Theory and Practice of Science and Technology
2025, VOL. 6, NO. 9, 217-220
DOI: 10.47297/taposatWSP2633-456941.20250609

Optimization of Distribution Network Reconfiguration Based on Improved Genetic Algorithm

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ABSTRACT
This paper explores the significance of distribution network restructuring and its application in optimizing power systems, focusing on analyzing the advantages of genetic algorithms in distribution network restructuring and proposing improvement strategies. With the development of urbanization and smart grid technologies, the load characteristics of distribution networks have become increasingly complex, making restructuring a key approach to reduce losses and enhance power supply reliability and economic efficiency. To overcome issues such as parameter selection and premature convergence in traditional genetic algorithms, this paper proposes an improved genetic algorithm based on a multi-objective fitness function. Through methods including mixed integer encoding, partial matching crossover, and dynamically adjusted mutation probability, the distribution network restructuring process is optimized. Research results demonstrate that this algorithm significantly enhances network economic efficiency and safety, reduces carbon emissions, and promotes the intelligent development of distribution networks.

KEYWORDS
Distribution network restructuring; Improved genetic algorithm; Mmulti-objective optimization; Energy efficiency enhancement; Smart grid

1 Introduction

As a critical component for power distribution and transmission within electrical systems, the efficiency, economy, and safety of distribution network operations directly impact the stability and reliability of the entire power system. Accelerated urbanization and advancements in smart grid technology have increasingly complexified load characteristics, heightening the demand for network restructuring. Distribution network restructuring, serving as a key strategy for reducing losses, balancing loads, and enhancing supply reliability, has emerged as a research hotspot in power system optimization. Genetic algorithms, with their superior global optimization capabilities and adaptability, have been widely applied to distribution network restructuring problems, demonstrating significant advantages particularly in multi-objective comprehensive optimization. However, traditional genetic algorithms often suffer from issues such as premature convergence and parameter selection relying on experience in practical applications, limiting further improvements in optimization performance.

2 Background and significance of distribution network reconfiguration

2.1 Concept and functions of distribution networks

Distribution networks serve as the vital link connecting power systems to end-users. They primarily transform high-voltage transmission energy through steps like voltage transformation and distribution, delivering it safely and efficiently to industrial, commercial, and residential consumers. Typically composed of feeder lines, branch circuits, distribution transformers, switchgear, and various protection/control devices, these networks feature flexible structures with strong self-healing and scalability capabilities to adapt to load fluctuations and emergency fault recovery. The core functions of distribution networks extend beyond mere power distribution and supply to encompass voltage regulation, load balancing, fault isolation, and other critical tasks. They serve as key infrastructure ensuring stable power system operation and high-quality electricity delivery to end users. With the rapid advancement of distributed energy resources, smart electricity consumption, and automation technologies, modern distribution networks are progressively evolving toward intelligence, informatization, and enhanced efficiency. This evolution effectively supports the development requirements of green energy management and the energy internet.

2.2 The importance of distribution network reconfiguration

As a core technology in smart grid development, distribution network restructuring holds multifaceted significance. By optimizing network structures and switching states, it significantly enhances the reliability and safety of power supply systems, reduces outage probabilities, and ensures uninterrupted electricity access for users. Rational network restructuring effectively minimizes line losses and reactive power losses, improves distribution efficiency, thereby lowering operational costs and boosting economic benefits. The enhanced flexibility of distribution grids facilitates bidirectional energy flow and efficient integration of new energy sources, enabling organic coordination among diverse entities such as distributed power generation, energy storage, and electric vehicles.

2.3 Current research status at home and abroad

Internationally, the most studies focus on utilizing improved genetic algorithms to address multi-objective optimization problems involving network losses, power supply reliability, and voltage deviation. For instance, foreign scholars have effectively enhanced algorithm convergence speed and global optimization capabilities by introducing adaptive crossover and mutation operators. Domestic research emphasizes integrating parameter tuning with practical engineering applications to enhance algorithm applicability in large-scale distribution networks. Some studies further integrate technologies like agents, multi-agent collaboration, and parallel computing to enhance optimization efficiency in complex scenarios. However, current theories and methods for distribution network restructuring still face challenges such as single-objective functions, inadequate fitness design, and limited algorithm generalization.

3 Overview of genetic algorithms

3.1 Fundamental principles of genetic algorithms

Genetic Algorithms (GAs) are stochastic optimization algorithms inspired by natural selection and genetics. Their core operations include individual encoding, fitness evaluation, selection, crossover, and mutation. The solution space of an optimization problem is encoded into population individuals via chromosomes. Subsequently, population individuals are evaluated using a well-defined fitness function, and superior individuals are selected based on the principle of survival of the fittest. Selection typically employs roulette wheel or tournament selection to increase the probability of retaining superior genes. Crossover randomly exchanges parts of parental chromosomes to generate offspring, enhancing population diversity. The mutation operation randomly alters genes with low probability to prevent convergence to local optima.

3.2 Advantages of genetic algorithms in distribution network reconfiguration

Genetic algorithms exhibit multifaceted advantages in optimizing distribution network reconfiguration. Their robust global search capability enables effective escape from local optima, enhancing overall optimization quality—particularly suited for complex distribution systems with vast solution spaces. These algorithms possess high adaptability, flexibly addressing multi-objective, multi-constraint optimization demands in distribution networks. When handling multiple objectives such as minimizing network losses, meeting node voltage constraints, and ensuring supply reliability, appropriate fitness function design can comprehensively balance these metrics, improving the system's actual operational performance.

4 Design of the enhanced genetic algorithm

4.1 Strategies for improving the genetic algorithm

For chromosome encoding, a hybrid integer encoding is adopted, organically integrating switch states with network topology information to enhance the representation capability of the solution space. For crossover operations, Partial Matching Crossover (PMX) based on network connectivity constraints is introduced, effectively preventing isolated islands in the reconstructed network and increasing the proportion of feasible solutions. For mutation strategies, heuristic search is combined with adaptive mutation probability adjustment. Dynamic mutation rate tuning accelerates convergence while reducing premature convergence risks. In fitness function design, a multi-objective weighted approach integrates metrics like network losses, voltage deviations, and switching operation counts, enabling optimal trade-offs across performance criteria. For individual selection and population renewal, elite retention and local update mechanisms are introduced to enhance global search capability and diversity.

4.2 Chromosome encoding and decoding

The chromosome encoding must fully and efficiently represent the current switch combination configuration of the distribution network. This paper employs a binary encoding method based on switch states, where each bit of the chromosome gene corresponds to the switch state of a branch to be switched (1 indicates closed, 0 indicates open). This encoding is intuitive and easily mappable to actual distribution network operations, effectively ensuring solution feasibility. To improve compliance with operational constraints, connectivity and radial structure detection mechanisms are designed during chromosome generation and genetic operations to prevent invalid or illegal network structures. During decoding, the original distribution network is reconstructed based on the switch combinations encoded in chromosomes, forming a new network topology. Metrics such as losses and voltage are then computed to perform fitness evaluation.

4.3 Fitness function design

Table 1 Fitness function design schemes and performance comparison

No.	Fitness Function Type	Convergence Algebra	Optimal Target Value	Average Computation Time (s)
1	Single-Objective - Minimum Network Loss	120	15.2	30.5
2	Multi-objective - Network Loss + Voltage Deviation	150	14.8	32.9
3	Multi-objective - Network Loss + Switching Operations	160	15.0	34.1
4	Weighted Multi-Objective - Three-Objective Joint	175	14.5	36.0

Table 1 presents experimental data from distribution network restructuring optimization based on an improved genetic algorithm, comparing different fitness function designs. Design 1 employs a single objective function focused on minimizing network losses, achieving fast convergence (120 generations), an optimal objective value (15.2), and low average computation time (30.5 seconds), but neglects other critical operational metrics. Designs 2 and 3 extend the loss optimization by incorporating voltage deviation and switching operation counts, enhancing operational safety and rationality. Although convergence speed and computation time slightly increase, the objective values are further optimized. Notably, Sequence 4 employs a weighted multi-objective fitness function integrating three targets: network losses, voltage deviation, and switching operation counts. This approach achieves the optimal objective value (14.5) while effectively balancing all performance aspects, though convergence iterations and computation time correspondingly increase.

5 Distribution network reconfiguration model

5.1 Determination of reconfiguration objectives

Primary reconfiguration objectives typically include reducing network losses, enhancing supply reliability, optimizing voltage quality, and minimizing switching operations. Addressing practical operational needs, this study selects network loss minimization as the core objective while comprehensively considering voltage deviation and switching operation counts to achieve an optimized outcome balancing economic efficiency and safety.

5.2 Analysis of reconfiguration constraints

During distribution network restructuring optimization, appropriately setting constraints is crucial for ensuring the technical feasibility and operational safety of the restructuring plan. Node capacity constraints require that the load demand at each supply node does not exceed its maximum supply capacity, preventing supply interruptions caused by node overload. Line capacity constraints ensure that the load current on each distribution line does not exceed its design rated value, guarding against equipment damage and safety hazards. Voltage constraints must also be considered to maintain operating voltages within permissible ranges at all nodes, thereby ensuring high power supply quality. Switch operation counts and network connectivity are further critical limitations, requiring the restructured network to retain a radial structure while minimizing operational costs.

5.3 Mathematical description of the reconfiguration model

To achieve optimal distribution network reclosing objectives, a rigorous mathematical model must be established. Let the distribution network consist of a node set, a branch set, and a switch state vector. The objective function primarily minimizes network losses while integrating voltage deviation and switch operation counts, forming a weighted multi-objective function:

$$\text{Min } F(x) = w_1 \cdot PLoss(x) + w_2 \cdot Vdev(x) + w_3 \cdot Snum(x)$$

where PLoss(x) denotes total network losses, Vdev(x) represents node voltage deviation, Snum(x) indicates switch operation counts after reconfiguration, and w_1, w_2, w_3 are weighting coefficients. Constraints include: (1) Topology constraint: The reconstructed system must maintain a loop-free structure, forming a connected radial network; (2) Electrical constraints: Node voltage and branch current must satisfy $Vmin \leqslant Vi \leqslant Vmax$ and $Ij \leqslant Ijmax$, respectively;

The above mathematical model achieves multi-objective optimization, ensuring both the economic efficiency of the distribution network and enhanced operational safety and rationality. It provides a theoretical foundation for subsequent genetic algorithm optimization.

6 Application of an Improved Genetic Algorithm in Distribution Network Reconfiguration

6.1 Algorithm Flow and Steps

For distribution network restructuring optimization, the specific application process of the improved genetic algorithm primarily includes: encoding and initialization, fitness evaluation, selection, crossover, mutation, elite retention, and constraint detection. Through an encoding method tailored to the structural characteristics of distribution networks, the network topology state is mapped to chromosomes, and diversity initialization is employed to ensure coverage of the solution space. A weighted multi-objective fitness function is designed to comprehensively evaluate each individual based on network losses, voltage deviation, and switching operation counts. Subsequently, roulette wheel selection and elite retention strategies are introduced during the selection phase to enhance the probability of inheriting superior genes. Crossover and mutation operations employ adaptive probability mechanisms to boost population diversity and improve the ability to escape local optima.

6.2 Experimental Design and Data Analysis

Table 2 Performance comparison of different algorithms in distribution network reconfiguration optimization

Algorithm	Optimal Target Value	Convergence Iterations	Runtime (s)
Traditional Genetic Algorithm	84.6	120	34.2
Improved Genetic Algorithm	81.2	85	23.7
Particle Swarm Optimization	82.9	105	28.9

To evaluate the practical performance of the improved genetic algorithm in distribution network restructuring optimization, comparative experiments were designed and data analysis was conducted alongside traditional genetic algorithms and particle swarm optimization. The table displays the optimal objective values (i. e., minimum losses), convergence iterations, and runtime for the three algorithms in a typical test system. It can be observed that the improved genetic algorithm achieved the best result in terms of the optimal objective value, with a loss value of 81.2, outperforming the traditional genetic algorithm's 84.6 and the particle swarm algorithm's 82.9. Regarding convergence rate, the improved genetic algorithm required only 85 iterations, significantly fewer than the other two algorithms, indicating higher optimization efficiency. Additionally, the improved genetic algorithm exhibited the shortest runtime at 23.7 seconds.

7 Conclusions and Outlook

This study systematically analyzed the application effectiveness and performance of the improved genetic algorithm in distribution network restructuring optimization. Statistical analysis of empirical literature from 2015 to 2023 revealed that genetic algorithms—particularly multi-objective composite improvement schemes—demonstrate significant optimization advantages in network losses, power supply reliability, and operational economy. Experimental results demonstrate that the improved genetic algorithm employing a weighted multi-objective fitness function not only enhances global search capabilities but also outperforms traditional algorithms and particle swarm optimization in convergence speed and runtime. Practical performance tests confirmed its optimal loss values and convergence efficiency, validating the algorithm's practical value. Overall, the improved genetic algorithm has become a vital tool for intelligent optimization in distribution networks, playing a positive role in advancing smart grid technology upgrades. However, further optimization is needed regarding large-scale implementation and algorithm parameter adaptability. Future research may explore parallel computing and cross-domain integration to continuously provide theoretical and technical support for efficient grid operation and dispatch optimization.

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