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Simultaneous Network Reconfiguration and Capacitor Placement in Distribution Systems Using the Proposed Discrete PSO Algorithm with Chaos Module

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Abstract

In this study, a simultaneous optimization method is proposed for distribution network reconfiguration in the presence of harmonic disturbances, along with determining the optimal size and location of switchable capacitors. The main objectives are to reduce active power losses and improve voltage profiles while considering operational constraints and power quality. The optimization objective function includes active power loss costs, capacitor installation costs, and penalty terms for constraint violations. To enhance convergence speed and optimization accuracy, candidate buses for capacitor placement are selected using sensitivity analysis, and the search space is efficiently reduced. The proposed algorithm is a novel Discrete Particle Swarm Optimization (PSO) with chaos module (PSOCM), which delivers fast and superior results compared to conventional methods. The applied constraints include the maximum allowable reactive power of installed capacitors and bus voltage limits according to the IEEE-519 standard. The algorithm is implemented on the Sirjan distribution network, and the results demonstrate significant performance improvements.

1. Introduction

The installation of shunt capacitors in distribution networks is generally one of the most effective methods for reducing power losses in distribution systems. Capacitor placement is also used for reactive power compensation, voltage regulation, and power factor correction. The effectiveness of compensation largely depends on the capacitor's location within the distribution system. Therefore, determining the optimal placement, sizing, and type of capacitors in the distribution network is essential [1-2].

Distribution network reconfiguration is another effective method for loss reduction. Medium-voltage distribution networks are typically designed with a loop structure but operated radially. These networks contain normally closed switches and several normally open switches that can be reconfigured to achieve an optimal radial configuration, thereby reducing losses while improving bus voltage profiles. Numerous techniques with various approaches have been proposed for optimal capacitor placement [3-4] and distribution network reconfiguration [5-9]. Some studies have addressed simultaneous reconfiguration and capacitor placement [10-15]. In [10], the status of capacitors and network branches is modified using an ant colony algorithm, ultimately determining which branches should remain open upon convergence. In [12] a P-PSO algorithm is employed to capacitor placement and reconfiguration in the presence of non-linear loads. In [13], an improved adaptive genetic algorithm is employed for optimal capacitor placement as the primary objective. Although the evaluation of the results indicates that the condition of preventing loop formation in the reconfiguration process has not been met. In [14], simultaneous reconfiguration and capacitor placement are performed using a binary genetic algorithm, considering different load patterns to reduce losses; however, a closer examination reveals that the radiality constraint was not strictly enforced.

While most of these techniques are computationally fast, their main weakness lies in their susceptibility to local optima. To date, the simultaneous optimization of network configuration and capacitor placement considering harmonic loads has not been adequately addressed. This paper presents a comprehensive approach that incorporates harmonic conditions under varying load levels in the network. The methodology first performs optimal capacitor placement with the objective of loss reduction while adhering to voltage magnitude constraints. Subsequently, the same optimization is conducted simultaneously with network reconfiguration to determine the optimal system configuration.

Given the inherent complexity of this optimization problem, a novel two-layer Particle Swarm Optimization (PSO) algorithm is proposed. This innovative approach enhances particle diversity and significantly improves the algorithm's ability to avoid premature convergence to local optima, thereby ensuring more robust and globally optimal solutions. The proposed optimization method is similar to the one suggested in [15], with the difference that the chaos generation mechanism in particles has been enhanced, further reducing the likelihood of getting trapped in local optima. The rest of the paper is organized as follows. In section 2 problem formulation consist of objective function and constraints formulations are presented. Section 3 Describes how to implement PSOCM method. The implementation method of the reconfiguration process is described in Section 4. Simulation scenarios and results are provided in section 5 and section 6 discusses the results and concludes the paper.

2. Problem Formulation

This section presents the mathematical formulation of the problem, including the objective function, problem constraints, and the power flow calculation framework.

2.1. Objective Function and Problem Constraints

The primary objectives of optimal network reconfiguration and capacitor placement are to determine:

1.The optimal network configuration

2.The optimal locations and sizes of capacitor units in the distribution system

3.The minimization of energy losses and active power losses at both fundamental and harmonic frequencies

The capacitor placement objective function to be minimized is formulated as follows:

$$F = K_e T P_{loss} + K_p P_{loss} + \sum_{j=1}^{nc} C_j B_j + \alpha \sum_{i=1}^{n} |(1 - V_i)| \tag{1}$$

In equation (1), ke and kp represent the constant cost coefficients of energy losses and power losses respectively and Bj and Cj denote the available capacitor kVAr and the cost coefficient per kVAr of capacitors installed at each candidate bus, respectively. This function consists of the sum of four components: power loss cost, energy loss cost, capacitor installation cost, and a voltage violation penalty to maintain maximum voltage regulation.

Candidate buses are determined through sensitivity analysis [16].

Capacitor Unit Constraints: The total installed capacitor units are also constrained by the following equation:

$$\sum_{j=1}^{nc} B_j < B \tag{2}$$

Typically, B is selected as the sum of reactive power loads connected to the studied network.

For the network reconfiguration problem, the following constraints are applied:

1. Fixed number of system branches (the total number of lines remains constant)

2. Radial topology preservation (the network must maintain a radial structure after reconfiguration).

2.2. Power Flow Calculations

template, prepare your technical work in single- For distribution system analysis, a specialized power flow algorithm is required to determine power losses and bus voltages at the fundamental frequency. This study employs the backward-forward sweep method, specifically designed for radial distribution systems.

Implementation Steps:

1.Formation of BIBC Matrix: A three-phase Bus Injection to Branch Current (BIBC) matrix is constructed based on the system's topological structure. This matrix establishes the relationship between bus current injections and branch currents

2.Iterative Voltage Calculation: All bus voltages are computed through an iterative process using the BIBC matrix. The voltage at each three-phase bus during the k-th iteration is calculated using Equation (3) [17]:

$$[V]^k = [V_0] - [BIBC]^T[Z][BIBC][I]^{(k)} \quad (۳)$$

Where:
- $[V]^{(k)}$: Vector of bus voltages at iteration k
- V_0: Vector of slack bus voltages (reference node)
- [BIBC]: Bus Injection to Branch Current matrix (topology-based current distribution mapping)
- [Z]: Primitive impedance matrix (includes line impedances and mutual couplings)
- $[I]^{(k)}$: Load current vector at iteration k (calculated from power demands and voltages)

3. PSO Algorithm

PSO is an optimization technique designed to solve complex optimization problems. The fundamental concept relies on generating a random population where each individual, called a "particle," represents a potential solution. Each particle dynamically adjusts its position and velocity in the search space based on: Its own flight experience (cognitive component) and the collective knowledge of neighboring particles (social component)

3.1. Basic PSO Algorithm

current solution coordinates of particle i, Particle Velocity is defined as: $V_i=(V_{i1}, V_{i2},\dots, V_{iD})$ Determines the direction and magnitude of movement. $P_i=(P_{i1}, P_{i2},\dots, P_{iD})$ is best position found by particle i so far. $P_g=(P_{g1}, P_{g2},\dots, P_{gD})$ is best position found by the entire swarm.

At each iteration k+1, velocity and position update as [18]:

$$(t+1) = V_{id}(t) + c_1 r_1 \left(P_{id}(t) - X_{id}(t)\right) + c_2 r_2 \left(P_{gd}(t) - X_{id}(t)\right) \quad (4)$$

$$X_{id}(t+1) = X_{id}(t) + V_{id}(t+1) \quad (5)$$

c_1 and c_2 are acceleration constants controlling cognitive and social influence and r_1 and r_2 are uniformly distributed random numbers $\in$ [0,1]. Particle velocities are constrained by V_{max} to prevent overshooting. For capacitor placement and switch status optimization: Binary representation for capacitor units (0=absent, 1=present) Switch states (0=open, 1=closed). When minimizing objective function f in D-dimensional space, particle ii updates its position at iteration t+1 as:

$$P_i(t+1) = \begin{cases} X_i(t+1) & if\ f\left(X_i(t+1)\right) < f(\ P_i(t)) \\ P_i(t) & other\ wise \end{cases} \quad (6)$$

3.2. Proposed PSO Algorithm

Here, to better control the exploration and exploitation capabilities, the parameter ω depends on the fitness of the particles (rather than time). Therefore, particles with lower fitness are assigned lower velocities to aid exploitation, while particles with higher fitness values are assigned higher velocities, guiding them towards greater exploration. The velocity of the i-th particle is calculated as follows:

$$\omega_i = (\omega_{max} - \omega_{min}) * G_i + \omega_{min} \quad (7)$$

ω_{max} and ω_{min} are the maximum and minimum velocity values, respectively, equal to 0.9 and 0.4. The fitness G_i is normalized as follows:

$$G_i = \frac{f(P_i) - f_{min}}{f_{max} - f_{min}} \quad (8)$$

f_{max} and f_{min} represent the maximum and minimum fitness values of the personal experience of each particle in the population. According to Equation (8), G_i decreases for a particle with lower fitness and vice versa. Finally, the velocity V_i of the ith particle is updated as follows:

$$V_{id}(t+1) = \omega_i V_{id}(t) + c_1 r_1 \left(P_{id}(t) - X_{id}(t)\right) + c_2 r_2 \left(P_{gd}(t) - X_{id}(t)\right) \quad (9)$$

P_k represents the best personal experience among the neighboring particles in the vicinity of the ih particle. N_i is the number of particles in the neighborhood, c_k is the acceleration coefficient, which is uniformly distributed among the neighboring particles as ($c_k = c/|N_i|$), where c = 4.1, and r_k is a random number in the range [0, 1].

3.2.1. Proposed Chaos module

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This module prevents premature convergence by introducing controlled chaos when optimization stagnates (no improvement for 5 or more iterations).

Counter f_c increments by 1 each iteration if no fitness improvement occurs and triggers disturbance when f_c>m (threshold m = 5).

Perturbation Process:

- Randomly select 10%–50% of dimensions (D) from the global best solution (P_g).
- Modify selected dimensions using:

$$P_{\text{g-disturbed}} = P_g + \sigma \cdot N(0'1) \cdot I_{selected} \quad (10)$$

All paragraphs must be indented. All paragraphs must be justified, i.e. both left-justified and right-justified.

Where:

σ: Scaling factor (0.4).

(0,1): Standard Gaussian noise.

I_selected: Binary mask (1 for selected

dimensions, 0 otherwise).
Here, since the presence or absence of each capacitor unit and the open/closed status of each line switch are determined using binary values (0 and 1) respectively, Binary PSO is employed. In this approach, whenever the particle's position is updated, it is converted to binary form using the following sigmoid function:

$$\mathrm{Sigmoid}\left(P_{id}{}^{k}\right) = \frac{1}{1+e^{-P_{id}{}^{k}}} \quad (11)$$

$$P_{id}{}^{k} = \begin{cases} 1 & \text{if rand} < S\left(P_{id}{}^{k}\right) \\ 0 & \text{other wise} \end{cases} \quad (12)$$

4. Reconfiguration Process

To increase the speed and quality of optimization, appropriate tools have been used wherever possible. In the case of capacitor placement, candidate buses are determined using sensitivity analysis. For the reconfiguration process, if the status of all network switches were to be determined solely by optimization under the constraint of maintaining a radial network, the search space would become excessively large, reducing the likelihood of reaching an optimal solution. Therefore, to reduce the search space, first, switches whose status must clearly remain closed are eliminated from the problem's solution space. That is, switches feeding end buses must definitely remain closed and are not considered as unknowns in the problem.
However, in most conventional methods, a potential solution is not considered valid until it passes the radiality test, which itself hinders the speed and accuracy of optimization. In this paper, a method of dividing the network into different loops is used, the details of which are presented in [19]. Each loop consists of one normally open switch and several normally closed switches. Then, following, the loop spreading matrix and the T-node degree method are employed to ensure that the resulting configuration from optimization is radial and supplies all buses in the system. The flowchart of the proposed method for solving the problem is shown in Figure 1.

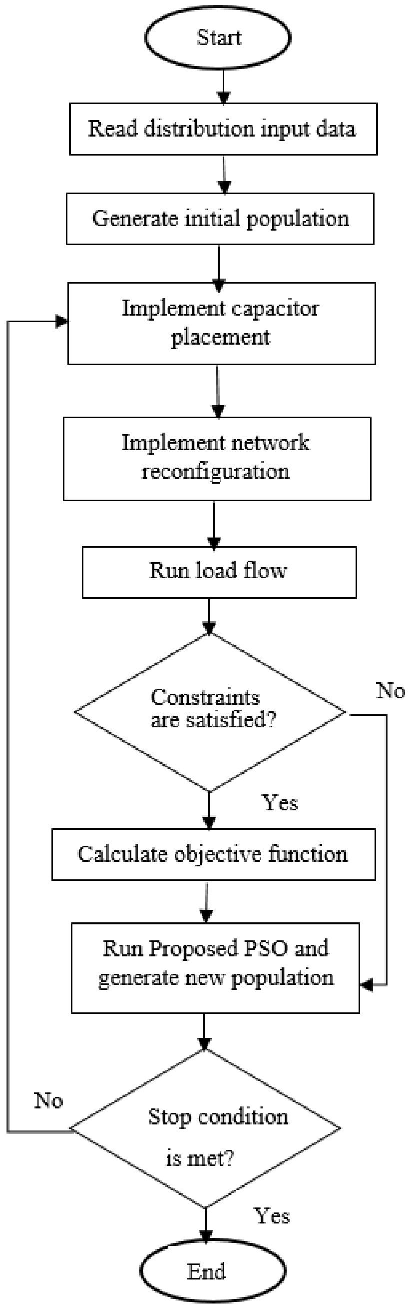

Figure 1: Flowchart of the proposed method

5. Numerical Results

The effectiveness of the proposed method for simultaneous reconfiguration and capacitor placement in the distribution network is demonstrated using the 77-bus Sirjan network (figure 1), whose load and line specifications are provided in [14].

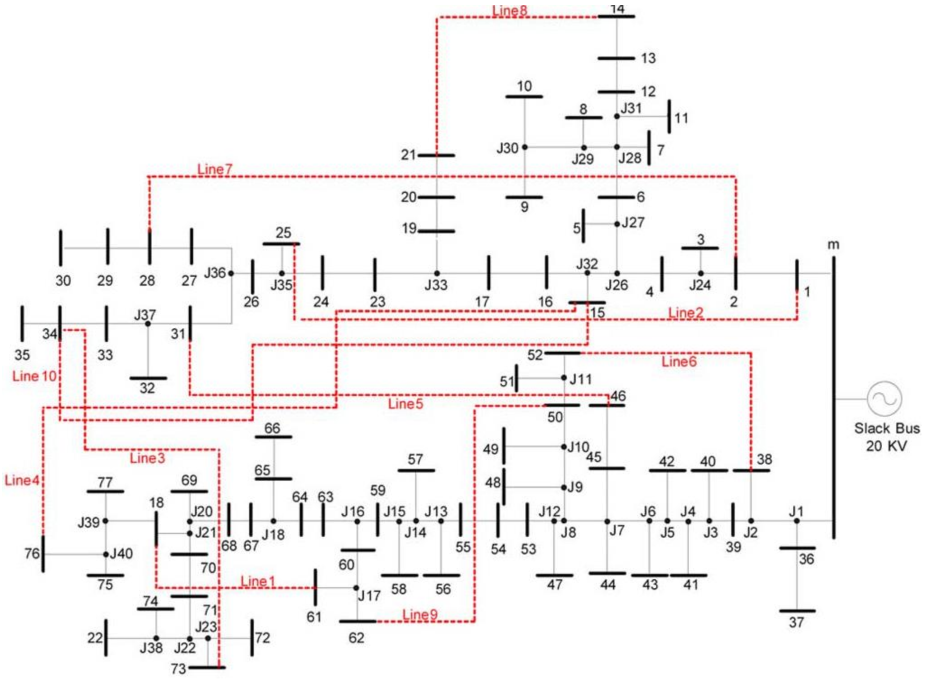

Figure 2: Single-line diagram of the 77-bus Sirjan distribution network

Table 1: Capacitor Units (in kVAR) and Their Cost Coefficients (in $/kVAR)

Capacitor (kVAR)	**150**	**300**	**450**	**600**	**750**	**900**	**1200**	**1350**
Cost Coefficient ($/kVAR)	0.5	0.35	0.253	0.22	0.276	0.183	0.17	**0.207**

The network consists of 114 normally closed switches (numbered) and 10 normally open switches, with their corresponding lines labeled as $Line_1$, $Line_2$, …, $Line_{10}$.

Using sensitivity analysis, the most sensitive buses in the system are identified as Buses 76, 75, 42, 59, 39, 38, 37, 24, 11, and 9.

To demonstrate the effectiveness of the proposed method for simultaneous network reconfiguration and capacitor placement, as well as the capability of the proposed optimization technique, six different cases are implemented on the Sirjan network. The coefficient K_p in Equation (1) is set to 150 according to reference [12], while the value of K_e is considered as a variable based on reference [20]. Optimization is performed using the proposed method in all cases except Case 4:

Case 1: Network reconfiguration only
Case 2: Capacitor placement only
Case 3: Reconfiguration followed by capacitor placement
Case 4: Simultaneous optimal capacitor placement and network reconfiguration using standard PSO
Case 5: Simultaneous optimal capacitor placement and network reconfiguration using the proposed method

Table 2: Network Reconfiguration Results

Case	**Switches to be Opened**
Cases 1 & 3	12-13, 15-32j, 16-17, 27-28, 31-36j, 7j-8j, 9j-10j, 63-16j, 70-71, Line1

Case	Switches to be Opened
Case 4	12-31j, 15-32j, 24-35j, 26-35j, 31-36j, 7j-8j, 9j-10j, 17j-61, 64-18j, 18-21j
Case 5	12-13, 15-32j, 18-21j, 26-35j, 27-28, 50-10j, 67-18j, 7j-8j, 4-26j, 18-39j

Table 3: Program Execution Results

Parameter	Before Compensation	Case 1	Case 2	Case 3	Case 4	Case 5
Minimum Bus Voltage (pu)	0.944	0.998	0.987	0.998	0.998	0.998
Maximum Bus Voltage (pu)	0.998	1.000	1.000	1.000	1.000	1.000
Active Power Loss (kW)	229.443	201.85	208.00	196.00	192.00	

The available capacitor units and their cost coefficients considered in the objective function are listed in Table 1.

The coefficient α in the term included in the objective function to enhance voltage regulation is set to 10,000. For the optimization process, the population size is set to 50 and the maximum iterations to 100. The results obtained from running the program are presented in Tables 2 and 3. The parameters for conventional PSO are set as follows: c_1 and c_2 equal to 1.99 and 2.05 respectively, r_1 and r_2 are random numbers between 0 and 1, the maximum velocity is set to 1.05, and the population size is 50. Table 2 shows the results of the network reconfiguration program execution. According to Table 3, standalone capacitor placement (Case 2) improves voltage but remains below optimal (0.987 pu min). Combined approaches show better voltage profile improvement. proposed method achieves optimal voltage profile (0.998-1.033 pu), Lowest power losses (177 kW) and 23% reduction compared to base case.

Table 4: Capacitor kVAR Allocation at Candidate Buses

Bus Number	76	75	42	59	39	38	37	24	11	9	Total
Case 2	1050	-	-	900	1650	-	-	1650	-	-	5250
Case 3	300	-	600	-	900	600	300	600	450	900	4650
Case 4	300	-	750	1050	-	600					

The results demonstrate that implementing simultaneous network reconfiguration and capacitor placement reduces the total required kVAr capacity compared to standalone capacitor placement. This reduction is particularly significant when using co-optimization, which harmonizes both network topology and capacitor values for optimal performance. The proposed method achieves faster convergence speed (reduced iteration count) and higher solution quality (improved objective function values). The convergence characteristics are visualized in Figure 3.

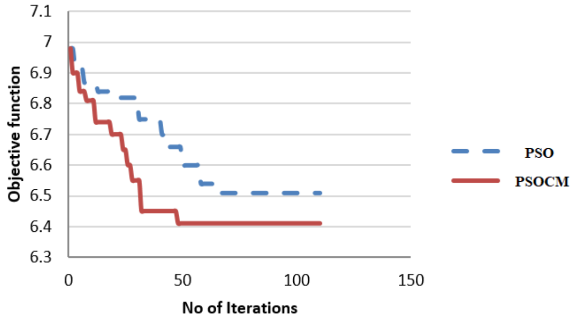

Figure 3: Convergence Comparison Between the PSO and PSOCM

6. Conculusion

Implementation on the 77-bus Sirjan test system proves the algorithm's practical effectiveness, delivering simultaneous improvements across three critical aspects: 23% reduction in power losses, voltage profile enhancement within 0.998-1.00 pu range, and 11.4% decrease in required capacitor investment (4650 kVAr vs 5250 kVAr). The coordinated optimization of capacitor placement and network reconfiguration yields solutions that properly balance technical and economic objectives.

The results demonstrate that the proposed chaotic-enhanced PSO algorithm successfully overcomes the limitations of conventional optimization approaches in solving complex distribution network problems. By intelligently integrating chaotic search mechanisms with sensitivity analysis and loop-based network partitioning, the method achieves superior performance in both solution quality and computational efficiency. These improvements stem from the algorithm's adaptive search strategy that dynamically adjusts exploration/exploitation balance while maintaining feasible radial configurations through innovative constraint-handling techniques.

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