

Harmony Search-Based Integrated Optimization of Distribution Networks Considering Feeder Reconfiguration, Capacitor Placement, and DG Allocation

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Abstract-- The optimization of distribution networks to minimize power losses and enhance voltage profiles remains a critical challenge in the design and operation of power systems. This study proposes an integrated optimization framework that simultaneously addresses network reconfiguration, optimal capacitor placement, and distributed generation (DG) allocation. The primary objective is to reduce active power losses and improve voltage quality by optimizing network topology and equipment deployment. To solve this problem, the Harmony Search Algorithm (HSA) is employed as an efficient metaheuristic method with strong adaptability to the nonlinear and combinatorial nature of distribution systems. The proposed model is implemented in MATLAB using the standard IEEE 33-bus test system. Simulation results demonstrate that the simultaneous application of network reconfiguration, capacitor placement, and DG integration achieves a significant reduction in power losses by up to 88.8% and voltage deviation by up to 47.9%, compared to the base case. These findings confirm the effectiveness of the proposed HSA-based framework in optimizing distribution network performance. The outcomes of this research can serve as a practical decision-support tool for distribution system operators, ultimately contributing to improved operational efficiency and economic benefits.

Index Terms-- Distribution network, Network reconfiguration, Capacitor placement, Distributed generation (DG), Harmony Search Algorithm (HSA)

I. INTRODUCTION

The power system is acknowledged as one of the largest and most complex industries worldwide [1]. This system encompasses the generation, transmission, and distribution of electrical energy, while simultaneously meeting stringent security standards and maintaining high reliability, all while minimizing costs and environmental impacts [2]. The inherent complexity of power systems arises from the interactions among physical, cyber, and human layers, which has motivated the use of complex network theory to analyze system robustness and resilience [3].

Given the critical role of power systems in modern society and the ongoing transformations driven by increased interconnectivity between communication and energy networks, new challenges have emerged in system monitoring and control [4].

Loss reduction in power systems is a critical issue for national economies. Rising generation and fuel costs in power plants have driven electrical system planners toward designing networks with minimum power losses. From an economic perspective, optimizing power systems to reduce losses is of great importance. Research indicates that, in addition to

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expanding generation capacity, significant attention must be paid to reducing losses in transmission and distribution networks.

The importance of this issue is evident in various countries where power losses and their associated economic values are systematically evaluated. For instance, in Iran's power industry, losses in transmission and distribution lines account for approximately 18.23% of the net electricity generated by power plants. Reducing these losses leads to lower operational costs and contributes to environmental preservation [5].

The majority of power losses occur in the distribution sector, accounting for nearly 75% of total system losses [6]. Consequently, extensive research efforts have focused on reducing distribution network losses using methods such as network reconfiguration, installation of distributed generation (DG) units, capacitor placement, and voltage level enhancement. The optimal application of these techniques can result in substantial loss reduction.

Distribution network reconfiguration is one of the key automation functions that enhances system reliability and power quality in distribution networks at relatively low cost [7]. This process is performed by changing the status of switches and modifying feeder topologies. System operators can adapt the network structure to load demand variations through switch operations, leading to load balancing, overload mitigation, and loss reduction. Moreover, under fault conditions, network reconfiguration can minimize the outage area and enable rapid service restoration after fault clearance.

Network reconfiguration is inherently a multi-objective optimization problem, with primary objectives typically including loss minimization, load balancing, voltage profile improvement, and service restoration [8]. Various studies have addressed objectives such as loss reduction and performance enhancement [9], load balancing [10], and service restoration [11]. Transferring heavily loaded sections to adjacent feeders during reconfiguration improves voltage drop conditions and reduces losses. This process enhances load balance and power quality, as documented in several studies focusing on loss reduction [12]–[16] and load balancing in distribution and sub-transmission systems [17].

Transformer load redistribution and voltage optimization address issues such as feeder overloading and excessive losses, while ensuring transformer loading security [18]. Additionally, reconfiguration contributes to voltage deviation reduction, and incorporating voltage-dependent load models provides more flexible and realistic solutions [19]–[20]. Overall, distribution network reconfiguration plays a significant role in improving system performance, reducing losses, and mitigating voltage deviations.

Capacitors play a crucial role in reducing power losses and voltage deviations in distribution networks. Various optimization algorithms, such as the Remora Optimization Algorithm (ROA) [21], Dingo Optimization Algorithm (DOA), and comparative analyses of DG and capacitor compensation [22], have been proposed for optimal capacitor allocation. Studies demonstrate that optimal capacitor placement can reduce real and reactive power losses by up to 35.20%, improve

voltage profiles [23], and enhance overall power quality.

The combined application of distribution network reconfiguration and optimal capacitor placement [24] further improves power loss reduction and voltage characteristics. Proper placement of network components based on load distribution, along with energy injection at high-loss buses, contributes significantly to loss minimization [25]. In this regard, a recent study employed the Cuckoo Search Algorithm (CSA) for the simultaneous optimization of network reconfiguration and capacitor placement, achieving improved voltage stability and a reduction in total power loss of up to 4.02% in the IEEE 33-bus distribution system [26]. These findings confirm that the effectiveness of capacitor placement and reconfiguration strongly depends on the accurate determination of both the location and capacity of the installed capacitors.

With the continuous growth in energy consumption within distribution systems, the demand for additional power supply has increased, leading to higher transmission losses and operational costs. The installation of distributed generation (DG) units has been recognized as an effective solution to address these challenges. DG units generate electricity at or near load centers, thereby reducing transmission losses and mitigating environmental concerns [27]–[28]. Furthermore, DG integration can relieve stress on the main grid and enhance overall system reliability [29]. DG units contribute to voltage profile improvement and loss reduction in distribution networks [30]–[32], and through voltage control, they enhance system operational performance [33].

Optimal placement of DG units plays a critical role in maximizing these benefits. The application of optimization algorithms such as genetic algorithms and particle swarm optimization for determining the optimal location and size of DG units has proven effective in reducing power losses and voltage fluctuations, thereby improving network efficiency [34]–[38]. Due to the combinatorial and nonlinear characteristics of network reconfiguration and DG integration problems, evolutionary optimization algorithms are particularly suitable for solving such complex optimization tasks.

Recent advances in telecommunications and the integration of Distributed Generators (DGs) have enabled effective Voltage and Reactive Power (Volt & Var) control using DGs, Static Var Compensators (SVCs), Load Tap Changers (LTCs), and Interruptible Loads (ILs), which can be optimized efficiently using metaheuristic algorithms such as Harmony Search Algorithm (HSA) [39].

Problem Statement, Research Gap, and Contributions of the Study

The integration of distributed generation (DG) units into distribution networks has a major influence on key operational decisions, including feeder reconfiguration, capacitor placement, and DG allocation. When these elements are optimally coordinated, they can significantly reduce power losses, improve voltage profiles, and increase overall system reliability. However, optimizing all three aspects at the same time creates a challenging mixed-integer nonlinear programming (MINLP) problem. The difficulty stems from the combination of discrete decisions (such as switch statuses and

locations) and continuous variables (DG and capacitor sizes), all of which must satisfy important operational constraints like maintaining a radial network structure, keeping bus voltages and branch currents within limits, and ensuring feasible power flow.

Although many studies have examined network reconfiguration, capacitor placement, and DG allocation—either separately or in pairs—relatively limited attention has been paid to their full simultaneous integration within a single unified framework. In addition, details regarding decision variable encoding, methods for enforcing radiality during optimization, and the statistical robustness of results are often not fully reported, making it difficult to reproduce or fairly compare different approaches.

To help address these limitations, this study proposes an integrated optimization model that simultaneously considers feeder reconfiguration, optimal capacitor placement (location and size), and DG allocation (location and capacity) in radial distribution networks. The Harmony Search Algorithm (HSA) is used to solve this problem, chosen for its proven ability to handle complex, nonlinear, and mixed-variable optimization tasks effectively.

The main contributions of this work are as follows:

- A unified formulation and solution framework that enables the simultaneous optimization of network reconfiguration, capacitor placement, and DG allocation.
- An HSA-based approach specifically adapted to the mixed discrete-continuous nature of the decision variables, including clear mechanisms for handling constraints such as radiality.
- A detailed scenario-based analysis that evaluates the individual contributions as well as the combined effects of the three strategies on the standard IEEE 33-bus test system.
- A comprehensive performance assessment focusing on active power loss reduction and voltage deviation improvement.

Overall, this framework provides a systematic and reproducible way to explore the synergistic benefits of the three planning actions and offers practical guidance for improving the operation and planning of distribution networks, especially those facing notable technical losses.

II. REVIEW OF PREVIOUS STUDIES

Distribution network reconfiguration, achieved by changing the status of sectionalizing and tie switches, is an economical

approach for power loss reduction. This method can be implemented without the need for new equipment, relying solely on existing infrastructure, with costs mainly limited to computational efforts and operational implementation. Compared to alternative loss reduction strategies that require substantial capital investment, distribution network reconfiguration is considered a cost-effective solution.

Although a large number of possible network configurations exist, many of them are technically infeasible due to operational constraints such as unacceptable voltage drops or feeder overloading. Optimization algorithms are therefore employed to identify optimal or near-optimal configurations based on criteria such as minimum energy loss and improved voltage profiles.

Metaheuristic optimization algorithms have attracted significant attention for solving reconfiguration problems due to their high computational efficiency and flexibility. Commonly applied methods include genetic algorithms [40]–[41], particle swarm optimization [42], ant colony optimization [43], tabu search [44], and the firefly algorithm [45].

In this study, the Harmony Search Algorithm is utilized to optimize the distribution network reconfiguration. Owing to its favorable convergence speed and multi-objective optimization capability, this algorithm effectively avoids entrapment in local optima.

Distribution networks, as one of the essential components of electric power systems, are responsible for delivering electrical energy to end consumers [46]. However, a considerable portion of the generated energy is lost within these networks due to technical losses, imposing substantial financial burdens on electric utility companies. To mitigate these losses and enhance voltage stability, various approaches have been proposed, including capacitor installation, integration of distributed generation (DG) units, demand-side management during peak load periods, and feeder reconfiguration in distribution networks [47].

The concept of distribution network reconfiguration for loss reduction was first introduced in 1975 by Back and Merlin. Their approach was based on the successive elimination of loops in a meshed distribution system, leading to a radial network structure with reduced power losses [48].

While these studies have made valuable contributions, relatively little attention has been given to the full simultaneous integration of reconfiguration, capacitor placement, and DG allocation with detailed constraint handling and statistical validation. This motivates the integrated HSA-based approach developed in the present study.

TABLE I
A Summary Of The Most Important Methods, Strategies, Objectives, And Key Findings Of Previous Studies.

Reference	Optimization Method	Network Reconfiguration	DG Installation	Capacitor Placement	Objective Function	Key Findings
[7]	Approximate switch exchange	✓	✗	✗	Power loss reduction	Development of an approximate formulation for loss reduction through switch exchange
[17]	Load balancing–based optimization	✓	✗	✗	Power loss reduction, load balancing	Incorporation of load balancing into reconfiguration objectives and improvement of the voltage profile
[49]	Genetic Algorithm (GA)	✓	✓	✗	Power loss reduction, voltage profile improvement	Significant loss reduction achieved by combining reconfiguration and DG integration

Reference	Optimization Method	Network Reconfiguration	DG Installation	Capacitor Placement	Objective Function	Key Findings
[50]	Cuckoo Search Algorithm	✓	✓	✗	Power loss reduction, voltage profile improvement	Enhanced network performance using the cuckoo search-based optimization approach
[51]	UVDA method	✓	✓	✗	Power loss reduction	Maximum loss reduction obtained through combined reconfiguration and optimal DG placement
[52]	Improved Genetic Algorithm	✓	✗	✓	Power loss reduction, voltage improvement	Voltage enhancement and loss reduction achieved through optimal capacitor allocation
This study	Harmony Search Algorithm (HSA)	✓	✓	✓	Power loss reduction, voltage deviation minimization	Simultaneous optimization of three strategies resulted in 88.8% loss reduction and 47.9% voltage deviation reduction

III. RESEARCH METHODOLOGY

Problem Definition and Proposed Framework

The objective of this study is the simultaneous optimization of distribution network reconfiguration along with the optimal allocation of distributed generation (DG) units and capacitor banks. The key decision variables of this optimization problem include the status of tie switches (open or closed), as well as the number, capacity, and installation locations of DG units and capacitors.

These decision variables can be represented in the form of a binary–continuous decision vector as follows:

$$X = [Tie_1, Tie_2, \dots, Tie_{N_{Tie}}, CapBus_1, CapBus_2, \dots, CapBus_{N_{Cap}}, MVAR_1, MVAR_2, \dots, MVAR_{N_{Cap}}, SW_1, SW_2, \dots, SW_{N_{Tie}}, P_{DG1}, P_{DG2}, \dots, P_{DGN_{DG}}] \quad (1)$$

In this representation, X denotes the vector of control variables. Tie represents the status (open or closed) of the tie switches in the network, and N_{Tie} is the total number of tie switches. $CapBus$ indicates the bus numbers selected for capacitor installation, while N_{Cap} denotes the number of installable capacitors. $MVAR$ represents the reactive power ratings of capacitors installed at each bus. SW_i denotes the indices of sectionalizing switches in the network. Finally, P_{DG} represents the active power output of the distributed generation units.

This section presents the mathematical formulation of the optimization problem, including the objective functions and operational constraints.

A. Objective Functions

This research considers two main objectives:

- Minimization of active power losses in the distribution network
- Minimization of voltage deviation at network buses

The ultimate goal is to determine the optimal system configuration that simultaneously reduces power losses and improves the voltage profile across all buses.

Combined Objective Function:

Since active power loss and voltage deviation are conflicting and dimensionally different quantities, they are combined into a single scalar fitness function using the weighted-sum method.

Each objective is first normalized by its corresponding base-case (uncompensated network) value, so that both terms are dimensionless and comparable in magnitude:

$$f(X) = w1 \cdot \left(\frac{F_1(x)}{F_1^0} \right) + w2 \cdot \left(\frac{F_2(x)}{F_2^0} \right) \quad (2)$$

where F_1^0 and F_2^0 denote the active power loss and voltage deviation of the base-case network, respectively, and $w1$ and $w2$ are the weighting coefficients satisfying $w1 + w2 = 1$. This normalization removes the dimensional inconsistency between the two objectives and enables their simultaneous optimization within a single scalar fitness function.

The weighting coefficients were selected to reflect the relative importance of the two optimization objectives. Since active power loss has a direct impact on the operational efficiency and economic performance of the distribution system, whereas voltage deviation primarily represents a power-quality criterion, a greater weight was assigned to the power-loss objective.

Active Power Losses:

In distribution systems, feeder lines are typically modeled as short lines. First, the current flowing through each branch is calculated, and then the total system losses are evaluated using the following expression:

$$F_1(x) = \sum_{i=1}^{N_b} R_i |I_i|^2 \quad (3)$$

where N_b denotes the number of network branches, and R_i and $|I_i|$ represent the resistance and the RMS current magnitude of branch i , respectively [53].

Voltage Deviation of Network Buses:

The second objective function represents the voltage deviation at the network buses and is defined as:

$$F_2(x) = \text{Max}_i |V_i - V_{rate}| \quad (4)$$

where V_{rate} is the rated (nominal) bus voltage, and V_i denotes the actual voltage magnitude of bus i [54].

B. Optimization Constraints

Radiality and Connectivity Constraint:

During the distribution network reconfiguration process, it is

C. Base Case (Initial System without Optimization)

In this scenario, the IEEE 33-bus network is considered in its original configuration, without any DG units or capacitor installation. This scenario serves as a reference for comparison with other cases. The total active power loss in this case is 0.2027 MW, and the voltage deviation is approximately 0.0695 p.u. The network comprises 33 buses and 32 lines, operating at a base voltage of 12.66 kV, configured radially with multiple sectionalizing switches and feeders to ensure standard operational conditions.

The initial network configuration corresponding to the base case is depicted in Fig. 2.

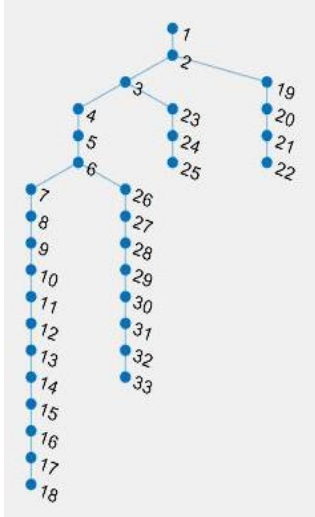


Fig. 2. The network configuration of the base case.

D. Scenario 1: Distribution Network Reconfiguration

In this scenario, only network reconfiguration is performed. The optimal open switches are 7, 14, 21, 24, and 29. As a result, the active power loss is reduced to 0.1485 MW (a 26.7% reduction), and the voltage deviation decreases to 0.0672 p.u. This improvement is mainly attributed to the redistribution of power flows among the feeders, which results in a more balanced feeder loading and reduced branch currents, thereby lowering the overall losses of the network. The resulting network topology after Scenario 1 is illustrated in Fig. 3.

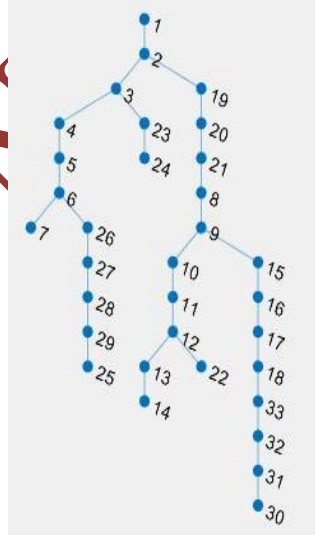


Fig. 3. The network configuration after Scenario 1.

E. Scenario 2: Reconfiguration with Capacitor Placement

In addition to network reconfiguration, four capacitors with ratings of 1.2457, 0.6826, 0.5008, and 0.6902 MVAR are optimally placed at buses 30, 23, 28, and 15, respectively. The installation of capacitors supplies reactive power locally, thereby reducing reactive power flow through the feeders. This decreases branch currents and consequently lowers the active power losses to 0.1315 MW (a 35.1% reduction), while the voltage deviation improves to 0.0570 p.u. The network configuration obtained with capacitor placement in Scenario 2 is shown in Fig. 4.

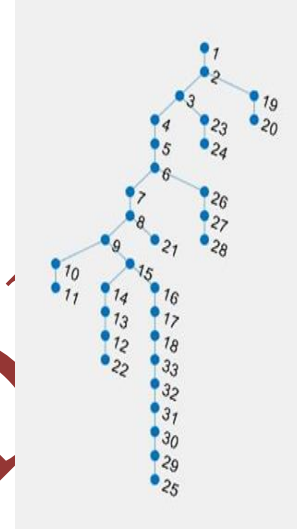


Fig. 4. The network configuration after Scenario 2.

F. Scenario 3: Reconfiguration with Distributed Generation (DG) Integration

In this scenario, in addition to network reconfiguration, three DG units with capacities of 557.25 kW, 536.81 kW, and 576.60 kW are installed at buses 33, 32, and 31, respectively. DG locations and sizes are optimized using the Harmony Search Algorithm (HSA). The integration of DG units provides local power supply, reduces transmission losses, and improves the voltage profile, resulting in a reduction of active power losses to 0.0407 MW and voltage deviation to 0.0425 p.u. The resulting network configuration for Scenario 3 is presented in Fig. 5.

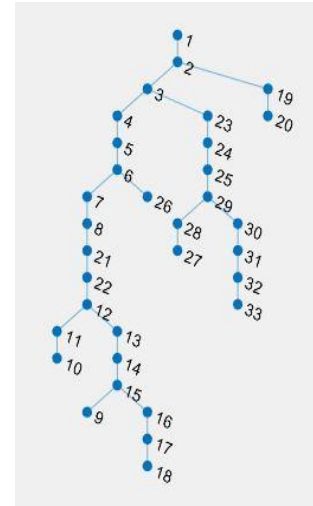


Fig. 5. The network configuration after Scenario 3.

G.Scenario 4: Reconfiguration with Simultaneous DG and Capacitor Integration

Scenario 4 combines all previous strategies and yields the best network performance. In this case, network reconfiguration, optimal DG placement, and capacitor allocation are simultaneously performed using HSA. This integrated approach reduces active power losses to 0.0227 MW and voltage deviation to 0.0362 p.u. Switches numbered 36, 7, 21, 10, and 28 are open after optimization. This scenario achieves the highest improvement in voltage quality and the lowest system losses. The final network configuration obtained through simultaneous optimization in Scenario 4 is depicted in Fig. 6.

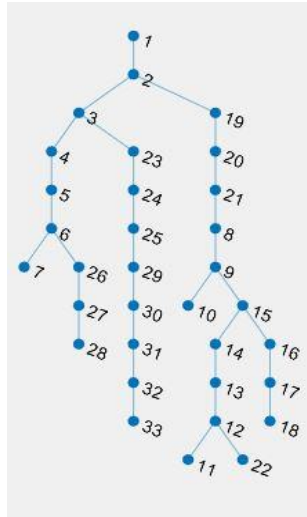


Fig. 6. The network configuration after Scenario 4.

H.Comparative Analysis:

The numerical results obtained for all investigated scenarios are summarized in Table II. As shown in the table, each additional optimization strategy contributes to further reductions in both active power loss and voltage deviation. The largest improvement is achieved when network reconfiguration, capacitor placement, and DG allocation are optimized simultaneously, demonstrating the complementary nature of these techniques.

TABLE II.
Performance Indices for All Scenarios

Scenario	Active Power Loss (MW)	Voltage Deviation (p.u.)	Loss Reduction (%)
Base Case	0.2027	0.0695	—
Reconfiguration (Scenario 1)	0.1485	0.0672	26.7
Reconfiguration + Capacitors (Scenario 2)	0.1315	0.0570	35.1
Reconfiguration + DG (Scenario 3)	0.0407	0.0425	79.9
Reconfiguration + DG + Capacitors (Scenario 4)	0.0227	0.0362	88.8

Table III compares the proposed approach with selected previous studies in terms of active power loss, voltage deviation, and loss reduction. Since the studies may differ in formulation and operating conditions, the comparison is provided for indicative purposes only.

TABLE III.
Comparison with Previous Studies

Reference	Active Power Loss (MW)	Voltage Deviation (p.u.)	Loss Reduction (%)
This Study	0.0227	0.0362	88.8
[57]	0.0739	0.0538	63.53
[58]	0.1395	0.0586	31.15
[59]	0.1410	0.0920	30.41

The proposed approach shows favorable performance in terms of active power loss reduction and voltage profile improvement, owing to the simultaneous optimization of network reconfiguration, DG allocation, and capacitor placement.

VI. CONCLUSION

This study proposed an integrated optimization framework based on the Harmony Search Algorithm (HSA) for the simultaneous consideration of network reconfiguration, capacitor placement, and distributed generation (DG) allocation in radial distribution systems. The effectiveness of the proposed approach was evaluated on the standard IEEE 33-bus test system through four progressive scenarios.

The simulation results demonstrated that network reconfiguration alone reduced active power losses by 26.7%, while the combination of reconfiguration and capacitor placement achieved a 35.1% reduction. When reconfiguration was combined with DG allocation, the loss reduction increased to 79.9%. The simultaneous optimization of all three strategies yielded the best performance, reducing active power losses by 88.8% (from 0.2027 MW to 0.0227 MW) and improving the voltage deviation from 0.0695 p.u. to 0.0362 p.u.

These findings indicate that the coordinated optimization of feeder topology, reactive power compensation, and distributed generation can provide greater technical benefits than applying these strategies individually or in pairs. The proposed HSA-based framework can therefore provide a useful basis for decision support in distribution system planning aimed at improving network efficiency and voltage quality.

Future research may focus on extending the proposed method to larger distribution systems, incorporating renewable energy uncertainty, and considering multi-objective formulations that include economic and reliability criteria.

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CONFLICTS OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this article.

DATA AVAILABILITY

All data produced or examined in the course of this study are fully contained within this published article.

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