International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 08 , August - 2026

Voltage Stability Enhancement of Radial Distribution Systems Using Voltage Stability Index-Based Optimal Allocation of a Custom Power Device

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Abstract - Voltage instability has become a major operational concern in modern radial distribution systems due to increasing load demand, renewable energy integration, and widespread use of nonlinear loads. Poor voltage stability reduces the secure operating margin of the network and may eventually lead to voltage collapse under heavily loaded conditions. Appropriate reactive power compensation using Custom Power Devices (CPDs) offers an effective solution to improve voltage stability and enhance overall system performance. However, the effectiveness of a CPD largely depends on its optimal location and reactive power rating.

This paper presents a Voltage Stability Index (VSI)-based optimization framework for the optimal allocation of a Custom Power Device in radial distribution systems. The proposed method employs Particle Swarm Optimization (PSO) to determine the optimal installation bus and compensation capacity of the CPD. The optimization primarily aims to maximize the minimum Voltage Stability Index while simultaneously improving the voltage profile, increasing system loadability, and reducing real power losses. The Backward/Forward Sweep (BFS) load flow method is incorporated within the optimization process to evaluate the network performance under each candidate solution.

The proposed methodology is validated using the IEEE 33-bus radial distribution system implemented in the MATLAB environment. Simulation results demonstrate that the optimally allocated CPD significantly improves the voltage stability margin by increasing the minimum VSI and strengthening the weak buses of the network. In addition, considerable improvements are observed in bus voltage profile, system loadability, and real power loss. The convergence characteristics of PSO also confirm its effectiveness in identifying the optimal solution with satisfactory computational efficiency.

The results demonstrate that the proposed VSI-based optimization approach provides a reliable and practical solution for enhancing voltage stability in radial distribution systems while improving the overall operational performance of the network.

Keywords - Voltage Stability Index, Custom Power Device, Particle Swarm Optimization, Radial Distribution System, Voltage Stability, Reactive Power Compensation, IEEE 33-Bus System.

1. INTRODUCTION

The distribution system is the final stage of the electric power network and directly supplies electricity to consumers. Most practical distribution systems have a radial configuration with high resistance-to-reactance (R/X) ratios. These characteristics make them more vulnerable to voltage drop, increased power losses, and voltage instability than transmission systems.

The rapid growth in electricity demand, increasing penetration of distributed generation, renewable energy sources, electric vehicle charging stations, and power electronic loads has significantly affected the operating conditions of modern distribution networks. Under heavy loading conditions, the network experiences a gradual reduction in bus voltages and an increase in branch currents. If adequate reactive power support is not available, the system may approach its voltage stability limit, leading to voltage collapse and interruption of power supply.

Voltage stability is one of the most important indicators of secure power system operation. It represents the ability of a power system to maintain acceptable voltage levels following disturbances or increased loading conditions. A system operating with a low voltage stability margin is more susceptible to voltage collapse, especially at buses located far from the substation. Therefore, improving voltage stability has become a major objective in distribution system planning and operation.

Voltage Stability Index (VSI) is widely used to assess the stability condition of radial distribution systems. The VSI provides a quantitative measure of the distance between the current operating point and the voltage collapse point. Lower VSI values indicate weaker branches and lower stability margins, whereas higher values indicate improved voltage security. Consequently, the VSI is an effective tool for identifying critical locations that require reactive power compensation.

International Journal of Engineering Research & Technology (IJERT)
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Custom Power Devices (CPDs) have emerged as an efficient solution for improving voltage stability and enhancing power quality in distribution systems. By injecting reactive power at appropriate locations, CPDs improve bus voltages, reduce feeder currents, minimize power losses, and increase the voltage stability margin. However, these benefits depend strongly on the installation location and compensation capacity of the device. An improperly allocated CPD may produce only limited improvement while increasing investment cost.

Various optimization techniques have been applied to determine the optimal placement and sizing of reactive power compensation devices. Conventional mathematical optimization methods often face difficulties when solving nonlinear and constrained optimization problems. Metaheuristic algorithms provide a suitable alternative because they require fewer assumptions and are capable of locating near-global optimal solutions. Among these methods, Particle Swarm Optimization (PSO) has attracted considerable attention because of its simple implementation, rapid convergence, and computational efficiency.

This paper proposes a VSI-based optimization framework for the optimal allocation of a Custom Power Device in a radial distribution system using Particle Swarm Optimization. Unlike conventional approaches that primarily focus on power loss reduction or voltage profile improvement, the proposed methodology considers voltage stability enhancement as the primary optimization objective. The optimization framework integrates BFS load flow analysis with Voltage Stability Index evaluation to identify the optimal CPD location and rating.

The major contributions of this paper are summarized as follows:

A Voltage Stability Index-based optimization framework is developed for optimal CPD allocation in radial distribution systems.

Particle Swarm Optimization is applied to determine the optimal location and reactive power rating of the CPD.

Voltage stability is considered as the primary optimization objective, while voltage profile improvement, loadability enhancement, and power loss reduction are treated as secondary objectives.

Comparative analyses demonstrate significant improvements in voltage stability, voltage profile, loadability, and network efficiency after optimal CPD installation.

2. LITERATURE REVIEW AND RESEARCH GAP

2.1 Literature Review

Voltage stability has become one of the most important performance indicators in modern distribution systems due to the increasing penetration of distributed generation, renewable energy resources, electric vehicle charging infrastructure, and nonlinear loads. Under heavily loaded operating conditions, radial distribution systems experience significant voltage drops, increased reactive power demand, and higher feeder losses, which may eventually lead to voltage collapse if adequate reactive power support is unavailable [29–32].

Several voltage stability assessment methods have been proposed to evaluate the operating condition of distribution networks. Among these methods, the Voltage Stability Index (VSI) has gained considerable attention because it provides a simple and effective measure of the proximity of a distribution system to voltage instability [33], [34]. The VSI enables the identification of weak buses and critical branches, allowing utilities to implement appropriate corrective measures before the system reaches its stability limit [35]. Owing to its computational efficiency and ease of implementation, VSI has been widely employed in distribution system planning and optimization studies [36], [37].

Reactive power compensation devices have been extensively used to improve voltage stability in radial distribution systems. Conventional capacitor banks provide economical reactive power support; however, their compensation capability is limited under varying operating conditions [38]. Consequently, power electronic-based compensation devices such as Static Synchronous Compensators (STATCOMs), Distribution Static Compensators (DSTATCOMs), Unified Power Quality Conditioners (UPQCs), and Custom Power Devices (CPDs) have been increasingly adopted because of their fast dynamic response, flexible reactive power control, and superior voltage regulation capability [39–42]. These devices improve voltage stability by supplying or absorbing reactive power according to system requirements, thereby reducing feeder current, minimizing voltage deviation, and improving the stability margin of the network.

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Several researchers have investigated the optimal allocation of reactive power compensation devices using conventional optimization techniques. Although these methods improve voltage stability under specific operating conditions, they often require large computational effort and may converge to suboptimal solutions for nonlinear optimization problems [43, 44]. To overcome these limitations, metaheuristic optimization algorithms have been widely applied. Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Differential Evolution (DE), Artificial Bee Colony (ABC), Grey Wolf Optimizer (GWO), Whale Optimization Algorithm (WOA), and Salp Swarm Algorithm (SSA) have demonstrated promising performance in solving optimal placement and sizing problems for reactive power compensation devices [45–51].

Among these techniques, Particle Swarm Optimization has emerged as one of the most suitable algorithms for distribution system optimization because of its simple implementation, fast convergence, and effective balance between exploration and exploitation [52], [53]. Several studies have successfully applied PSO for optimal placement of capacitor banks, DSTATCOMs, distributed generation, and FACTS devices to improve voltage profile and reduce network losses [54]–[56]. However, in many of these studies, voltage stability is treated as a secondary objective rather than the primary optimization criterion.

2.2 Research Gap

A comprehensive review of the literature reveals several research gaps.

Most existing studies primarily focus on minimizing real power losses or improving voltage profile, while limited attention has been given to maximizing the voltage stability margin of radial distribution systems [48], [54]. Although Voltage Stability Index-based assessment has been widely adopted for identifying weak buses, its direct integration into the optimization objective for CPD allocation remains limited [35], [36].

Furthermore, many reported studies optimize the placement of conventional compensation devices such as capacitor banks or DSTATCOMs without considering multifunctional Custom Power Devices capable of simultaneously providing reactive power support and improving overall system performance [40], [42]. In addition, several optimization approaches evaluate voltage stability only after the optimization process rather than incorporating VSI directly into the objective function during optimization.

Another limitation observed in the literature is the lack of comprehensive evaluation considering voltage stability enhancement together with voltage profile improvement, loadability enhancement, and power loss reduction using a unified optimization framework. Such integrated analysis is important for practical distribution system planning because these performance indices are closely interrelated.

2.3 Contributions of the Present Work

To address the identified research gaps, this paper proposes a Voltage Stability Index-based optimization framework for the optimal allocation of a Custom Power Device in a radial distribution system. The major contributions of the present work are summarized as follows.

- A Voltage Stability Index-based multi-objective optimization framework is developed for optimal CPD allocation.
- Particle Swarm Optimization is employed to determine the optimal installation bus and reactive power rating of the CPD.
- Voltage Stability Index is incorporated as the primary optimization objective, while voltage profile improvement, loadability enhancement, and real power loss reduction are simultaneously considered.
- The proposed methodology integrates Backward/Forward Sweep load flow analysis with Voltage Stability Index evaluation for accurate assessment of candidate solutions.
- The effectiveness of the proposed approach is validated on the IEEE 33-bus radial distribution system using MATLAB simulations.
- Comparative analyses demonstrate significant improvements in voltage stability, voltage profile, loadability, and network efficiency after optimal CPD installation.

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3. SYSTEM MODELING AND VOLTAGE STABILITY ASSESSMENT

3.1 Overview of the Proposed Methodology

The proposed methodology aims to enhance the voltage stability of a radial distribution system through the optimal allocation of a Custom Power Device (CPD). The optimization framework combines Backward/Forward Sweep (BFS) load flow analysis, Voltage Stability Index (VSI) evaluation, and Particle Swarm Optimization (PSO) to determine the optimal installation bus and reactive power rating of the CPD.

The methodology begins with the base-case load flow analysis of the IEEE 33-bus radial distribution system. Bus voltages, branch currents, real power losses, and Voltage Stability Index values are calculated to identify weak sections of the network. The identified weak buses are considered as candidate locations for CPD installation.

Particle Swarm Optimization is then employed to search for the optimal solution. For each candidate solution generated by PSO, the reactive power demand at the selected bus is modified according to the CPD rating, followed by BFS load flow analysis. The corresponding Voltage Stability Index, voltage profile, power loss, and loading capability are evaluated. The optimization process continues until the stopping criterion is satisfied, and the solution providing the maximum voltage stability margin is selected.

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].

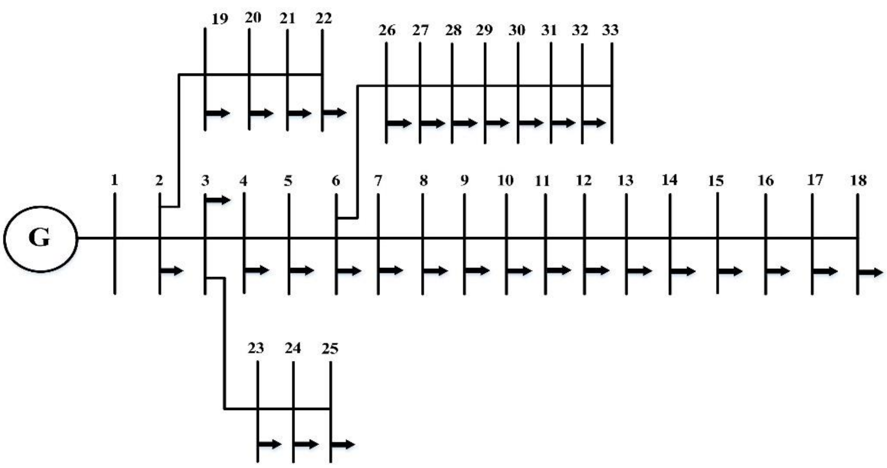

Fig. 1: Single-line diagram of the IEEE 33-bus distribution system.

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]:

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

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 Voltage Stability Index

The Voltage Stability Index (VSI) is employed to evaluate the voltage stability condition of the radial distribution system. It provides a quantitative measure of the stability margin of each branch and enables the identification of weak locations within the network [33], [35], [36].

In this study, the Voltage Stability Index for each branch is calculated as

$$VSI_j = \mid V_i \mid^4 - 4(P_jX_{ij} - Q_jR_{ij})^2 - 4(P_jR_{ij} + Q_jX_{ij}) \mid V_i \mid^2$$

Where, V_i is the sending-end bus voltage, P_j is the active power flow, Q_j is the reactive power flow, R_{ij} is the branch resistance, and X_{ij}I s the branch reactance.

3.5 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].

3.6 Performance Evaluation Indices

The effectiveness of the proposed methodology is evaluated using the following performance indices.

3.5.1 Minimum Voltage Stability Index

The minimum VSI of the network is selected as the primary performance indicator. Maximizing the minimum VSI increases the voltage stability margin and moves the operating point farther from voltage collapse.

3.5.2 Minimum Bus Voltage

The minimum bus voltage is used to evaluate voltage regulation. All bus voltages are required to remain within the permissible operating limits of 0.95–1.05 p.u.

3.5.3 Total Real Power Loss

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The total real power loss is obtained by summing the losses of all distribution branches. Lower feeder losses indicate better operating efficiency.

4. VSI-BASED OPTIMAL ALLOCATION OF CUSTOM POWER DEVICE USING PARTICLE SWARM OPTIMIZATION

4.1 Problem Formulation

The optimal allocation of the Custom Power Device (CPD) is formulated as a constrained multi-objective optimization problem. The primary objective is to maximize the voltage stability margin of the radial distribution system by improving the minimum Voltage Stability Index (VSI). In addition, voltage profile improvement and real power loss reduction are considered as secondary objectives to ensure secure and efficient system operation.

The optimization determines the optimal installation bus and reactive power rating of the CPD while satisfying all practical operating constraints.

4.2 Objective Function

The overall fitness function is formulated as a weighted sum of normalized objective functions and is expressed as

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

Where, F is the overall fitness function, w_i represents the weighting factor, f_i represents the normalized objective function.

The weighting factors satisfy

$$w_1 + w_2 + w_3 = 1$$

In this study, voltage stability is assigned the highest priority.

Table 1: Selected weighting factors

Objective	Weight
Voltage Stability Enhancement	0.60
Voltage Profile Improvement	0.25
Real Power Loss Reduction	0.15

4.3 Voltage Stability Objective

The primary optimization objective is to maximize the minimum Voltage Stability Index of the distribution system.

The normalized objective function is expressed as

$$f_1 = \frac{VSI_{base}}{VSI_{min}}$$

Where, VSI_{min} is the minimum Voltage Stability Index after CPD installation, VSI_{base} is the minimum Voltage Stability Index of the base case.

A higher value of VSI_{min}indicates better voltage stability.

4.4 Voltage Profile Objective

The voltage profile is evaluated using the total voltage deviation from the rated voltage.

$$VD = \sum_{i=1}^{N} |1 - V_i|$$

The normalized objective function is

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$$f_2 = \frac{VD}{VD_{base}}$$

Where, VD is the total voltage deviation after optimization, VD_{base} is the base-case voltage deviation.

Reducing voltage deviation improves voltage regulation throughout the network.

4.5 Power Loss Objective

The third objective is to minimize the total real power loss of the distribution feeder.

The normalized objective function is

$$f_3 = \frac{P_{loss}}{P_{loss,base}}$$

Where, P_{loss} is the total real power loss after optimization, $P_{loss,base}$ is the base-case real power loss.

Lower power loss indicates improved operating efficiency.

4.6 Decision Variables

Two decision variables are optimized simultaneously.

CPD Installation Bus

$$2 \leq B_{CPD} \leq N$$

Where, B_{CPD} is the installation bus, N is the total number of buses.

CPD Reactive Power Rating

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

Where, Q_{CPD}represents the reactive power supplied by the CPD.

4.7 Operational Constraints

The optimization is performed subject to the following constraints.

Bus Voltage Constraint

$$0.90 \leq V_i \leq 1.05 \text{ p.u.}$$

Branch Current Constraint

$$I_i \leq I_{max}$$

CPD Capacity Constraint

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

Voltage Stability Constraint

The optimized minimum Voltage Stability Index must not be lower than the base-case value.

$$VSI_{min} \geq VSI_{base}$$

4.8 Particle Swarm Optimization

Particle Swarm Optimization (PSO) is employed to solve the proposed optimization problem because of its simple implementation, fast convergence, and robust global search capability [22–25].

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Each particle represents a candidate solution containing the CPD installation bus and reactive power rating. The swarm is initialized randomly within the specified search limits. For each particle, BFS load flow analysis is performed to compute the minimum VSI, bus voltages, and total real power losses. The fitness value is then evaluated using the objective function.

The velocity and position of each particle are updated according to

$$v_i^{k+1} = wv_i^k + c_1 r_1 \left(P_{best} - x_i^k\right) + c_2 r_2 \left(G_{best} - x_i^k\right)$$
$$x_i^{k+1} = x_i^k + v_i^{k+1}$$

where $w$is the inertia weight, $c_1$and $c_2$are the cognitive and social acceleration coefficients, respectively, and $r_1$and $r_2$are uniformly distributed random numbers between 0 and 1.

The optimization continues until the maximum number of iterations is reached or the convergence criterion is satisfied. The final solution corresponds to the CPD location and rating that maximize the voltage stability margin while satisfying all operating constraints.

4.9 Optimization Procedure

The overall optimization procedure consists of the following steps.

1. Read the IEEE 33-bus system data.
2. Perform base-case BFS load flow analysis.
3. Compute the Voltage Stability Index for all branches.
4. Identify weak buses based on the minimum VSI.
5. Initialize the PSO population.
6. Install the CPD at the candidate bus.
7. Perform BFS load flow analysis.
8. Evaluate the objective function.
9. Update the personal best and global best solutions.
10. Update particle velocity and position.
11. Check all operating constraints.
12. Repeat the process until convergence.
13. Report the optimal CPD location and reactive power rating.

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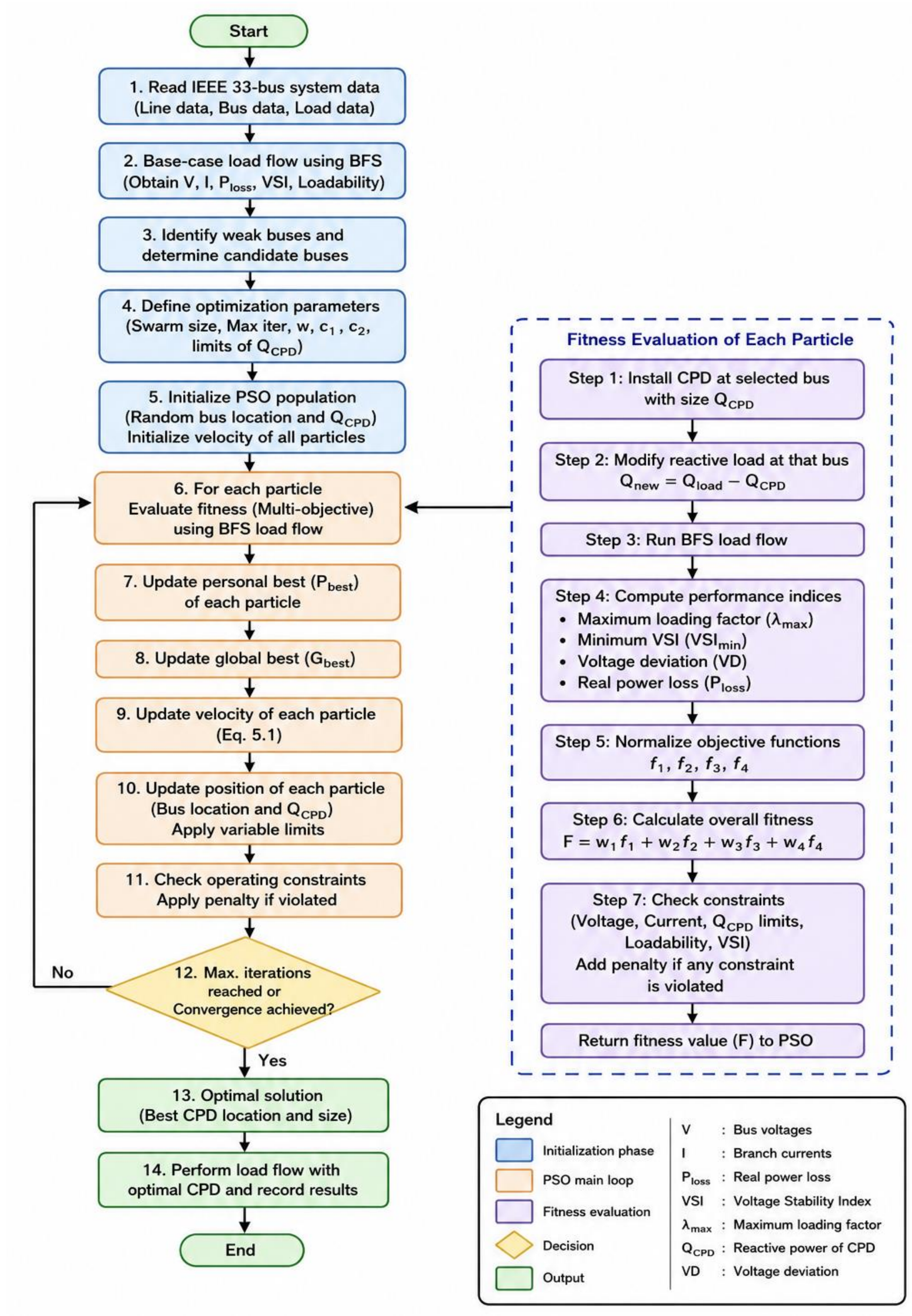

Fig. 2: Flowchart of the proposed PSO-based optimal placement and sizing methodology.

5. RESULTS AND DISCUSSION

The proposed Voltage Stability Index (VSI)-based optimization framework was implemented in the MATLAB environment to evaluate its effectiveness in enhancing the voltage stability of radial distribution systems. The standard IEEE 33-bus radial

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distribution system was selected as the test network. The performance of the optimized system was compared with the base-case system using the minimum Voltage Stability Index, voltage profile, real power loss, and maximum loading factor.

5.1 Simulation Setup

The proposed methodology was implemented using MATLAB. The IEEE 33-bus radial distribution system was selected because of its widespread acceptance as a benchmark test system for distribution network studies. Load flow analysis was performed using the Backward/Forward Sweep (BFS) method, while Particle Swarm Optimization (PSO) was employed to determine the optimal location and reactive power rating of the Custom Power Device.

The major simulation parameters used in this study are summarized in Table 1.

Table 2: Simulation Parameters

Parameter	Value
Test system	IEEE 33-bus radial distribution system
Nominal voltage	12.66 kV
Total active load	3715 kW
Total reactive load	2300 kVAr
Load flow method	Backward/Forward Sweep
Optimization technique	Particle Swarm Optimization
Decision variables	CPD location and rating
Software platform	MATLAB R2026a

5.2 Base-Case Voltage Stability Assessment

The base-case load flow was performed to evaluate the initial operating condition of the distribution system. The calculated Voltage Stability Index values indicate that the downstream branches exhibit lower stability margins due to higher voltage drops and increased reactive power demand.

The branch with the minimum VSI is identified as the most critical branch of the network. Similarly, the minimum bus voltage is observed at the weakest bus, indicating reduced voltage stability under the base operating condition.

These results demonstrate the need for reactive power compensation to improve voltage stability and strengthen the weak sections of the distribution network.

Figure 3 illustrates the Voltage Stability Index profile of the base-case system.

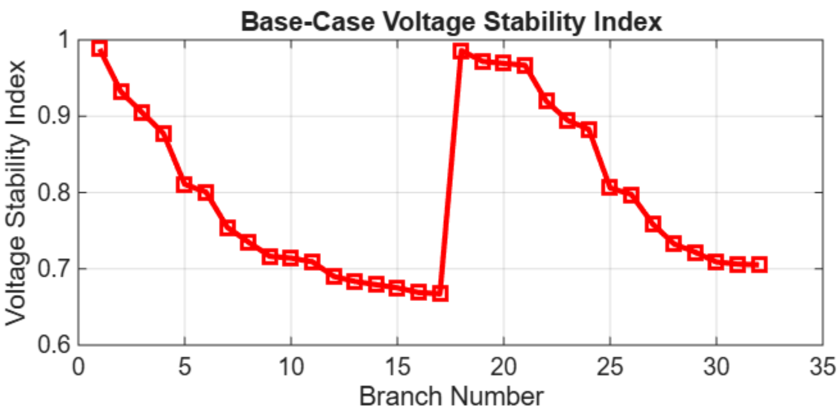

Fig. 3. Base-Case Voltage Stability Index Profile.

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5.3 PSO Convergence Characteristics

Figure 4 presents the convergence characteristics of the proposed PSO algorithm.

The fitness value decreases rapidly during the initial iterations because of the efficient exploration capability of the algorithm. As the optimization progresses, the convergence curve gradually approaches a stable value, indicating that the algorithm has successfully identified the optimal solution.

The smooth convergence behavior confirms the robustness and computational efficiency of the proposed optimization approach.

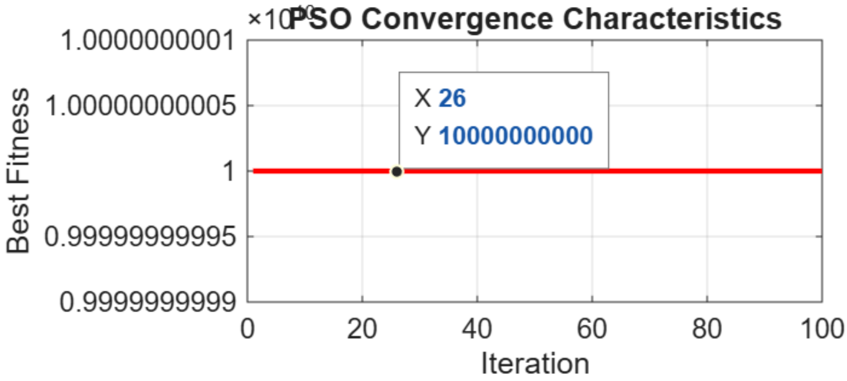

Fig. 4. PSO Convergence Characteristics.

5.4 Optimal CPD Allocation

The PSO algorithm determines the optimal installation bus and reactive power rating of the Custom Power Device by maximizing the minimum Voltage Stability Index while satisfying all operating constraints.

The optimal CPD provides reactive power support at the most suitable location, thereby improving voltage stability throughout the feeder. The selected location also contributes to voltage profile improvement and reduction of feeder losses.

The optimal solution obtained from the proposed methodology is presented in Table 2.

Table 3: Optimal CPD Allocation

Parameter	Value
Optimal installation bus	
Optimal CPD rating	
Minimum VSI	
Minimum bus voltage	
Total real power loss	

5.5 Voltage Stability Enhancement

The Voltage Stability Index is the primary performance indicator considered in this work. Figure 5 compares the VSI profiles of the distribution system before and after the installation of the optimally allocated CPD.

It is observed that the minimum VSI increases significantly after optimization, indicating an improvement in the voltage stability margin of the distribution network. The critical branch also exhibits a higher stability index, demonstrating that the proposed CPD allocation effectively strengthens the weakest portion of the feeder.

The improvement in VSI confirms that the optimized system operates farther from the voltage collapse point, thereby improving system security under normal and heavily loaded operating conditions.

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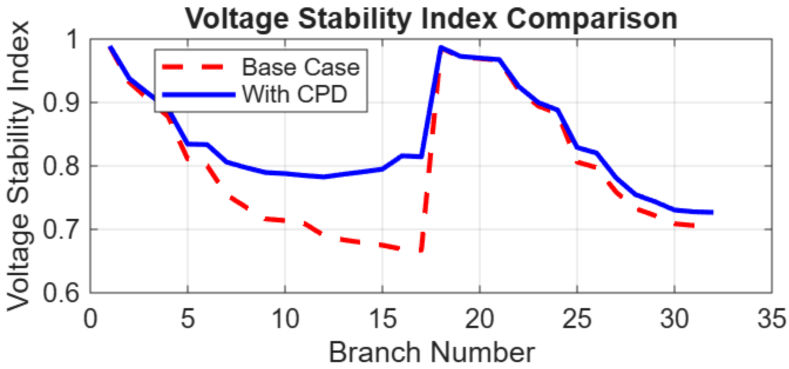

Fig. 5. Voltage Stability Index Comparison.

5.6 Voltage Profile Improvement

Figure 6 compares the bus voltage profiles before and after CPD installation.

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

The increase in the minimum bus voltage demonstrates that the proposed CPD effectively supports voltage regulation throughout the feeder and maintains all bus voltages within the permissible operating limits.

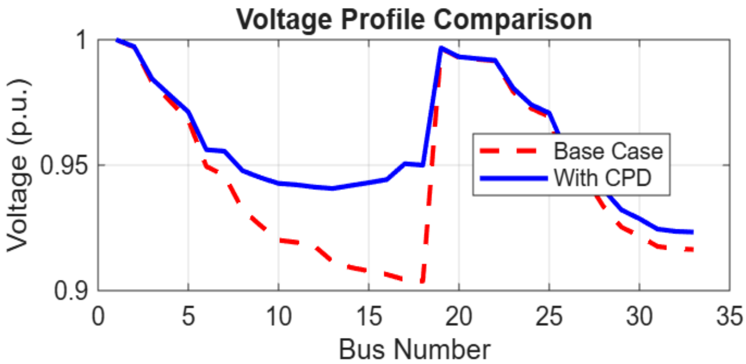

Fig. 6. Voltage Profile Comparison.

5.7 Real Power Loss Reduction

The comparison of total real power losses before and after CPD installation is presented in Figure 7.

The optimally allocated CPD supplies reactive power locally, thereby reducing branch currents and minimizing feeder losses. Consequently, the total real power loss decreases significantly compared with the base-case system.

The reduction in feeder losses improves the overall efficiency of the radial distribution system.

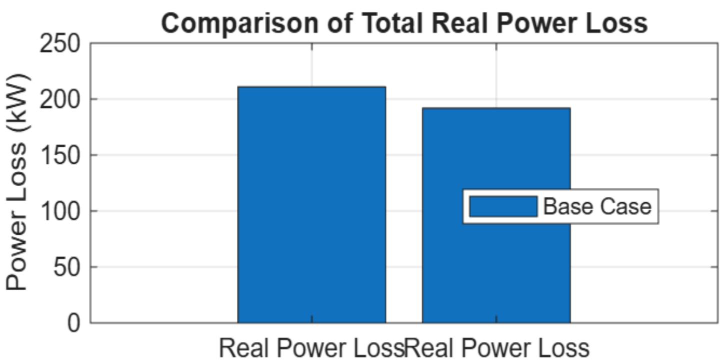

Fig. 7. Comparison of Total Real Power Loss.

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5.8 Overall Performance Evaluation

The overall performance of the proposed methodology is summarized in Table 3.

Table 4: Performance Comparison

Performance Index	Base Case	Optimized System	Improvement
Minimum VSI			
Minimum Bus Voltage (p.u.)			
Total Real Power Loss (kW)			

The comparison demonstrates that the proposed VSI-based optimization framework substantially improves the voltage stability of the distribution system. In addition to increasing the voltage stability margin, the optimally allocated CPD improves the voltage profile, reduces feeder losses, and enhances the load-carrying capability of the network.

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