sum_{k=1}^{N_b-1} P_{loss,k} + K_C \sum_{j=1}^{N_C} Q_{C,j} \quad (5)$$

Subject to:

Voltage constraints: $V_{min} \leq V_i \leq V_{max}$

Power flow limits: $|P_{flow,k}| \leq P_{flow,k}^{max}$

Capacitor size limits: $Q_{C,i}^{min} \leq Q_{C,i} \leq Q_{C,i}^{max}$

TCSC compensation: $X_{new} = X_L(1 - k_{TCSC})$, with $0 < k_{TCSC} \leq 0.7$

Power factor: $PF_{overall} \geq PF_{min}$

The Mult objective optimization minimizes power losses and cost while maximizing voltage stability and reliability indices.

4.1 Simulation and Optimization with MATLAB

Simulations are carried out in MATLAB R2023b using Mat power for power flow analysis and custom scripts for PSO and CSOA algorithms.

85-Bus System (CFBPSO):

Initial power loss: 315.7 kW

Optimized loss: 155.45 kW

Voltage range: 0.9296–0.9976 p.u.

Capacitor buses: {8, 27, 41, 51, 63}

Total capacitor power: 2648 kVAr

Annual savings: €26,972/year

30-Bus System (CSOA):

Optimal TCSC locations: Bus 16 and Bus 36

Compensation sizes: -0.189 p.u. and -0.185 p.u.

Loss reduction: from 9.3163 MVA to 5.97323 MVA

Voltage stability index improvement: 0.1811 → 42.5624%

Reliability improvement: 0.9161 → 0.9486

V. Results and discussion

5.1 Distribution System with TLBO

The proposed TLBO-based approach was applied to a radial distribution system. Results showed significant reduction in energy and power losses, improved voltage stability, and cost savings, validating the applicability of the method.

Table I: Results of 10-bus test case

Out put	Initial	Optimized
Loss(kw)	783.7763	704.64
Energy Loss (kwh)	6,371,219.877	6,100,342.29

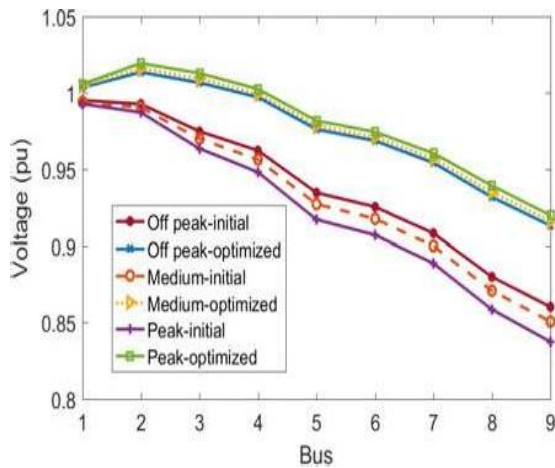


Figure4: Voltage profile of 10-bus test case

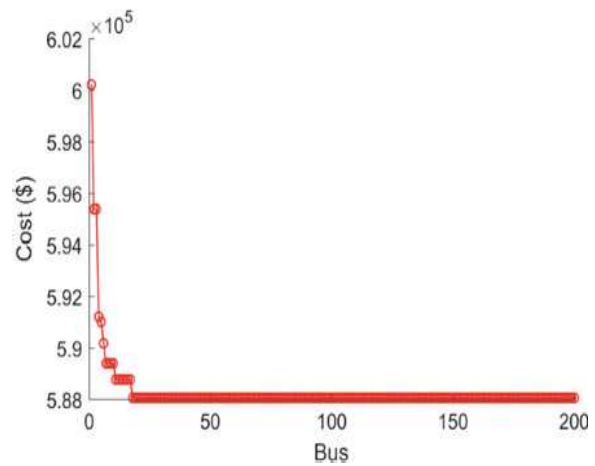


Figure5: Convergence of 10-bus test case

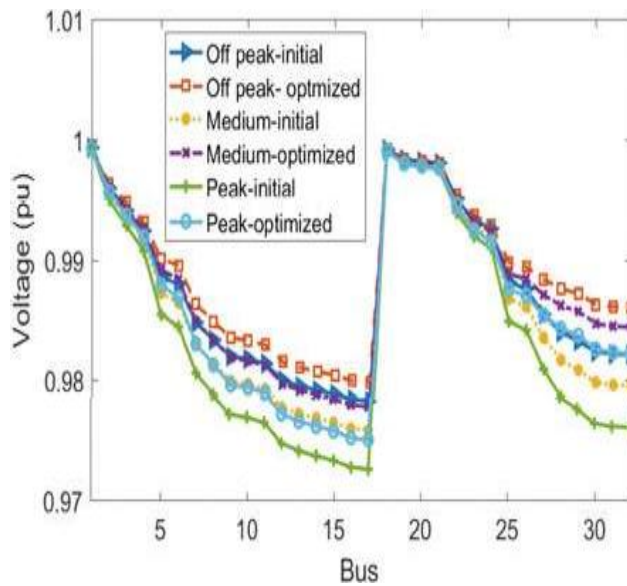


Figure6: Voltage profile of 33-bus test case

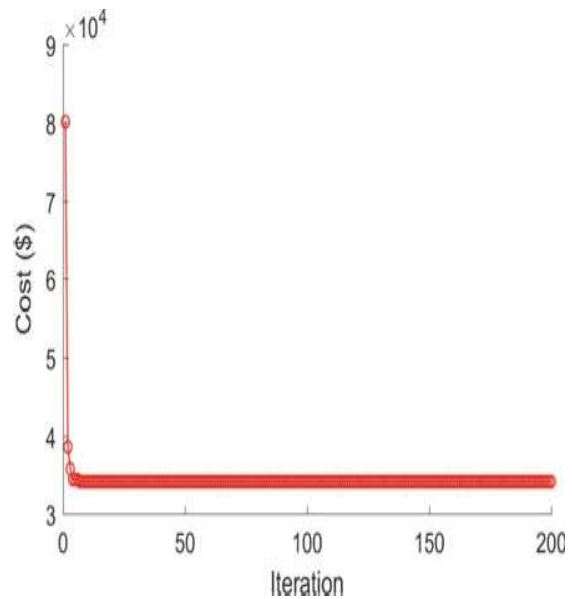


Figure7: Convergence of 33-bus test case

Table II: Results of 33-bus test case

Out put	Initial	Optimized
Loss(kw)	57,489	43.41
Energy Loss (kwh)	387,058.972	348,408.4

5.2 85-Bus System and Industrial Network with CFBPSO

The LSI-CFBPSO method was tested on an 85-bus distribution network and a real industrial system. Results showed up to 50% loss reduction, improved voltage profiles, corrected power factor, and significant annual economic savings compared to PSO, PGSA, and MINLP methods.

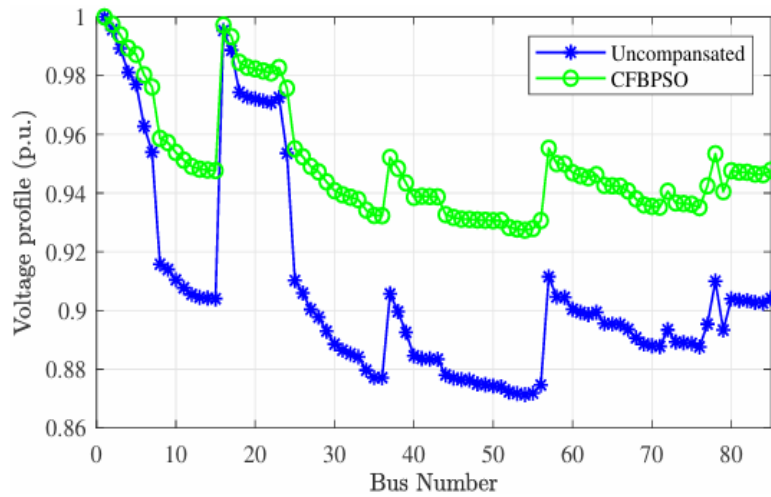


Figure 8: Voltageprofilefor85-bus test system

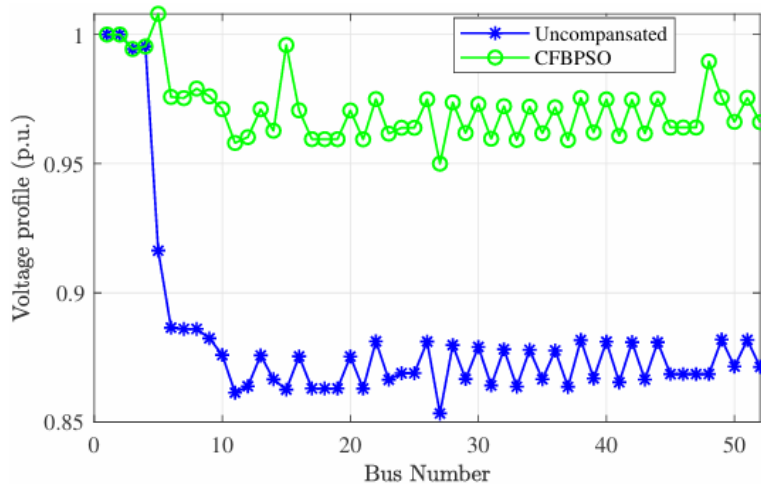


Figure 9: Voltage profile for industrial power test system

5.3 30-Bus System with TCSC Allocation Using CSOA

CSOA was implemented on the 30-bus system to determine optimal TCSC allocation. Results demonstrated reduced active and reactive power losses, improved voltage profile, enhanced reliability, and significant improvement in voltage stability index. Generator rescheduling after TCSC integration further improved system economics and reliability.

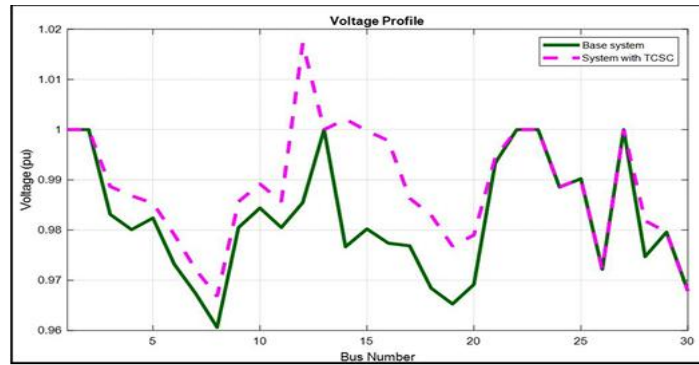


Figure10: Voltage profile comparison for 30 bus base system and system with TCSC

Table III: The integration of CFBPSO and CSOA shows superior performance in optimizing both distribution and transmission networks.

System	Method	Loss Reduction (%)	PF Improvement	Voltage Min (p.u.)	Savings (€ /year)
85-Bus	Base	—	0.71	0.871	—
85-Bus	PSO	48.27	0.9983	0.9156	25,650
85-Bus	CFBPSO	50.83	1.00	0.9296	26,972
30-Bus	Base	—	—	0.961	—
30-Bus	CSOA	35.8	—	0.967	Loss reduced by 0.35884%

VI. DISCUSSION

The three optimization approaches collectively demonstrate that intelligent, metaheuristic-based methods outperform traditional techniques in solving reactive power compensation problems. Capacitor placement strategies significantly improve distribution system efficiency and economics, while TCSC allocation enhances transmission system stability and reliability. Together, these methods provide a holistic solution to modern power system challenges.

VII. CONCLUSION

This combined research underscores the importance of optimal reactive power compensation in ensuring efficient, stable, and reliable power system operation. The integration of TLBO, LSI-CFBPSO, and CSOA for capacitor placement and TCSC allocation demonstrates substantial benefits in terms of power loss reduction, voltage profile improvement, cost savings, and enhanced reliability. These findings confirm that metaheuristic optimization techniques are powerful tools for modern power system planning and operation, making them highly relevant for both distribution and transmission networks. This integrated study demonstrates that combining CFBPSO-based capacitor optimization and CSOA-based TCSC allocation provides a robust framework for reactive power management. The 85-bus system achieved 50.83% power loss reduction, while the 30-bus system realized notable voltage stability and reliability improvements. Metaheuristic-based hybrid optimization proves to be a powerful approach for future smart grid applications involving multi-device compensation and coordinated voltage control.

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