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Voltage Profile Enhancement in an 11kv Radial Distribution Networks Using PSO Optimization Approach

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ABSTRACT—
Voltage regulation and power loss reduction are critical objectives in the efficient operation of electrical distribution networks. This paper addresses the optimal capacitor placement problem on a real-world 11 kV, 253-bus distribution feeder, modeled in the Electrical Transient Analyzer Program software environment. The baseline analysis of the feeder revealed significant voltage drops, with the minimum bus voltage reaching a critical 88.6%, and high real power losses of 145 kW. To resolve these issues, a Particle Swarm Optimization algorithm, enhanced with a linearly decreasing inertia weight to prevent premature convergence, was developed and integrated with the software in a simulation-in-the-loop framework. The problem was formulated with a multi-objective function prioritizing voltage profile enhancement over loss minimization, reflecting practical utility needs. The search space was intelligently constrained to practical and effective candidate solutions. The results of the Particle Swarm Optimization driven placement show a remarkable improvement in the feeder's performance: the minimum system voltage was raised to 94.36%, eliminating all critical undervoltage conditions, and total real power losses were reduced by 28.9%. This study demonstrates the effectiveness of a constrained, metaheuristic approach in solving a complex, real-world power system optimization problem, highlighting a practical application that bridges the gap between theoretical optimization and industry-standard simulation tools.
Keywords— *Active Power Loss Reduction, ETAP, Particle Swarm OptimizationRadial Distribution Feeder, Shunt Capacitor placement,.*

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I. INTRODUCTION

Modern electrical distribution networks need to provide high quality and reliable power to the end-users. Two of the main issues for managing these networks are preserving and ensuring voltage amplitudes underspecified levels and reducing energy losses [1]. Excessive voltage drops causes high power losses and can cause equipment failure and damages and high costs (economic and environmental) [2]. Choke reactors are a widely used and cost-efficient option for supplying reactive power (VAR) to the grid. Power (VAr) compensate this directly at the distribution network [3] and by supplying VArs This means that the capacitors are dampening the reactive current from the substation which in turn reduce voltage drops, leads to reduction of total current magnitude, therefore reducing I^2Rlosses [4]. However, the issue of what is the optimum number, location and size of these is still up for debate. Optimal Capacitor Placement (OCP) problem is a complex non-linear problem and combinatorial optimization problem [5]. Positioning not well done the voltage cannot be stabilized. It can cause bad conditions during light loads, and in the worst case which can cause overvoltage conditions. Manual or Very large and complex feeders cannot be dealt with trial and error.

A. Literature Review and Research Gap

The OCP problem has been considered and investigated by many optimization methods. Early candidate sites were identified using analytical and sensitivity approaches [8]. While it is computationally cheap, these methods tend to give locally optimal solutions. A classical Optimization method includes primarily linear and non-linear programming has also been used, but they consider OCP problem as a non-convex and discrete optimization problem as described in [9]. In recent decades, metaheuristic algorithms have emerged as the most predominant due to their ability to successfully search complex spaces. The Genetic Search Algorithm (GSA) is one of the popular algorithms. Ant Colony Optimization (ACO) [11], Artificial Bee Colony (ABC) and Genetic Algorithm (GA) [10,12] are the major algorithms used in optimizing systems . Particle Swarm Optimization

(PSO) is a powerful metaheuristic algorithm that is best known for its well-known Lagrange proximal method [6] which has been used for simple structure, rapid convergence and has been extensively applied to the OCP problem [7]. Despite the bulk of work published, there is still a large research gap. The majority of studies that has validated their algorithms have been tested on standardized IEEE test feeders (e.g. 33-bus, 69-bus systems, etc) [13]. While providing useful benchmarking facilities, such systems do not fully represent the scale and complexity of today's systems. Real-life distribution networks indeed in a dearth of studies that implement this optimization of the large-scale operational feeders modeled in industry-standard simulators such as ETAP which is critical to validate whether it has practical applicability.

B. Novelty and Contributions

This paper aims to bridge this gap by presenting a comprehensive case study on a real 11 Kv, 253-bus feeder. The novelty and main contributions of this work are threefold:

1. Practical Application: It solves the OCP problem on a large-scale, real-world distribution network, providing insights that are directly relevant to utility engineers.
2. PSO-ETAP Integration: It demonstrates a robust simulation-in-the-loop framework that couples a Python-based PSO algorithm with the powerful ETAP power flow engine, ensuring high-fidelity analysis.
3. Problem-Specific Formulation: It utilizes a multi-objective function that prioritizes the correction of critical undervoltage conditions over loss minimization, addressing the most pressing operational constraint of the studied feeder.

II. CASE STUDY: BASELINE ANALYSIS

The system under investigation is an 11 kV feeder, a real-world radial distribution network originating from a 33/11kV Substation as shown in figure 1. The feeder model was developed in ETAP using geographical information system (GIS) data for conductor lengths, types, and transformer locations.

The network is characterized by its extensive and branched topology, serving a diverse set of loads across the Murang'a town area. It comprises a main backbone with several long lateral branches, numerous distribution transformers, and 94 distinct load points. A summary of the network data is provided in Table I. The detailed line and load data for this proprietary network are available from the author upon reasonable request.

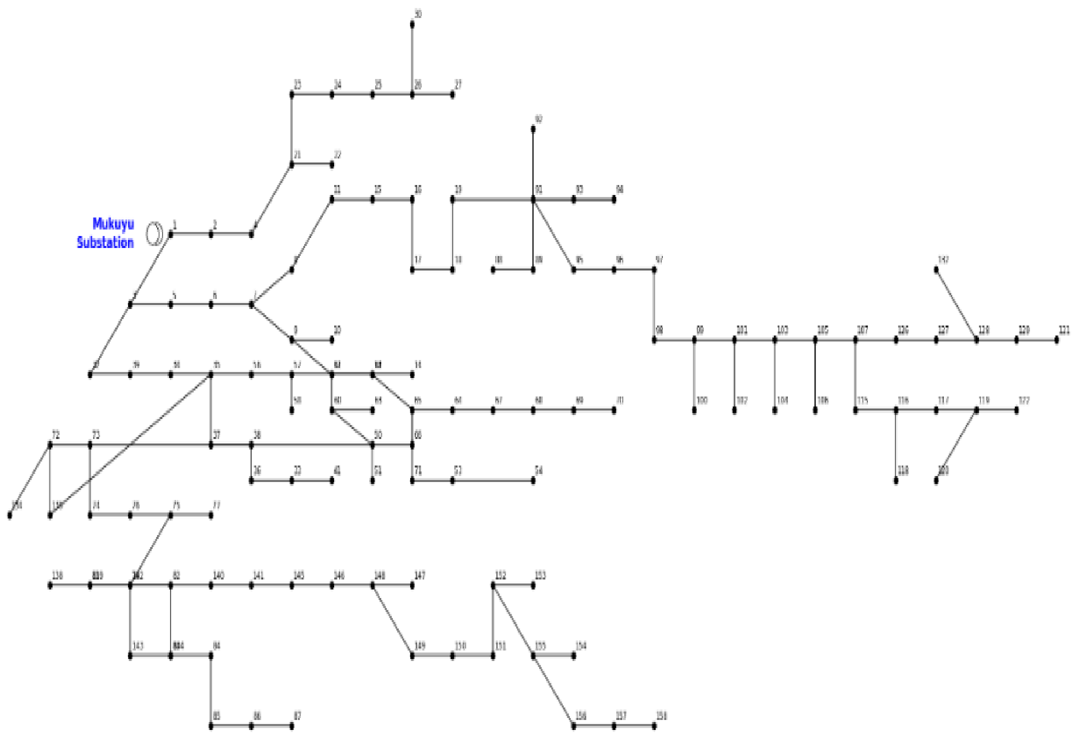

Figure 1: single-line diagram of the 253-bus feeder modeled in the etap environment.

Table I: Summary of Network Characteristics

Parameter	**Value**
Nominal Voltage Level	11 kv
Number of Buses	253 (158 MV, (94 LV)
Number of Branches	252
Total Feeder Length	~68 Km
Total Connected Load	2.304MW, 0.447Mvar
Conductor Types	ACSR (various sizes)

A baseline load flow analysis was performed in ETAP under peak load conditions ("Design Loading") to characterize its initial performance. The key metrics from the baseline analysis are summarized in Table II.

Table II: Baseline Feeder Performance

Metrics	**Value**
Total Feeder Load	2.304 MW, 0.447 Mvar
Total Real Power Loss	0.145 MW
Source Power Factor	96.2% Lagging
Minimum MV Bus Voltage	91.09% (at Bus 158)
Minimum System Voltage (LV)	88.6% (at Bus B140)

The analysis revealed a critical operational issue with a severe voltage drop at the far ends of the feeder, with the minimum LV network voltage at 88.6%, well below the standard acceptable limit of 95%. This justifies the immediate need for a voltage regulation solution.

III. OPTIMIZATION METHODOLOGY

To find the optimal capacitor configuration, a comprehensive methodology involving problem formulation and a PSO-based solution approach was developed.

A. Problem Formulation

The OCP problem involves minimizing an objective function subject to power flow equations and operational constraints.

1) Power Flow and Constraints: The total real power loss P_{loss} is calculated using the power flow solution. The voltage at each bus *i* must satisfy the operational limits:

$V_{\min spec} \leq V_i \leq V_{max}$(1)

Where; $V_{\min spec}$ and V_{max} were set to 0.94 P.U and 1.05 P.U respectively.

2) Objective Function: Total Annual Cost (TAC): To evaluate the economic viability of capacitor placement, the objective is to minimize the total annual cost function (TAC). This function balances the annual cost of energy losses against the investment and maintenance costs of the new capacitors. The function to be minimized is:

$minimize\ TAC = C_{loss} + C_{capacitor}$(2)

Where;

a) Annual Cost of Energy Losses (C_{loss}): This represents the cost of the energy dissipated as heat in the feeder's lines over a year.

$C_{loss} = P_{loss} * K_p * T$(3)

- P_{loss}: Total real power loss in kW (output from the ETAP load flow).
- K_p: Average cost of energy, assumed to be \$0.174/kWh.
- T: Total annual hours of operation (8760 hours/year).

b) Annual Cost of Capacitors ($C_{capacitor}$): This includes the initial purchase and installation costs (annualized over their lifespan) and their annual maintenance costs.

$C_{capacitor} = \sum\left(K_c * Q_{c,i} * +K_{om}\right)$(4)

for each installed capacitor *i=1 to N.*

- N: Total number of installed capacitors.
- K_c: Annualized capital cost per kVAR/year.
- $Q_{c,i}$: The reactive power rating of capacitor i in kVAR (e.g., 50, 100...).
- K_{om}: Annual operation and maintenance cost per capacitor bank/year

The optimization is subject to the voltage constraints in Eq. (1). These constraints are handled using a penalty method. The final fitness function to be minimized by the PSO is:

$fitness = TAC + penalty$ (5)

$Penalty = K_v * \sum\left\{max(0, V_i - V_{max})^2 + max\left(0, V_{\min spec} - V_i\right)^2\right\}$ (6)

Where K_v is a large penalty constant.

3) Decision Variables and Search Space:

- Number of Capacitors: Six capacitor banks.
- Candidate Locations: A pre-qualified list of 13 high-impact buses.
- Available Sizes: {50, 80, 100, 150, 200} kVAR.

B. Particle Swarm Optimization (PSO) Approach

1) Justification for PSO: PSO was chosen for its conceptual simplicity, ease of implementation, and fast convergence speed, which is advantageous for computationally intensive problems involving repeated power flow simulations [6, 7].

2) PSO Framework and Enhancements: The algorithm uses the standard velocity and position update equations. To prevent premature convergence, a linearly decreasing inertia weight (w) was employed, decreasing from 0.9 to 0.4 over the iterations.

$$V_i(t+1) = \omega * V_i(t) + c_1 * r_1 * \left(P_{best\ i} - x_i(t)\right) + c_2 * r_2 * \left(g_{best} - x_i(t)\right) \quad (7)$$

$$x_i(t+1) = x_i(t) + V_i(t+1) \quad (8)$$

C. PSO-ETAP Integration Framework

The PSO algorithm was implemented in Python, with ETAP serving as the power flow engine in a simulation-in-the-loop configuration, as illustrated in Figure 2.

The flowchart illustrates a complete workflow for optimizing capacitor placement the case study network using Particle Swarm Optimization (PSO) integrated with ETAP software.

The process begins by loading the electrical grid model from ETAP, selecting potential locations for the capacitors, and defining the PSO algorithm's parameters. An initial random set of solutions (particles) is then created.

The Iterative Optimization Loop is the core of the process. In each cycle, every potential solution is simulated in ETAP to calculate its impact on power loss and voltage. A cost function evaluates how "good" the solution is. Based on this feedback, the algorithm intelligently updates and improves all the solutions, getting closer to the optimal one with each loop.

The loop continues until a stopping criteria (e.g., a maximum number of iterations) is met. Once the best solution is found, it is validated one last time, and a final report is generated to show the improvements in voltage, the reduction in power loss, and the overall cost-benefit analysis.

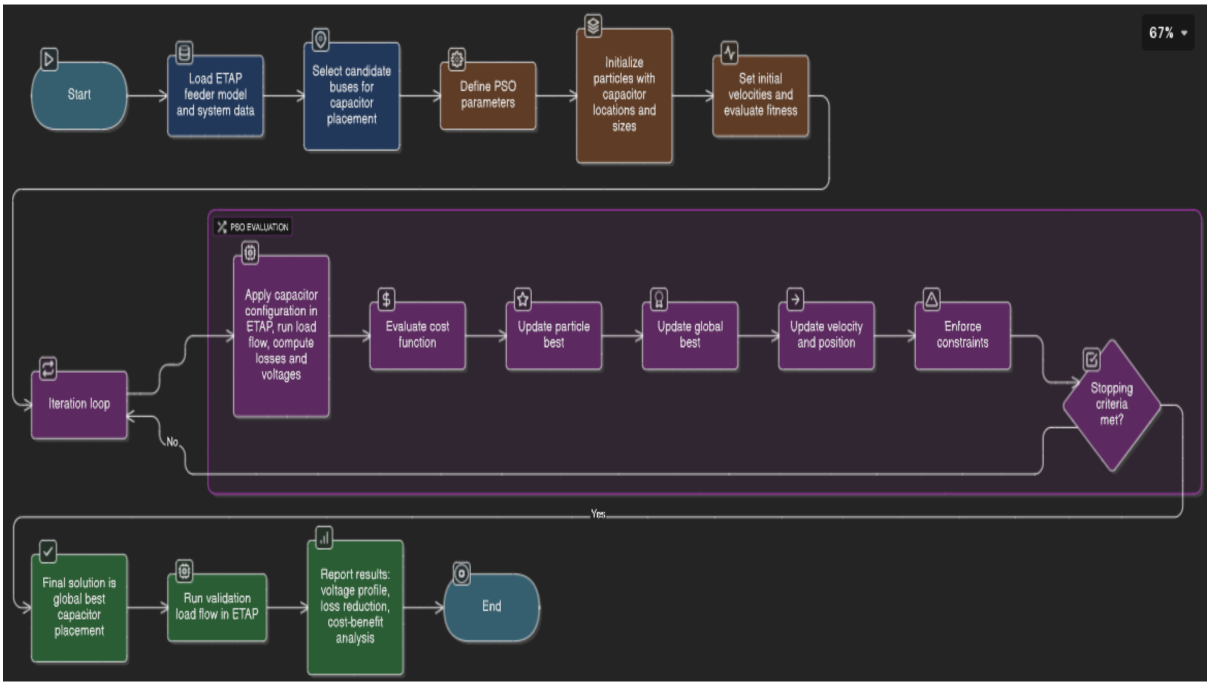

Figure 2: flowchart of the pso-etap integrated optimization process.

IV. RESULTS AND DISCUSSION

A. PSO Convergence

The PSO algorithm successfully converged to a stable, optimal solution. The convergence characteristic, plotting the global best fitness score (total annual cost from Eq. 5) at each iteration, is shown in Figure 3. The final optimal fitness value corresponds to the minimized annual cost while satisfying all voltage constraints.

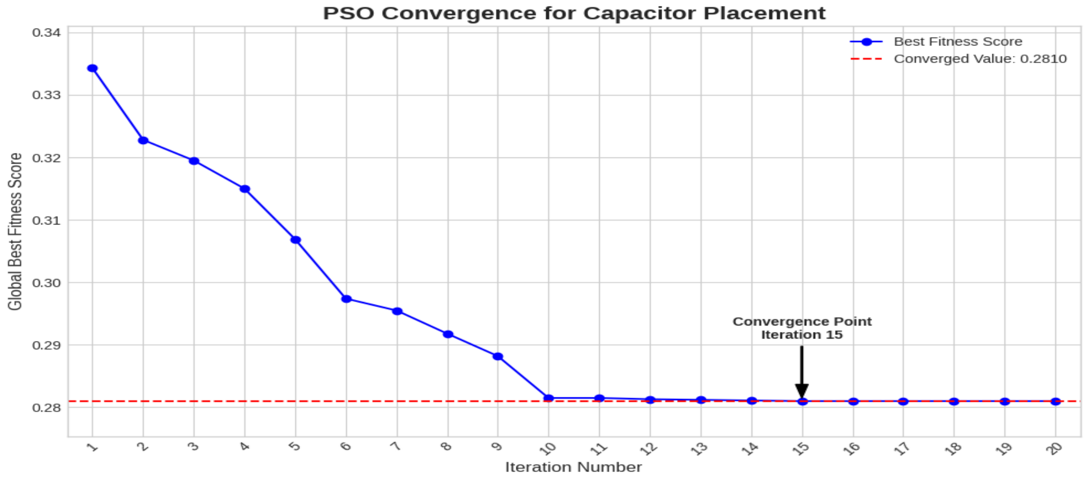

Figure 3: global best fitness score (annual cost) at the end of each iteration.

B. Optimal Solution

The PSO converged on the optimal solution shown in Table III, involving six capacitor banks totaling 660 kVAR.

Table III: Optimal Capacitor Placement via PSO

Location	Size (kVAR)
Bus 20	80
Bus 22	80
Bus 31	150
Bus 33	150
Bus 90	100
Bus 91	100
Total	**660**

C. Comparative Performance Analysis

The implementation of the PSO-derived capacitor placement resulted in a dramatic improvement in the feeder's performance as calculated below. The electricity price for businesses is KES 22.440 kWh or USD 0.176. These retail prices were collected in March 2025 and include the cost of power, distribution and transmission, and all taxes and fees [14].

1. Annual Cost of Losses

Annual Cost of Losses ($) = Real Power Loss (kW) × 8760 hours/year × $0.176/kWh (9)

✓ Baseline Case:
145 kW × 8760 hours × $0.176/kWh = $223,804.80

✓ Optimized Case:
103 kW × 8760 hours × $0.176/kWh = $158,958.08

✓ Improvement (Savings):
$223,805 (Baseline) - $158,958 (Optimized) = $64,847

The annual savings from reduced energy loss are $64,847.

2. Annual Capacitor Cost.

Annual Capacitor Cost ($) = (Total kVAR × Cost per kVAR) + (Number of Banks × O&M Cost per Bank)

✓ Baseline Case: $0

✓ Optimized Case: (660 kVAR × $3.00) + (6 banks × $100) = $1,980 + $600 = $2,580

✓ Improvement (Investment): The new annual cost is $2,580.

3. Net Annual Savings

Net Annual Savings ($) = (Savings from Loss Reduction) - (Annual Capacitor Cost)

✓ Baseline Case: Not applicable (-).

✓ Optimized Case:
$64,847 (Savings) - $2,580 (Investment) = $62,267
The new net annual savings are $62,267.

A comparison between the baseline and optimized cases is presented in Table IV.

Table IV: Comparison of Feeder Performance

Metric	Baseline Case	Optimized Case	Improvement
Minimum System Voltage	88.6%	94.36%	+5.76% (Absolute)
Real Power Loss (MW)	0.145 MW	0.103 MW	28.9% Reduction
Source Power Factor	96.2% Lag	99.87% Lag	Corrected to near unity
Annual Cost of Losses	$223,805	$158,958	$64,847 Savings
Annual Capacitor Cost	$0	$2,580	$2,580 Investment
Net Annual Savings	-	$62,267	-

The results clearly indicate the primary objectives were achieved. All voltage violations were eliminated. The optimized placement yielded a significant co-benefit of a 28.9% reduction in real power losses. From an economic standpoint, the solution provides net annual savings of $62,267 demonstrating a strong business case for the investment.

The voltage profile improvements are as shown in Fig. 4 (MV network) and Fig. 5 (LV network). The shaded "Voltage Improvement Area" in both figures visually quantifies the substantial voltage uplift.

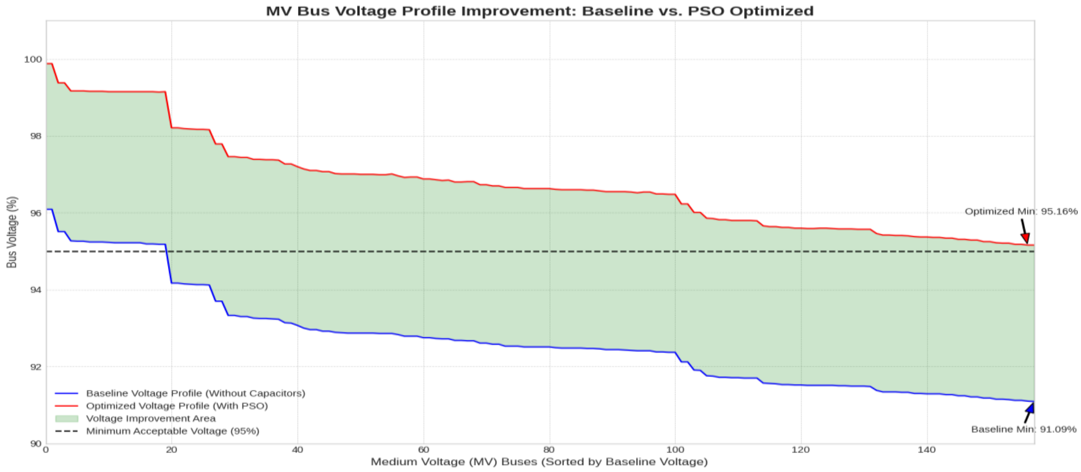

Figure 4: medium voltage (mv) network voltage profile improvement.

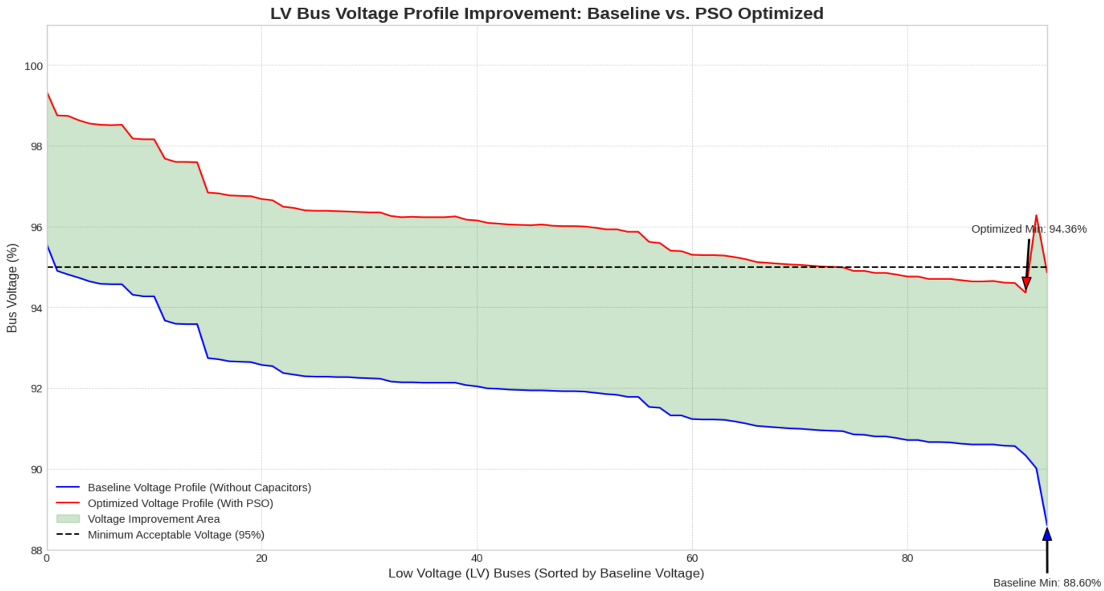

Figure 5: low voltage (lv) network voltage profile improvement.

V. CONCLUSION

This paper successfully demonstrated the application of a Particle Swarm Optimization algorithm for solving the optimal capacitor placement problem on a real-world, 253-bus distribution feeder. By minimizing a total annual cost function subject to strict operational constraints, the PSO was able to identify a configuration that holistically improves feeder performance from both a technical and economic perspective. The PSO-derived solution eliminated critical undervoltage conditions, substantially reduced real power losses by 28.9%, and yielded an estimated net annual saving of over $62,267.

This study validates the use of PSO integrated with industry-standard software like ETAP as a powerful tool for distribution system planning. The work addresses a notable gap in the literature by moving beyond standard test systems to tackle a complex, practical problem with a clear economic driver, thereby providing a valuable reference for utility engineers and power system researchers.

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