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Optimal Placement and Sizing of a Custom Power Device for Load Enhancement of Radial Distribution Systems Using Particle Swarm Optimization

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Abstract

The increasing penetration of nonlinear loads, distributed energy resources, and rapidly growing electricity demand has significantly affected the operational performance of modern radial distribution systems, leading to excessive power losses, poor voltage regulation, reduced voltage stability, and limited loadability margins [1–3]. Custom Power Devices (CPDs) have emerged as an effective solution for enhancing power quality and improving the performance of distribution networks through reactive power compensation and voltage support [4, 5]. However, the effectiveness of a CPD strongly depends on its optimal location and appropriate sizing within the distribution system [6, 7].

This paper presents a Particle Swarm Optimization (PSO)-based methodology for the optimal placement and sizing of a Custom Power Device to improve the loadability of radial distribution systems while simultaneously enhancing voltage stability and minimizing power losses. The proposed approach integrates Backward/Forward Sweep (BFS) load flow analysis, Voltage Stability Index (VSI), and loadability assessment into a unified multi-objective optimization framework. Particle Swarm Optimization is selected because of its simple implementation, fast convergence, and proven effectiveness in solving nonlinear power system optimization problems [8, 9]. The optimization objective considers four performance indices, namely maximum loadability enhancement, voltage stability improvement, voltage profile enhancement, and reduction of real power losses under practical operating constraints.

The proposed methodology is evaluated on the standard IEEE 33-bus radial distribution system using MATLAB. The simulation results demonstrate that the optimally allocated and properly sized CPD substantially improves the network operating performance. The maximum loading factor is significantly increased while maintaining acceptable voltage limits throughout the network. Moreover, the minimum bus voltage and Voltage Stability Index are considerably improved, and the total real power losses are reduced. These results demonstrate that the proposed PSO-based optimization framework provides an effective and computationally efficient solution for enhancing the operational capability of radial distribution systems.

Keywords
Custom Power Device; Particle Swarm Optimization; Radial Distribution System; Load Enhancement; Voltage Stability Index; Backward Forward Sweep Load Flow; Distribution System Optimization.

1. Introduction

The distribution system is the final stage of the electric power network. It delivers electricity from the utility to consumers. Most distribution systems have a radial structure with high resistance-to-reactance (R/X) ratios and long feeders. These characteristics make them more prone to voltage drop, high power losses, and voltage instability, especially under heavy loading conditions [1–4].

The continuous increase in electricity demand, rapid urbanization, renewable energy integration, and the use of nonlinear loads have increased the complexity of modern distribution systems. Power electronic devices, electric vehicle charging stations, and distributed generation also create challenges in voltage regulation, reactive power management, and power quality [5–8]. Therefore, improving the performance and reliability of distribution systems has become an important research area [9].

Loadability is an important performance index of a distribution system. It indicates the maximum load that the system can supply without violating voltage, thermal, and stability limits [10, 11]. As the system loading increases, bus voltages decrease, branch currents increase, and power losses become higher. If the loading exceeds the allowable limit, voltage collapse may occur [12, 13]. Therefore, enhancing the loadability of radial distribution systems is essential for secure and reliable operation.

Custom Power Devices (CPDs) are widely used to improve the performance of distribution networks. They provide reactive power support, improve voltage regulation, reduce power losses, enhance voltage stability, and improve overall power quality [14–17]. As a result, CPDs increase the load-carrying capability of existing distribution systems without major network expansion.

The performance of a CPD depends on its installation location and size. An improperly placed CPD may not provide the desired improvement [18, 19]. Therefore, selecting the optimal location and rating of the CPD is an important optimization problem. The objective is to improve voltage profile, reduce power losses, enhance voltage stability, and increase system loadability simultaneously.

Metaheuristic optimization techniques have been widely applied to solve such nonlinear optimization problems [20–22]. Among them, Particle Swarm Optimization (PSO) is popular because of its simple implementation, fast convergence, and good optimization capability [23, 24]. PSO efficiently searches for the optimal solution and has been successfully applied to many power system optimization problems, including optimal allocation of reactive power compensation devices in distribution networks [23-25].

In this paper, a PSO-based method is proposed for the optimal placement and sizing of a Custom Power Device in a radial distribution system. The proposed approach considers four objectives: maximum loadability enhancement, voltage stability improvement, voltage profile improvement, and real power loss reduction. Backward/Forward Sweep (BFS) load flow, Voltage Stability Index (VSI), and loadability analysis are integrated into the optimization process. The effectiveness of the proposed method is verified on the IEEE 33-bus radial distribution system using MATLAB.
The main contributions of this paper are as follows:

- A multi-objective optimization framework is developed for the optimal placement and sizing of a Custom Power Device.
- Loadability, voltage stability, voltage profile, and power loss are considered simultaneously in the optimization process.
- Particle Swarm Optimization is used to determine the optimal location and rating of the CPD.
- The proposed method is validated on the IEEE 33-bus distribution system using MATLAB simulations.
- The results demonstrate significant improvements in loadability, voltage profile, voltage stability, and power loss reduction after optimal CPD installation.

2. Literature Review and Research Gap

2.1 Literature Review

Power quality improvement and loadability enhancement have become important research areas in modern distribution systems due to the increasing penetration of nonlinear loads, distributed generation, and renewable energy sources [23–25]. Various Custom Power Devices (CPDs) and Flexible AC Transmission System (FACTS) devices have been proposed to improve voltage regulation, reduce power losses, and enhance voltage stability [22, 23]. Among these devices, Distribution Static Compensators (DSTATCOMs), Static Synchronous Compensators (STATCOMs), Unified Power Quality Conditioners (UPQCs), and hybrid CPDs have received significant attention because of their capability to provide fast reactive power compensation and improve overall system performance [14–17].

Several researchers have investigated the optimal placement and sizing of CPDs using conventional optimization techniques. These methods have demonstrated improvements in voltage profile and reductions in power losses; however, they often require extensive computational effort and may converge to local optimum solutions, particularly for large-scale nonlinear optimization problems [18, 19].

To overcome these limitations, metaheuristic optimization algorithms have been widely employed. Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Differential Evolution (DE), Artificial Bee Colony (ABC), Grey Wolf Optimizer (GWO), Whale Optimization Algorithm (WOA), and Salp Swarm Algorithm (SSA) have been successfully applied for the optimal allocation of distributed generation, capacitor banks, DSTATCOMs, and other reactive power compensation devices [40–46]. Among these techniques, PSO has gained considerable popularity because of its simple implementation, fewer control parameters, robust search capability, and fast convergence characteristics [24].

Most reported studies have primarily focused on minimizing power losses or improving the voltage profile [18–20]. Some researchers have included voltage stability enhancement as an additional optimization objective [21, 22]. However, only a limited number of studies have simultaneously considered loadability enhancement, voltage stability improvement, voltage profile enhancement, and power loss reduction within a unified multi-objective optimization framework [23, 24]. Furthermore, the application of a multifunctional Custom Power Device for improving the overall steady-state performance of radial distribution systems has received relatively less attention, highlighting the need for further investigation [15, 16].

2.2 Research Gap

Based on the available literature, the following research gaps are identified:

- Most existing studies consider only one or two optimization objectives, such as power loss reduction or voltage profile improvement.
- Loadability enhancement is often neglected, although it is an important indicator of distribution system performance.
- Many optimization methods require high computational effort or exhibit slow convergence.
- The combined effects of loadability, voltage stability, voltage profile, and power loss have not been adequately investigated for optimal CPD allocation.
- Limited research has been reported on the optimal placement and sizing of multifunctional Custom Power Devices using Particle Swarm Optimization.

These limitations indicate the need for an efficient optimization approach that simultaneously improves multiple performance indices while maintaining computational simplicity.

2.3 Contributions of the Present Work

To address the above research gaps, this paper proposes a Particle Swarm Optimization (PSO)-based methodology for the optimal placement and sizing of a Custom Power Device in a radial distribution system. The major contributions of this work are summarized as follows:

- A multi-objective optimization framework is developed for simultaneous improvement of loadability, voltage stability, voltage profile, and real power loss.
- A Custom Power Device is optimally located and sized using Particle Swarm Optimization.
- Backward/Forward Sweep load flow is integrated with loadability analysis for accurate performance evaluation.
- Practical operating constraints, including bus voltage limits, CPD rating limits, and branch current limits, are incorporated into the optimization process.
- Comparative results demonstrate significant improvements in loadability, voltage profile, voltage stability, and power loss reduction after optimal CPD installation.

3. System Description and Methodology

3.1 Overview of the Proposed Method

The proposed methodology aims to determine the optimal location and size of a Custom Power Device (CPD) for improving the performance of a radial distribution system. The optimization process combines Backward/Forward Sweep (BFS) load flow analysis with Particle Swarm Optimization (PSO). The objective is to maximize the system loadability while improving voltage stability, enhancing the voltage profile, and reducing real power losses.

The methodology begins with the base-case load flow analysis of the distribution system. The voltage profile, power losses, branch currents, and Voltage Stability Index (VSI) are calculated to identify the weak buses in the network. These buses are considered as candidate locations for CPD installation. Particle Swarm Optimization is then employed to determine the optimal bus location and the corresponding reactive power rating of the CPD. For each candidate solution generated by PSO, the BFS load flow is executed to evaluate the network performance. The optimization process continues until the stopping criterion is satisfied, and the best solution is selected based on the objective function.

3.2 IEEE 33-Bus Radial Distribution System

The proposed methodology is validated using the standard IEEE 33-bus radial distribution system. This test system is widely used for evaluating optimization techniques in distribution network studies because of its radial structure and relatively high R/X ratio [17–19].

Due to its radial configuration, the system experiences significant voltage drops and higher power losses under heavy loading conditions [18, 20]. These characteristics make it suitable for evaluating the effectiveness of the proposed CPD placement strategy [17, 21].

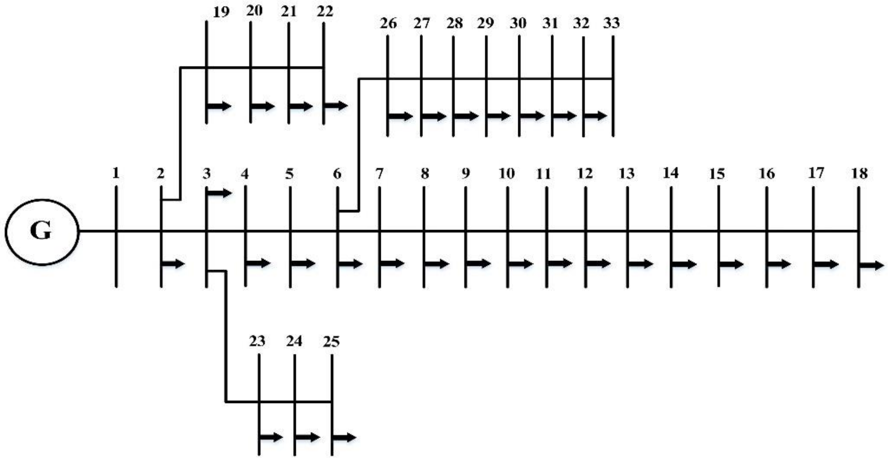

Fig. 3.1: Single-line diagram of the IEEE 33-bus distribution system.

3.3 Backward/Forward Sweep Load Flow

The Backward/Forward Sweep (BFS) load flow method is used to analyze the radial distribution system. Unlike conventional Newton–Raphson and Gauss–Seidel methods, the BFS algorithm is well suited for radial networks because of their high resistance-to-reactance ratio and tree-like structure [22]–[25].
The load flow solution is obtained in two stages.

During the backward sweep, branch currents are calculated starting from the terminal buses and moving towards the slack bus. The load current at each bus is calculated as [22], [24]:

$$I_i = \left(\frac{P_i + jQ_i}{V_i}\right)^*$$

Where, P_i is active power demand at bus i, Q_i is reactive power demand at bus i, V_i is bus voltage, $(\cdot)^*$ is complex conjugate.
During the forward sweep, bus voltages are updated from the slack bus towards the terminal buses using the calculated branch currents [62-63].

$$V_j = V_i - I_{ij}(R_{ij} + jX_{ij})$$

Where, R_{ij}= branch resistance, X_{ij}= branch reactance, and I_{ij}= branch current.
The backward and forward sweeps are repeated until the voltage mismatch satisfies the convergence criterion [23-25].

3.4 Custom Power Device Model

In this study, the Custom Power Device (CPD) is modeled as a shunt-connected reactive power compensation device. The CPD injects reactive power into the network to support bus voltage and improve the overall system performance [16–19].

After CPD installation, the reactive power demand at the compensated bus becomes [67, 69]:

$$Q_{\text{new}} = Q_{\text{load}} - Q_{\text{CPD}}$$

Where, Q_{load} is the original reactive load and Q_{CPD} is the reactive power supplied by the CPD.
The injected reactive power reduces feeder current, improves bus voltage, enhances voltage stability, and decreases real power losses [16, 18]. The CPD rating is treated as a decision variable during the optimization process [19, 21].

3.5 Performance Indices

The performance of the distribution system is evaluated using the following indices.

3.5.1 Loadability

Loadability represents the maximum loading level that the distribution system can support while satisfying all operating constraints. A higher loading factor indicates better utilization of the network.

3.5.2 Voltage Profile

The voltage profile is assessed by the voltage magnitude at each bus. The objective is to maintain all bus voltages within the permissible operating range of 0.90–1.05 p.u.

3.5.3 Voltage Stability Index

The Voltage Stability Index (VSI) is used to identify weak branches and assess the proximity of the system to voltage collapse. A higher VSI indicates better voltage stability.

3.5.4 Real Power Loss

The total real power loss is obtained by summing the losses in all distribution branches. Reducing power loss improves the overall efficiency of the distribution network.

4. Multi-Objective Problem Formulation

The optimal placement and sizing of the Custom Power Device (CPD) is formulated as a constrained multi-objective optimization problem. The objective is to determine the optimal bus location and reactive power rating of the CPD that maximize the operational performance of the radial distribution system.

The optimization simultaneously considers four performance indices: loadability enhancement, voltage stability improvement, voltage profile improvement, and real power loss reduction. Since these objectives have different units and ranges, they are normalized and combined into a single objective function using weighted coefficients.

4.1 Objective Function

The overall fitness function is expressed as

$$F = w_1 f_1 + w_2 f_2 + w_3 f_3 + w_4 f_4$$

Where, F is the overall fitness function, f_1 represents the loadability enhancement objective, f_2 represents the voltage stability enhancement objective, f_3 represents the voltage profile improvement objective, and f_4 represents the real power loss minimization objective.
In this work, the following weights are selected according to the priority of the objectives:

Objective	Weight
Loadability Enhancement	0.40
Voltage Stability Improvement	0.30
Voltage Profile Improvement	0.20
Power Loss Reduction	0.10

These weights assign the highest priority to loadability enhancement while ensuring that voltage stability, voltage profile, and power loss are also improved.

4.6 Decision Variables

The optimization algorithm simultaneously determines two decision variables:
1. CPD installation bus location: $2 \leq B_{\text{CPD}} \leq N$, where B_{CPD} is the candidate bus number, N is the total number of buses.

2. Reactive power rating of the CPD: $Q_{\min} \leq Q_{\text{CPD}} \leq Q_{\max}$, where Q_{CPD} is the reactive power supplied by the CPD.

4.7 Operational Constraints

The optimization is performed subject to the following practical operating constraints.

(a) Bus Voltage Constraint

The voltage magnitude at every bus must remain within the permissible operating limits.

$$0.95 \leq V_i \leq 1.05 \text{ p.u.}$$

(b) CPD Rating Constraint

The reactive power supplied by the CPD is limited by its operating capability.

$$Q_{\min} \leq Q_{\text{CPD}} \leq Q_{\max}$$

(c) Loadability Constraint

The optimized loading factor must not be less than the base-case loading factor.

$$\lambda_{\max} \geq \lambda_{\text{base}}$$

5. Particle Swarm Optimization for Optimal CPD Placement and Sizing

5.1 Particle Swarm Optimization

Particle Swarm Optimization (PSO) is a population-based optimization technique proposed by Kennedy and Eberhart in 1995. It is inspired by the social behavior of bird flocks and fish schools while searching for food [22, 23]. PSO is widely used for solving nonlinear optimization problems because of its simple implementation, fast convergence, and good search capability [24-25].

In PSO, each candidate solution is called a particle. A particle represents a possible solution to the optimization problem. In this study, each particle consists of two decision variables: CPD installation bus location and CPD reactive power rating [22, 24].

The particles move through the search space to find the optimal solution. During each iteration, every particle updates its position using its own best solution (personal best) and the best solution obtained by the entire swarm (global best) [22, 25].

5.2 Particle Representation

Each particle is represented as

$$X_i = [B_i, \ Q_i]$$

Where, B_i represents the CPD installation bus and Q_i represents the CPD reactive power rating.

5.3 Particle Initialization

The initial swarm is generated randomly within the specified search limits. Each particle is assigned a candidate bus selected from the feasible bus set, an initial CPD size within the allowable compensation range, and an initial velocity [22, 24].

The fitness value of every particle is calculated by performing BFS load flow analysis after installing the CPD at the selected bus [23, 20].

The best solution obtained by each particle is stored as the personal best (P_{best}), while the best solution among all particles is stored as the global best (G_{best}) [22, 24].

5.4 Velocity Update

The velocity of each particle is updated according to [72], [74]:

$$v_i^{k+1} = wv_i^k + c_1r_1(P_{best} - x_i^k) + c_2r_2(G_{best} - x_i^k)$$

Where, v_i^k is the current velocity, w is the inertia weight, c_1 is the cognitive learning coefficient, $c_2$is the social learning coefficient, $r_1$and $r_2$are random numbers between 0 and 1, $P_{best}$is the personal best position, $G_{best}$is the global best position.

5.5 Position Update

After updating the velocity, the particle position is calculated as [22, 24]:

$$x_i^{k+1} = x_i^k + v_i^{k+1}$$

The updated position is checked against the allowable limits. If any variable exceeds its specified range, it is adjusted to the nearest feasible value before fitness evaluation [24-25].

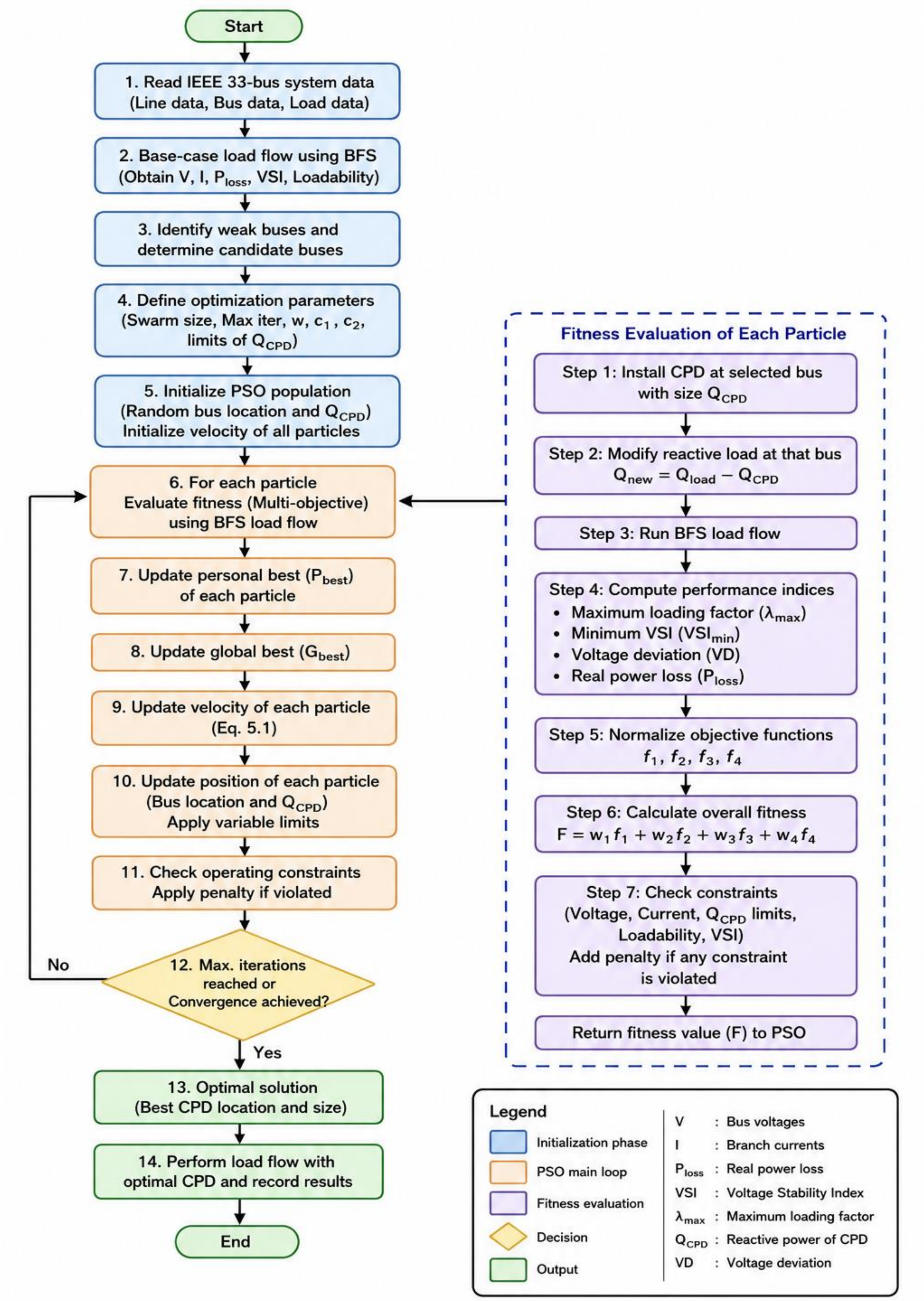

Fig. 5.1. Flowchart of the proposed PSO-based optimal placement and sizing methodology.

6. Results and Discussion

This section presents the simulation results obtained using the proposed Particle Swarm Optimization (PSO)-based methodology for the optimal placement and sizing of the Custom Power Device (CPD). The performance of the optimized system is compared with the base case using various performance indices, including loadability, voltage profile, voltage stability, branch current distribution, and real power loss.

6.1 Base-Case System Performance

The base-case load flow is performed before installing the CPD to evaluate the initial operating condition of the distribution system. The results indicate considerable voltage drop towards the end buses because of the radial feeder configuration.

The system also experiences relatively high real power losses and limited loadability under the base operating condition. These observations indicate that reactive power support is required to improve the overall performance of the distribution system.

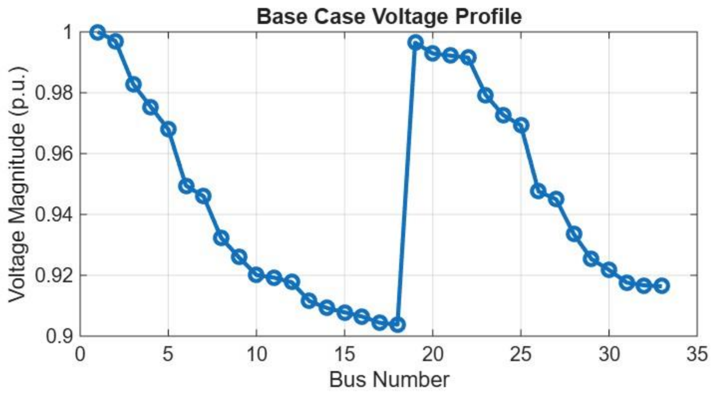

Fig. 6.1: Base case voltage profile

6.2 Optimal CPD Placement and Size Using PSO

The PSO algorithm determines the optimal installation bus and reactive power rating of the Custom Power Device by minimizing the multi-objective fitness function.

The selected location provides the maximum improvement in system loadability while simultaneously reducing power losses and improving voltage stability. Installing the CPD at the optimal bus provides better reactive power support to the weak portion of the feeder, thereby improving the voltage profile throughout the network.

The optimized CPD rating satisfies all operational constraints, including voltage limits, branch current limits, and reactive power compensation limits.

Table 1. Optimal CPD Placement Results

Parameter	Value
Optimal bus location	Bus 17
Optimal CPD rating	550 kVAr
loadability enhancement	21%
VSI Improvement	8.3%
Voltage Profile Improvement	33%

Power Loss Reduction	13%

6.3 Performance Evaluation

To evaluate the effectiveness of the proposed methodology, the optimized system is compared with the base-case system using different performance indices.

6.3.1 Loadability Enhancement

Loadability is one of the primary objectives of the proposed optimization framework. Figure 6.2 compares the loadability curves before and after CPD installation.

The optimized CPD significantly increases the maximum loading factor of the distribution system. The results clearly demonstrate that the proposed methodology effectively enhances the load-carrying capability of the radial distribution system.

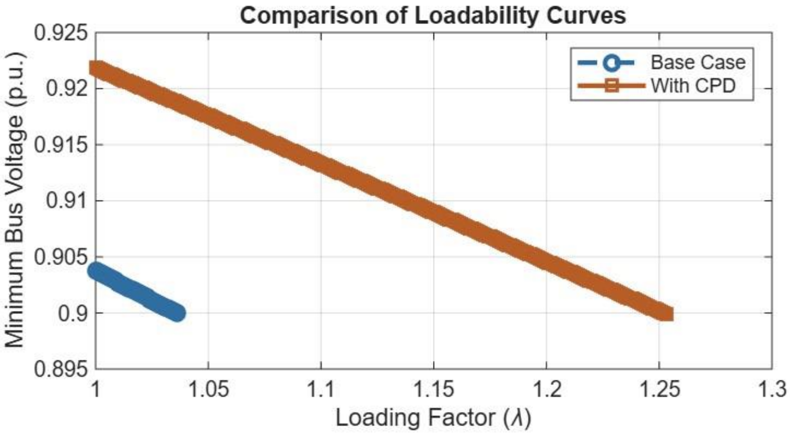

Fig. 6.2: Comparison of loadability curves for the base-case and compensated distribution system.

6.3.2 Voltage Profile Improvement

The voltage magnitude at all buses improves after optimization. The improvement is more significant at buses located farther from the substation, where voltage drops are generally higher.

The minimum bus voltage increases considerably after CPD installation, indicating better voltage regulation throughout the feeder. All bus voltages remain within the permissible operating limits.

These results confirm the effectiveness of the proposed CPD placement strategy in maintaining a healthy voltage profile.

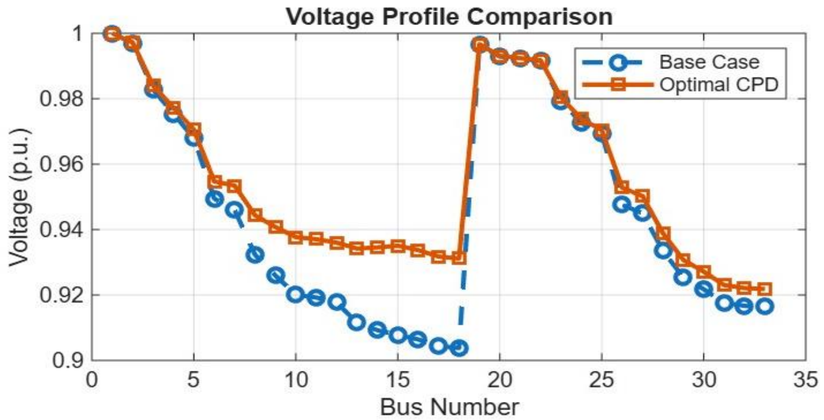

Fig. 6.3: Comparison of bus voltage profiles before and after CPD installation.

6.3.3 Voltage Stability Enhancement

Voltage Stability Index (VSI) is used to evaluate the stability margin of the distribution system.
The increase in VSI indicates that the system operates farther from the voltage collapse point and possesses a higher voltage stability margin under increased loading conditions.

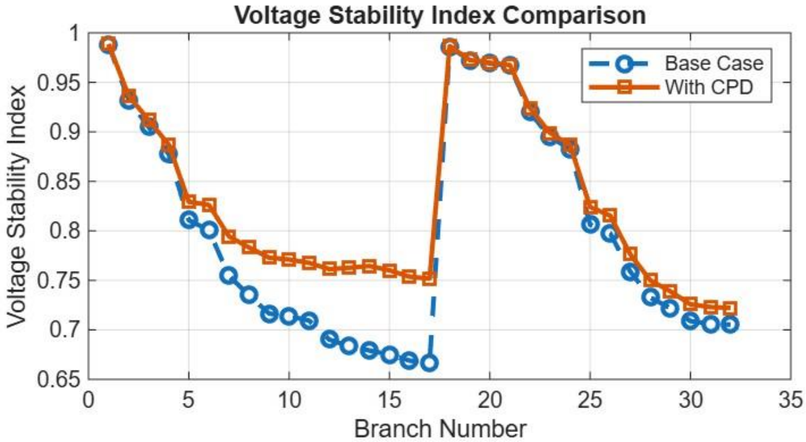

Fig. 6.4: Comparison of Voltage Stability Index (VSI) before and after CPD installation.

6.3.4 Power Loss Reduction

The optimized CPD reduces feeder current by supplying reactive power locally. As a result, there is reduction in power loss which improves the efficiency of the distribution system and contributes to better utilization of the existing infrastructure.

The power loss versus loading factor characteristics further demonstrate that the proposed method maintains lower losses even under increased loading conditions.

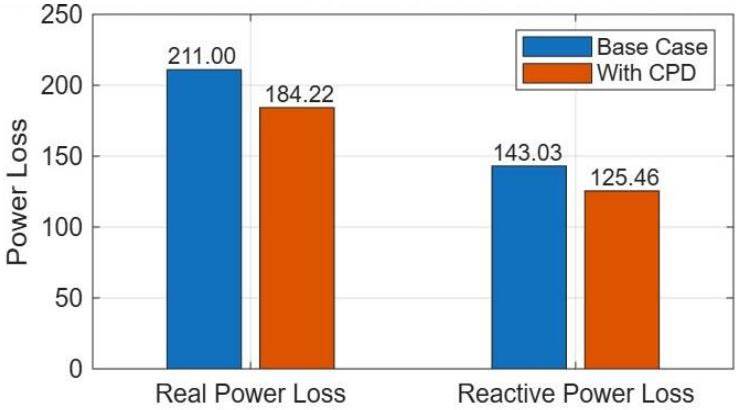

Fig. 6.5: Comparison of Power Losses Before and After CPD Installation.

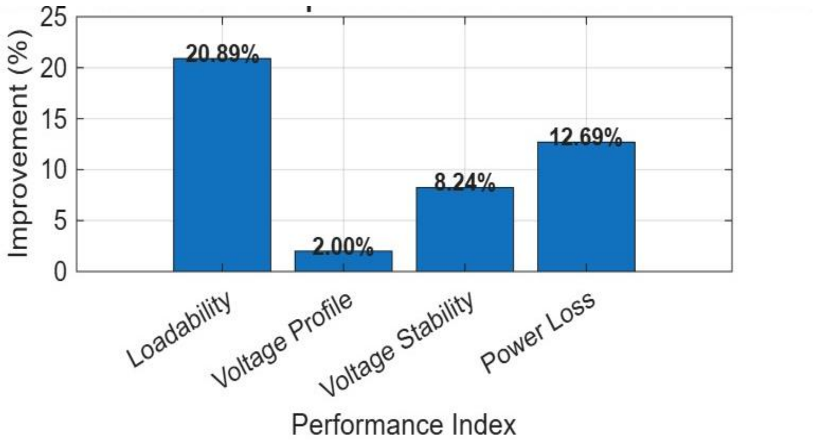

Fig. 6.6: Overall Performance Comparison

7. Conclusion

This paper presented a Particle Swarm Optimization (PSO)-based approach for the optimal placement and sizing of a Custom Power Device (CPD) to improve the performance of radial distribution systems. A multi-objective optimization framework was developed by considering loadability enhancement, voltage stability improvement, voltage profile enhancement, and real power loss reduction simultaneously. The Backward/Forward Sweep (BFS) load flow method was integrated with Voltage Stability Index (VSI) evaluation to accurately assess the performance of each candidate solution during the optimization process.

The proposed methodology was validated on the standard IEEE 33-bus radial distribution system using MATLAB. Results demonstrated that the optimally placed CPD significantly improved the overall performance of the distribution network. The installation of the CPD increased the maximum loadability of the system, improved the minimum bus voltage, enhanced the voltage stability margin, and reduced the total real power losses.

Overall, the proposed PSO-based optimization framework provides a simple, reliable, and computationally efficient tool for distribution system planning. The methodology can assist distribution utilities in improving network efficiency, voltage security, and load-carrying capability while satisfying practical operating constraints.

Future research may extend the proposed work by considering multiple CPDs, renewable energy integration, distributed generation, electric vehicle charging loads, energy storage systems, and uncertainty associated with load and renewable power generation. The application of advanced multi-objective optimization algorithms and real-time control strategies may further improve the operational flexibility and reliability of modern smart distribution networks.

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