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Intelligent optimisation of self-healing strategy of distribution network based on differential evolution and advanced fractal

Zhongqiang Zhou*, Jianwei Ma,
Yusong Huang, Ling Liang and Zhiqi Chen

Power Dispatching Control Center of Guizhou Power Grid Co., Ltd.,
Guiyang 550000, Guizhou, China

Email: sandy2124@163.com

Email: ygo2023@126.com

Email: surya22123@163.com

Email: vipnet0518@163.com

Email: cloud2321@163.com

*Corresponding author

Abstract: Traditional self-healing strategies for distribution networks are prone to getting stuck in local optima in complex power systems, resulting in the inability to find the globally optimal self-healing strategy. By introducing genetic algorithms and differential evolution optimisation, more effective self-healing strategies were sought to improve the robustness and anti-interference ability of the power system. The optimisation objective was to minimise the interruption time of power supply under the influence of faults, collect comprehensive data related to the power system, and apply genetic algorithm (GA), differential evolution (DE), and GA-DE to optimise the self-healing strategy of the distribution network. The experimental results indicate that the average convergence frequencies for GA, DE, and GA-DE were 716, 662, and 612, respectively. The average total power outage times were 195.3 seconds for GA, 178.8 seconds for DE, and 148.5 seconds for GA-DE. The GA-DE algorithm resulted in the fewest power outages over six years. By combining the strengths of GA and DE, the GA-DE algorithm enhances self-healing strategies in distribution networks, improving power system stability and reliability.

Keywords: distribution network self-healing; strategy optimisation; genetic algorithm; GA; differential evolution; DE; power outage time.

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Biographical notes: Zhongqiang Zhou has a Master's degree, Intermediate Engineer, and currently mainly engaged in power distribution automation professional technical work.

Jianwei Ma received his Bachelor's degree from Changsha University of Science and Technology, China. Currently, he works in Power Dispatching and Control Center of Guizhou Power Grid Co., Ltd. His research interests include power grid dispatching automation operation and management.

Yusong Huang has a Master's degree, Senior Engineer, and mainly engaged in professional technical work of dispatch automation

Ling Liang has a Bachelor's degree, Intermediate Engineer, and currently mainly engaged in power distribution automation operation management.

Zhiqi Chen has a Master's degree, Intermediate Engineer, and currently mainly engaged in power distribution automation professional technical work.

1 Introduction

The power system is an essential infrastructure in modern society, with the distribution system being a key component (Zhang et al., 2019b, 2020). Traditional distribution systems can no longer ensure safety, stability, and reliability (Dong et al., 2021a; Zhang et al., 2019a). To enhance robustness and adaptability, self-healing distribution networks use intelligent technology for automatic fault detection, localisation, isolation, and recovery (Bagherzadeh et al., 2021; Shen et al., 2019b). In the power system, rapid self-healing of faults is crucial for ensuring the stability and reliability of power supply. Genetic algorithm (GA) and differential evolution (DE) optimisation, as two types of evolutionary algorithms, are widely used to solve complex optimisation problems (Shanmugasundaram et al., 2019; Huang et al., 2021). Through the application of GA and DE optimisation, the intelligence level and fault response ability of the power grid have been improved. As the infrastructure of modern society, the reliability and robustness of the power system are vital. As the last layer of the power system, the self-healing ability of the distribution network directly affects the stability of the power supply. The self-healing strategy minimises power outage time and improves system reliability by quickly responding to and repairing faults. This paper optimises the distribution network self-healing strategy under six typical fault scenarios by comparing GA, DE, and the GA-DE algorithm that combines the two, and evaluates its performance in terms of convergence frequency, convergence time, total power outage time, and number of power outages, to improve the self-healing ability and overall operation efficiency of the power system.

This article explores the application of GA, DE, and GA-DE in optimising self-healing strategies for distribution networks to enhance power system performance. The aim was to minimise power supply interruption during faults and determine optimal grid topology and key parameters. Experimental results showed that GA outperformed DE in short-circuit fault scenarios, while GA-DE exhibited superior advantages by combining the strengths of both algorithms, effectively reducing outage time and convergence time. By introducing GA and DE optimisation strategies, this paper solves the problem that traditional distribution network self-healing strategies easily fall into local optimal solutions in complex power systems, making it impossible to find the globally optimal self-healing solution. The study uses a standard IEEE 33-node system as a model to simulate six typical fault scenarios, and comprehensively evaluates the performance of GA, DE and the GA-DE algorithm that combines the advantages of both in optimising the self-healing strategy of the distribution network. Experimental results show that compared with GA and DE used alone, the GA-DE algorithm has a lower

average convergence frequency of only 612 times, and the total number of power outages during the six-year period is the least, with an average of only 148.5 seconds, which is a significant reduction. A system power outage event occurred. The GA-DE algorithm combines the global search capabilities of GA and the local optimisation advantages of DE, which not only improves the self-healing efficiency of the distribution network, but also enhances the stability and reliability of the power system. This research provides an innovative optimisation method for the self-healing control strategy of smart grids, which is of great value in improving the adaptability and anti-interference capabilities of modern power networks.

This paper first summarises the key role of power systems in modern society and the challenges faced by traditional distribution networks in the introduction section, and emphasises the necessity of applying intelligent technologies in automatic fault detection, location, isolation and recovery. Subsequently, the method section introduces in detail the key parameter settings of GA, DE and GA-DE algorithms and their application in the optimisation of distribution network self-healing strategies, including the flexibility of the algorithms, convergence criteria and parameter adjustment strategies. The experimental design is based on the IEEE 33-bus system, and the effectiveness of the algorithms is verified through six typical fault scenarios. The results section presents the comparison of convergence frequency and power outage time of different algorithms, and the GA-DE algorithm shows the best performance. The discussion section analyses the applicability of the algorithm in distribution networks of different sizes and types, and explores the impact of uncertainty factors in the power system on the algorithm. Finally, the conclusion summarises the research findings, emphasising the important contribution of the GA-DE algorithm in optimising the self-healing strategy of distribution networks and its potential in improving the stability and reliability of power systems.

2 Related work

The distribution system, as the end of the power system, is directly related to the power supply quality of the end users. Many researchers have optimised the self-healing strategies of distribution networks to improve the operational efficiency and stability of power systems. The optimisation of self-healing strategies in distribution networks can enable the system to respond more quickly and accurately to faults and minimise the scope of fault impact, thereby improving the reliability of user power supply and reducing power outage time (Liu et al., 2021; Hou et al., 2022). Gazijahani et al. (2020) proposed a new spatiotemporal algorithm that divides the existing network into a group of self-healing microgrids. By dividing fault areas and performing resource rescheduling, network reconstruction, and load shedding, the load and power generation in isolated states were balanced, while maximising power generation profits. Shen et al. (2019a) proposed a distributed optimal service recovery strategy based on the alternating direction multiplier method, and considered operational constraints in the optimisation problem, which can provide the optimal service recovery solution in a reasonable time without the need for a central controller. Mousavizadeh et al. (2021) proposed a dynamic manufacturing grid generation and scheduling model for distribution systems based on mixed integer linear programming, which promoted self-healing ability by utilising the accumulated capacity of power generation resources and better-coordinated energy management during recovery while considering the system's switching ability. Pinto et al.

(2019) comprehensively considered reliability, distributed generation, capacitor and switch layout for distribution network expansion planning, and solved it by combining metaheuristic algorithms, stochastic simulation methods, and the application of optimal power flow. Jiaojiao et al. (2021) ensured operational constraints by checking the three-phase unbalanced power flow reconstructed by the fault network and then calculated reliability indicators through Monte Carlo simulation. Previous studies have shown that traditional self-healing strategies for distribution networks face a series of challenges when dealing with complex power systems, with low computational efficiency in

large-scale systems and susceptibility to being limited by local optimal solutions. The optimisation of distribution network self-healing strategies is crucial to improving the operating efficiency and stability of power systems. Researchers have proposed various methods, such as spatiotemporal algorithms, distributed optimal service restoration strategies, dynamic manufacturing generation scheduling models, and distribution network expansion planning, to address different challenges. However, traditional methods suffer from inefficiency and local optimal solution limitations when dealing with complex systems. Therefore, more efficient and reliable self-healing strategies are needed for large-scale systems, and further research is needed to address the limitations of current methods.

GAs and DE are widely used to solve complex optimisation problems. Researchers have attempted to use GAs and DE to optimise various aspects of the power system. In the field of power systems, GAs have been widely applied to various problems, including power system scheduling, energy markets, power grid planning, equipment optimisation configuration, etc. (Xu et al., 2020; Pan et al., 2019). The power system involves a large number of equipment and parameters, and DE can effectively handle high-dimensional problems and achieve optimisation of large-scale systems (Liu et al., 2021; Li et al., 2020). To quickly and accurately locate the fault location network of the distribution network and increase the stability of the distribution network, Huang et al. (2020) quickly achieved multi-objective fault recovery through GA and particle swarm optimisation. Hanjalic et al. (2023) determined the hosting capacity in intelligent distribution systems by using GAs to solve single objective-constrained optimisation problems. Chandak and Rout (2020) proposed a multi-objective binary DE algorithm to reconstruct systems and recover loads in independent microgrids. The power network was reconstructed into a capacity-constrained graph, where the capacity of edges is limited by the load capacity of feeders. GAs are known for their ability to search globally, while DE optimisation performs

well in handling high-dimensional and nonlinear problems. However, there is a relative lack of comparative research on these two methods in self-healing strategies for distribution networks in the existing literature.

3 Optimisation methods for self-healing strategies in distribution networks

3.1 Optimisation objectives

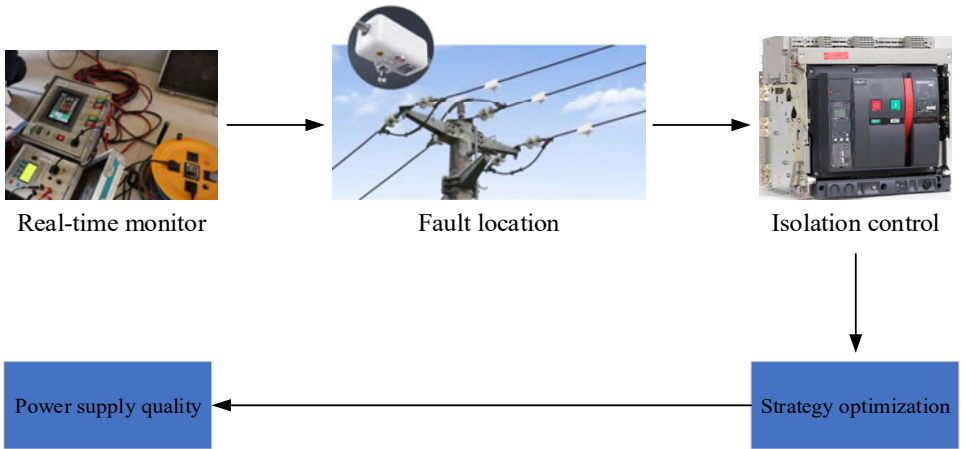
As power demand increases and the grid structure becomes more complex, the traditional distribution system may face longer outage time when facing faults, which brings inconvenience to social production and residents' lives (Gu et al., 2022; Chen et al.,

2022). By optimising the self-healing strategy of the distribution network, the system can respond to faults more quickly and accurately, minimise power outage time, significantly improve power supply reliability, and reduce the impact on users (Kong et al., 2022; Zhang, 2024).

With the continuous development of the power system and the demand for power supply reliability in society, optimising the self-healing strategy of the distribution network means more efficient and intelligent power system management, which is of great significance to the social economy and residents' lives. The self-healing framework of the distribution network is illustrated in Figure 1.

In Figure 1, the first step of self-healing in the distribution network is to monitor the status of the power system in real- time, including real-time monitoring of key parameters such as current, voltage, and equipment operation status. Monitoring data and system topology information are used to determine the affected area or device and identify the location of the fault point. By implementing isolation control through intelligent switches, circuit breakers, and other devices, the fault area is isolated from other power grids to prevent the spread of faults. By optimising decision-making, scheduling, and control strategies through intelligent algorithms, the adaptability and performance of the system are improved.

Figure 1 Framework for self-healing in distribution networks (see online version for colours)



The power system must meet basic stability and safety requirements at all times. The switch operations performed comply with the topology of the power grid and the physical limitations of the equipment to prevent additional faults or damage. Moreover, the restoration process of the power system does not cause new problems, such as voltage instability, frequency fluctuations, etc.

By using intelligent algorithms to find the optimal device status and switch operation strategy, the system can quickly and effectively detect, locate, isolate, and recover faults, minimising the interruption time of user power supply. Modelling the self-healing strategy problem of the distribution network as an optimisation problem helps to utilise mathematical modelling and optimisation algorithms to improve the automation level of the system, reduce the impact of faults, and enhance the reliability and robustness of the power system.

The topology structure of the power grid is obtained, including the connection relationships of elements such as distribution lines, substations, switches, and loads (Petthe et al., 2021; Singh et al., 2024). Information such as device operation status, device health status, and load data are collected. Real-time monitoring data of key parameters such as current, voltage, and power are obtained through intelligent sensors. Historical fault information is collected, including the time, location, type, and system self-healing response of the fault.

Part of the collected power system data is displayed in Table 1.

Table 1 Part of the collected power system data

<i>Acquisition time</i>	<i>Current (A)</i>	<i>Voltage (V)</i>	<i>Power (kW)</i>
2018-01-01 08:00	150	230	34.5
2018-01-01 09:00	155	235	36.1
2018-01-01 10:00	160	240	37.8
2018-01-01 11:00	145	225	32.6
2018-01-01 12:00	148	228	33.7
2018-01-01 13:00	162	242	38.5
2018-01-01 14:00	155	236	36.7
2018-01-01 15:00	147	229	33.2
2018-01-01 16:00	160	235	37.2
2018-01-01 17:00	155	233	36.3

In Table 1, part of the power system data is presented. By collecting real-time information such as current and voltage through intelligent sensors, the power grid status can be understood in real-time, accurately perceiving abnormal situations in the power grid, including potential faults and equipment performance issues. Data sources include power plants, substations, and transmission and distribution networks. The data collection method uses smart meters and sensors for real-time monitoring, which is summarised through the SCADA system and transmitted to the central database using IoT devices. In addition, telemetry technology is used for remote data collection, combined with big data platforms for storage and analysis to ensure the timeliness and accuracy of the data while complying with relevant privacy and security regulations.

The collected power system data is pre-processed to ensure the quality and availability of the data. The pre-processing content includes data cleaning and data standardisation. The presence of outliers and missing values affects the accurate understanding of power system status and the effective implementation of self-healing strategies in distribution networks.

Through visualised scatter plots, abnormal data and missing values in the data are detected, and through the mean of the data, abnormal values are replaced and missing values are filled in. For duplicate data records, they are deleted.

The calculation formula for the average data value is:

$$\bar{x} = \sum_{i=1}^n x_i / n \quad (1)$$

Data standardisation can convert data from different scales to the same scale. The formula for z-score standardisation is:

$$z = \frac{x - \mu}{\sigma} \quad (2)$$

In data cleaning and standardisation, missing or abnormal data are first deleted to ensure data integrity. Then the fault data is normalised to standardise each fault indicator to the range of 0–1. Next, the sliding window method is used to smooth the data and eliminate noise. Finally, the Z-score standardisation is used to convert the data into a standard normal distribution, which is convenient for subsequent algorithm processing and comparison.

3.2 Application of GA

GA is an optimisation algorithm that simulates natural evolution processes and is often used to solve search and optimisation problems (Garud et al., 2021; Shariati et al., 2020). GA can search for multiple solutions simultaneously in the solution space, with strong global search ability, and is widely used in complex, nonlinear, and high-dimensional optimisation problems (Memon et al., 2021; Abualigah and Alkhraisheh, 2022; Chen and Tang, 2024; Wang, 2024).

GA can gradually optimise the self-healing strategy of the distribution network through multiple iterations, fully considering factors such as the effectiveness of self-healing strategies, power grid stability, and user needs.

A set of initial solutions is randomly generated, with each solution representing a possible self-healing strategy. These solutions form the initial population. The fitness of each self-healing strategy is calculated, and the design of the fitness function comprehensively considers aspects such as power grid stability, fault recovery time, and user needs.

The fitness function is expressed as:

$$F = \sum_{k=1}^k F_k \cdot w_k \quad (3)$$

In equation (3), F_k represents the k^{th} factor being considered, and w_k represents the corresponding weight.

The selection operator is used, and the parent individuals are selected based on fitness, weighted based on fitness. Individuals with high fitness are more likely to be selected.

The selected parent individual is subjected to crossover operations to generate a new individual. Cross-operation simulates the process of gene exchange in organisms. The formula for the crossover process is:

$$O = \alpha \times P_1 + (1 - \alpha) \times P_2 \quad (4)$$

In equation (4), α is a random parameter.

The generated new individuals are subjected to mutation operations, which improve the diversity of the algorithm by introducing new genetic information. The formula for the mutation process is:

$$M = O + \beta \times R \quad (5)$$

In equation (5), R represents a random number generated within a certain range.

The newly generated individuals are used to replace individuals with lower fitness in the original population. New individuals, crossover, mutation, and other operations are repeatedly selected until the fitness value converges. The population with converging fitness values is used as the optimal self-healing strategy for the distribution network. The optimal self-healing strategy is applied in practical power systems to monitor their performance and make necessary adjustments.

3.3 DE optimisation

DE is an evolutionary algorithm used for global optimisation to solve parameter optimisation problems in real space, gradually optimising the quality of solutions through crossover and mutation operations during the evolution process (Li et al., 2023; Wu et al., 2020). The self-healing strategy of the distribution network involves a large number of parameters such as equipment, topology, current, voltage, etc., forming a high-dimensional optimisation problem. DE is relatively flexible in dealing with high-dimensional problems and can effectively search for high-dimensional parameter spaces.

A set of initial solutions is randomly generated, forming the initial population. Each solution is a possible self-healing strategy corresponding to the decision variables of the problem. The fitness of each individual is calculated; the advantages and disadvantages of each self-healing strategy are evaluated; factors such as power grid stability, fault recovery time, and user needs are comprehensively considered.

The evolutionary process includes differential variation and crossover operations. A group of parent individuals are selected and determined through a roulette wheel selection strategy. The selected parent individuals are subjected to differential mutation operations to generate a set of mutated individuals.

The mutation operation is obtained by the linear combination of parent individuals, and the mutation process is as follows:

$$B = A_{base} + h \times (A_{rand1} - A_{rand2}) \quad (6)$$

In equation (6), h is the scaling factor, and $rand1$ and $rand2$ are randomly selected individuals different from the .

Each mutated individual is subjected to a crossover operation with its corresponding target individual to generate a set of offspring individuals.

3.4 Fusion of GA and DE

GA and DE are integrated to comprehensively optimise the self-healing strategy of the distribution network. GAs can search globally, but they may fall into local optima when dealing with high-dimensional or complex nonlinear problems. DE has strong global search capabilities and is more advantageous for high-dimensional and nonlinear problems.

GA and DE are integrated, combining their advantages to improve global search capability and better adapt to different types of optimisation problems.

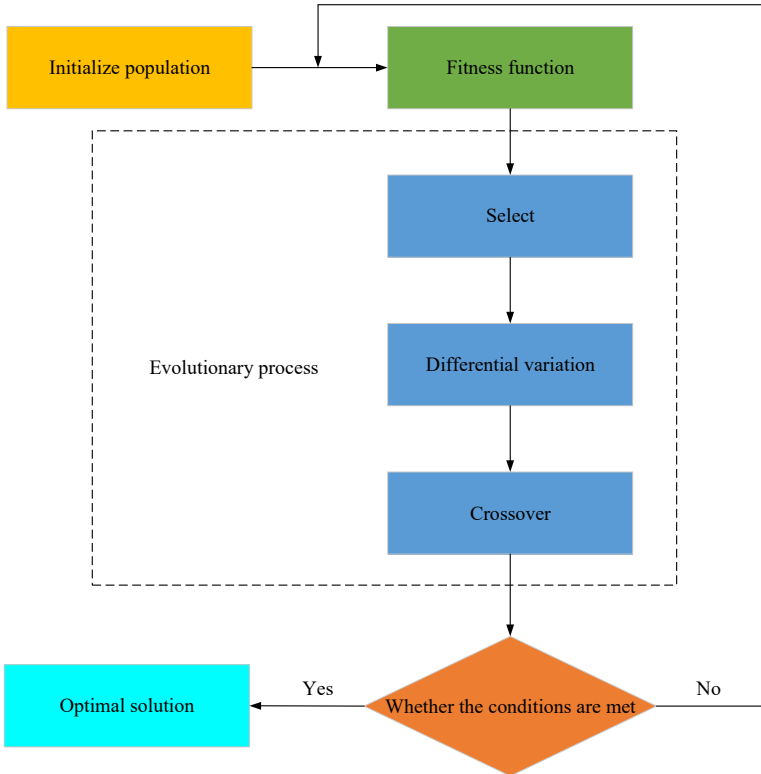
Each individual is calculated for fitness, and the strengths and weaknesses of each self-healing strategy are evaluated. Through roulette, a group of parent individuals are selected. The selected parent individuals are subjected to differential mutation operations to generate a set of mutated individuals.

Each mutated individual is subjected to a crossover operation with its corresponding target individual to generate a set of offspring individuals. The evolutionary process includes selecting individuals, differential variation, and crossover, repeating the evolutionary process until the fitness value converges.

The fusion optimisation process of GA and DE is shown in Figure 2.

In Figure 2, the GA-DE fusion optimisation process is described. The evolution process of GA-DE differs slightly from that of GA and DE. According to the fitness value, a certain number of individuals are selected as parents. The selected parent individual is subjected to differential mutation operation to generate a mutated individual. The mutated individual and the target individual are crossed to generate offspring individuals.

Figure 2 GA-DE fusion optimisation process (see online version for colours)



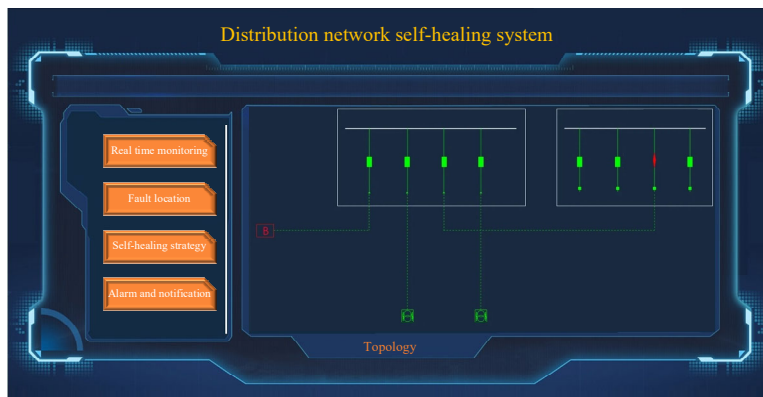
In the GA tuning process, the algorithm's search efficiency is first enhanced by selecting an appropriate population size and crossover and mutation probabilities. GA uses roulette to select excellent individuals, crossover operations simulate gene recombination, and mutation introduces new genetic information. DE tuning performs a global search by selecting appropriate differential weights and crossover probabilities, mutation operations

generate new solutions through linear combinations between individuals, and crossover operations ensure the diversity of solutions. Combining the advantages of both, the GA-DE fusion algorithm continuously adjusts parameters through multiple iterations during the optimisation process to achieve a global optimal self-healing strategy.

The fusion steps and strategies of GA and DE include the following aspects: First, when initialising the population, the selection, crossover, and mutation operations of GA are used to generate the initial solution. Next, the individuals evolved through the differential mutation and crossover strategies of DE to generate new candidate solutions. Then, combined with the fitness evaluation mechanism of GA, excellent individuals are selected to enter the next generation. During the fusion process, the mutation and crossover strategies of GA and DE are used alternately or mixed to enhance the diversity and global search capabilities of the algorithm. Finally, through iterative optimisation, the overall fitness of the population is continuously improved to ensure the quality and efficiency of the solution results.

As an important component of the power system, the distribution network involves a large number of equipment, lines, transformers, and other components, and is also affected by user demand and environmental changes. Optimising the self-healing strategy of the distribution network can respond more quickly and accurately to system faults, reduce the impact of faults on the reliability of the power grid, and improve the continuity and stability of power supply. A distribution network self-healing system is built through GA-DE optimisation. The interface of the distribution network self-healing system is shown in Figure 3.

Figure 3 Distribution network self-healing system interface
(see online version for colours)



In Figure 3, the interface of the distribution network self-healing system is described, including real-time monitoring, fault location, self-healing strategy, and warning function. Real-time power system status monitoring is provided, including real-time data on key parameters such as equipment status, current, voltage, etc. The location of faults in the power system is displayed to assist operation and maintenance personnel in quickly locating and taking corresponding measures. In the event of a malfunction or self-healing process, warnings and notifications are generated, and the optimal self-healing strategy is formulated to reduce power outage time.

4 Optimisation evaluation of self-healing strategies for distribution networks

The experiment was conducted on a high-performance computing platform. The hardware environment includes a computing server equipped with an Intel Xeon E5-2690 v4 processor, 128GB memory, and 1TB SSD. The software environment uses the Ubuntu 20.04 operating system, the programming language is Python 3.8, and scientific computing and optimisation libraries such as NumPy, SciPy, and DEAP are used. The algorithm implementation and testing are carried out through a custom simulation platform. The distribution network model adopts the standard IEEE 33-node system. By simulating six typical fault scenarios, the performance of GA, DE, and GA-DE algorithms in optimising the self-healing strategy of the distribution network is comprehensively evaluated.

The main parameters of the GA algorithm include population size, crossover probability, and mutation probability. The population size is set to 100, the crossover probability is 0.6, and the mutation probability is 0.01. The key parameters of the DE algorithm are differential weight and crossover probability. The differential weight is set to 0.5 and the crossover probability is 0.8. The GA-DE fusion algorithm combines the parameter settings of GA and DE. The population size remains at 100, the crossover probability and mutation probability are adjusted according to the parameter settings of GA, and the differential weight and crossover probability are adjusted according to the parameter settings of DE to balance global search and local search.

The algorithm's flexibility in responding to self-healing strategy analysis is reflected in its convergence frequency and convergence time. The algorithm can identify an optimisation objective-fulfilling solution more quickly the smaller its convergence frequency. An algorithm is more efficient the shorter its convergence time. The convergence criteria of GA are reaching the maximum number of iterations or the fitness of the population changes by less than 0.01% in five consecutive generations; the convergence criteria of DE are when the maximum number of iterations reaches 500 or there is no significant improvement in fitness in ten consecutive generations; the GA-DE fusion algorithm combines the two criteria and stops when the maximum number of iterations reaches 300 or the fitness changes by less than 0.005% in eight consecutive generations.

To comprehensively analyse the performance of different optimisation algorithms, the number of annual power outages in the power system within 6 years is calculated under the optimisation effect of self-healing strategies of different algorithms.

5 Results

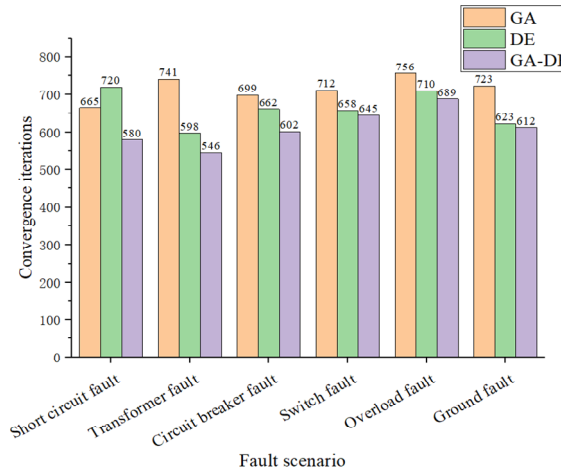
5.1 Convergence frequency

The convergence frequency of the three optimisation algorithms in different fault scenarios is shown in Figure 4.

In Figure 4, the comparison results of convergence frequency are described, with the horizontal axis representing 6 fault scenarios and the vertical axis representing the number of convergence iterations. The convergence frequency varies in different fault scenarios, mainly because different fault scenarios may involve different power system

topologies, equipment states, constraints, etc. The complexity of the problem can affect the time required for the algorithm to find the optimal solution. The convergence frequency of the GA-DE algorithm was the least, and the convergence frequency of the GA algorithm and DE algorithm each had their advantages and disadvantages. Compared to DE, the GA algorithm had fewer convergence frequency in short-circuit fault scenarios, but relatively more convergence frequency in other fault scenarios. The average convergence frequency of GA, DE, and GA-DE algorithms were 716, 662, and 612, respectively. GA-DE combines the advantages of both and can effectively reduce the number of convergence frequencies.

Figure 4 Convergence frequency (see online version for colours)

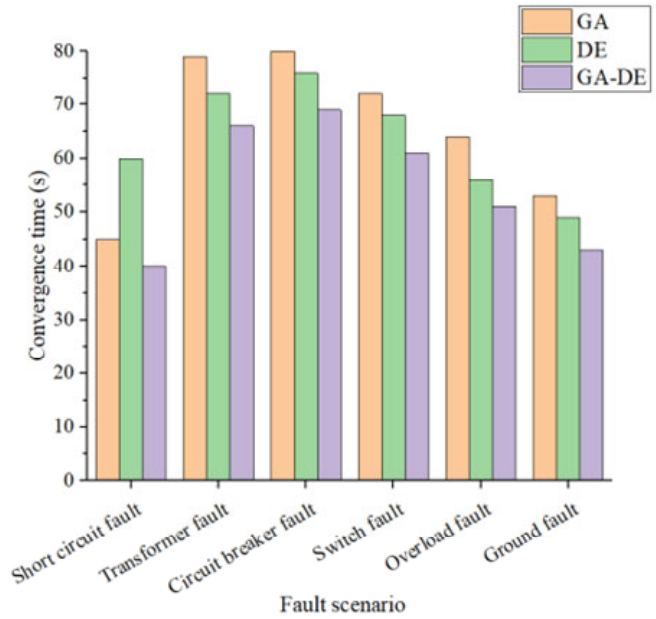


5.2 Convergence time

The convergence times of three optimisation algorithms in different fault scenarios are shown in Figure 5.

In Figure 5, the convergence time of the GA-DE algorithm was the shortest. The GA convergence time was smaller than DE in the short circuit fault scenario, but it was larger than DE in other fault scenarios. In short-circuit fault scenarios, stronger exploration ability may be required, while in other fault scenarios, a stronger ability to utilise existing information is required. The average convergence times of GA, DE, and GA-DE algorithms were 65.5, 63.5, and 55.0 seconds, respectively. The complexity of GA, DE, and GA-DE algorithms varies. The complexity of the GA algorithm mainly depends on the population size and the number of iterations, which is $O(N * G)$, where N is the population size and G is the number of iterations. The complexity of the DE algorithm is similar, which is $O(N * G)$, but due to the characteristics of its mutation and crossover operations, the actual running time may be longer. GA-DE fusion algorithm combines the advantages of GA and DE, and the complexity is also $O(N * G)$, but through a more efficient search mechanism, the GA-DE algorithm can achieve better convergence performance and solution quality at the same complexity.

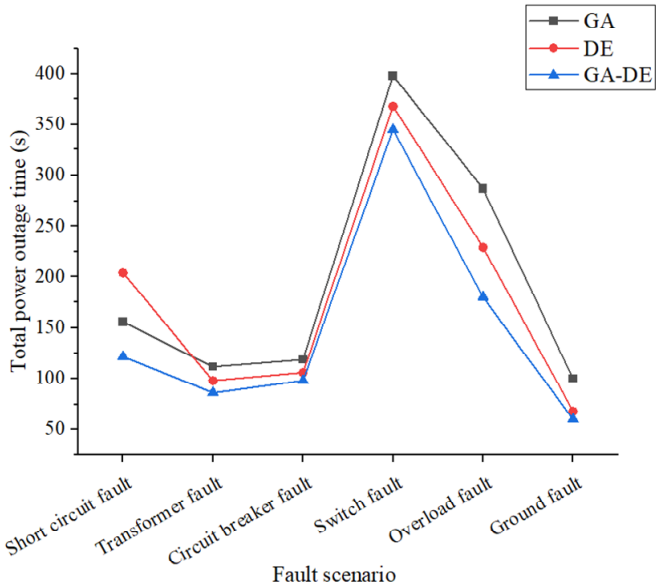
Figure 5 Convergence time (see online version for colours)



5.3 Total time of power outage

The total power outage time of three optimisation algorithms in different fault scenarios is shown in Figure 6.

Figure 6 Total time of power outage (see online version for colours)

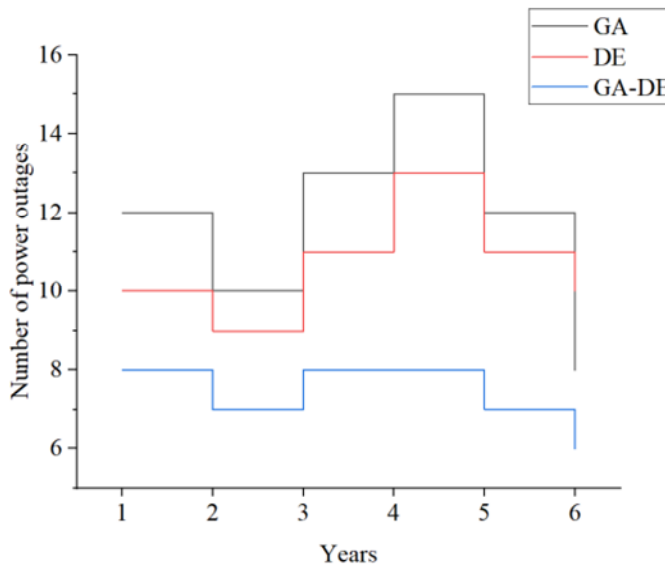


In Figure 6, the total power outage time under three optimisation methods of self-healing strategies for distribution networks is described. It can be seen that there were differences in the power outage time under different fault scenarios, mainly because the type of fault and the location of the fault have a significant impact on the execution time of self-healing strategies. The average total power outage time of GA, DE, and GA-DE algorithms was 195.3s, 178.8s, and 148.5s, respectively. The GA-DE algorithm performed better in outage time for optimising self-healing strategies. It combines the advantages of GA and DE, allowing for a more comprehensive exploration and utilisation of the search space during the search process.

5.4 Power outage times

The results of power outage times under three self-healing strategies in the distribution network are shown in Figure 7.

Figure 7 Power outage times (see online version for colours)



In Figure 7, the horizontal axis represents six years, and the vertical axis represents the number of power outages counted each year. The GA-DE algorithm resulted in fewer power outages compared to the GA and DE algorithms. By combining the strengths of both GA and DE, the GA-DE algorithm more effectively finds optimal solutions, thus reducing power outages in the system.

GA, DE, and GA-DE algorithms have wide applicability in distribution networks of different scales and types. For small-scale distribution networks, these algorithms can quickly find the optimal or near-optimal self-healing strategy, shorten the fault recovery time, and improve the reliability of the system. In medium and large-scale distribution networks, the GA-DE algorithm performs particularly well. Combining the global search capability of GA and the local search advantage of DE, it can handle complex fault scenarios more efficiently and reduce the duration and number of power outages.

Different types of distribution networks, such as urban, rural, and industrial distribution networks, have different topological structures and load characteristics. The optimisation algorithm in this paper has shown good adaptability by flexibly adjusting parameters and strategies and has the potential for wide application.

The uncertainties in the power system mainly include load fluctuations and equipment aging. Load fluctuations refer to changes in electricity demand, which may be caused by weather changes, fluctuations in economic activities, changes in residents' living habits, etc. Load fluctuations will affect the stability and reliability of the power system, resulting in insufficient or excessive power supply, which in turn affects the balance and safe operation of the system.

Equipment aging refers to the gradual degradation of equipment such as generators, transformers, and transmission lines in the power system over time. Equipment aging will reduce its performance, increase the probability of failure, and affect the reliability and safety of the system. In addition, the maintenance and replacement costs of aging equipment are high, which hurts the economy of the power system.

To cope with these uncertainties, the power system needs to adopt advanced monitoring, prediction, and optimisation technologies, improve the intelligence level of the system, enhance the ability to respond to load fluctuations and equipment aging, and ensure the safety, reliability, and economy of power supply.

6 Conclusions

This article compared three optimisation algorithms: GA, DE, and GA-DE. The experimental results showed that the GA-DE algorithm could effectively reduce the impact of power outages caused by faults and had a shorter convergence time. By integrating GA and DE, the advantages of both algorithms are fully utilised, balancing global and local search during the search process, covering the search space more comprehensively, and improving the possibility of finding the global optimal solution. The self-healing strategy was optimised to improve the operational efficiency of the power system, reduce power outage losses, and address the increasingly complex and intelligent challenges of the power system. However, this article lacks an analysis of more comprehensive power system faults, and in the future, the impact of more comprehensive power system faults can be explored. The limitations of this study include the small sample size, which may limit the generalisability of the results. In addition, the research method mainly relies on existing data and does not fully consider the impact of future technological developments on the power system. Finally, there is a certain degree of subjectivity in the selection and tuning process of model parameters, which may affect the accuracy and reliability of the results. Future research can consider expanding the sample size and increasing data diversity to improve the generalisability and reliability of the results. At the same time, the application of emerging technologies (such as blockchain and big data analysis) in power systems can be explored to further optimise model parameters and algorithms. Interdisciplinary research can also be carried out to comprehensively consider the impact of environmental and economic factors on the power system to improve the adaptability and stability of the overall system.

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