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Reliability Analysis and Improvement Strategies of Microcomputer Relay Protection Devices

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Abstract: In today's increasingly complex power system, microcomputer relay protection device plays a very important role in ensuring the safety and stability of power grid. In this paper, the characteristics of the equipment itself and the external environment are comprehensively considered, and various possible failure modes of relay protection equipment are deeply studied by means of FTA and FMEA. In this paper, a multidisciplinary approach is proposed to collect and analyze the existing failure data, simulate various failure scenarios, evaluate the response efficiency of equipment, and identify key weak links by statistical means. On this basis, combining the indoor test and field debugging results, the targeted improvement measures are put forward from the aspects of hardware redundancy design, software optimization and upgrading, and staff training. The purpose of this paper is to improve the reliability of equipment, reduce the occurrence of sudden power failure accidents and ensure the safety and stability of power grid. Due to the adoption of hardware redundancy technology, the failure detection rate of the system has increased from 85% to 97%, which shows a great improvement. The research results of this paper will greatly improve the adaptability and reliability of microcomputer-based relay protection and promote the scientific and technological progress and development of electric power industry.

1. Introduction

With the increasing complexity of modern power system, the role of microcomputer relay protection device is increasingly prominent, which plays a key role in ensuring the safe and stable operation of power grid. However, the reliability challenge of these systems also increases, and the occurrence of faults and abnormal situations may lead to serious power grid accidents. These studies show that improving the reliability of microcomputer relay protection devices is an important research direction at present. In this study, FTA and failure mode impact analysis methods are adopted, and combined with experimental and field investigation data, the weak points of the device are systematically analyzed and diagnosed, and further targeted promotion strategies are put forward. This research not only enhances the understanding of potential failure modes of relay protection devices, but also provides strategic support for improving the overall stability of power system.

The main research content of this paper focuses on the reliability analysis and promotion strategy of microcomputer relay protection device. Firstly, by analyzing the fault history and operation data of equipment, the most common fault modes and their causes are identified. Subsequently, FTA and FMEA methods are applied to systematically evaluate the potential impact of these failure modes on power system security, and how to effectively intervene through technical and management measures. In addition, this paper also discusses a variety of promotion strategies, including hardware upgrade, software optimization and operator training, in order to verify the actual effect and feasibility of these strategies through empirical research. Through these comprehensive methods, this study aims to improve the operation reliability of microcomputer relay protection devices, thus enhancing the safety and stability of the whole power system.

The structure of this paper is as follows: Firstly, the working principle of microcomputer relay protection device and its application background in power system are introduced in detail, as well as the main challenges facing this field at present. Then, the research methods and data collection process are analyzed, and the acquisition and analysis process of fault data, as well as the specific technical methods adopted, are described in detail. Finally, the research results are displayed, including the specific content and implementation effect of fault mode diagnosis, impact assessment and promotion strategy, and finally the theoretical and practical significance of the research is summarized, and suggestions for future research direction are put forward. Through rigorous data analysis and empirical research, the whole article tries to provide scientific and practical guidance for improving the reliability of microcomputer relay protection devices.

2. Related Work

As a new type of relay protection equipment, it is of great significance to study the microcomputer relay protection device deeply to ensure the safe and stable operation of the power grid. How to improve the effectiveness and accuracy of fault diagnosis is the focus of many scholars at present. For example, due to the adoption of artificial intelligence technology, the speed and accuracy of defect identification of the system have been significantly improved. Wang Junshan analyzed the reliability of relay protection and automatic control equipment in power system [1]. Wang Che conducted reliability research on relay protection and automatic control equipment in the power system [2]. Shi Jian conducted a study on the reliability of relay protection automation devices in power systems [3]. Sun Jie conducted a study on the reliability of relay protection and its automation devices in power systems [4]. Ding Xiaobing conducted a study on the testing method and failure rate of single particle effect in relay protection devices [5]. Despite the remarkable progress, the existing studies tend to neglect the performance of devices in extreme environments, and the adaptability and robustness to environmental factors are not sufficiently analyzed.

In addition, the reliability study of microcomputer relay protection devices is urgent for preventing large-scale power failures, which can reduce huge economic losses and social impacts. Ma Xiaoteng explored a relay protection device defect management system [6]. Liu Kui conducted a reliability study of intelligent substation relay protection and automation system [7]. Men Dianqing studied the online detection technology of relay protection reliability based on artificial intelligence [8]. Sizykh V N argued that the unified template can be used as an automation system for the trainability element of microprocessor relay protection devices [9]. Qi Z explored the flexible DC distribution grid relay protection operation and control methods compatible with distributed power sources [10]. Most of these studies focused on theoretical modeling and laboratory testing, and lacked long-term field validation in actual grid systems, making the practicality and generalizability of the results still need to be improved.

3. Method

3.1 Data Collection and Pre-processing

(1) Collection of fault data

In the reliability analysis of microcomputer relay protection device, it is necessary to collect relevant fault data comprehensively first. This includes detailed fault records from multiple power system operators, such as failure time, duration, failure type, failure impact range and recovery operation records. At the same time, the information of equipment operation state (temperature and humidity, equipment load, etc.) is collected to provide a basis for further failure mode analysis.

(2) Data pre-processing

In order to ensure the accuracy of the test results, the collected data were strictly preprocessed. The data preprocessing part mainly cleans up the data, records the data incompletely, formats the data, and processes the missing values. By using statistical methods, the essential characteristics of data such as mean, standard deviation and distribution are analyzed to find out possible outliers. On this basis, a data preprocessing method based on wavelet transform is proposed.

The failure rate λ is calculated as follows:

$$\lambda = \frac{z_c}{z_s} \tag{1}$$

z_c is the total number of failures and z_s is the total operating time. It is used to calculate the average failure rate of the microcomputer relay protection device, which is a basic parameter in reliability analysis to describe the frequency of failures per unit of time.

3.2 FTA Method

(1) Constructing the fault tree

When analyzing the reliability of microcomputer protection equipment, it is necessary to collect the relevant fault data comprehensively. This includes detailed fault records from multiple power system operators, such as failure time, duration, failure type, failure impact range and recovery operation records. At the same time, the information of equipment operation state (temperature and humidity, equipment load, etc.) is collected to provide basis for further fault tree analysis.

(2) Fault probability calculation

When determining the probability of each basic accident, it is generally based on previous accident data and expert experience. Bayesian network, Markov and other probability statistics methods are used to estimate the probability of extreme events. This step is the basis of evaluating the overall reliability of the system, and the weak links in the system are found by using the quantitative probability.

The system reliability metrics $R(t)$ are as follows.

$$R(t) = e^{-\lambda t} \tag{2}$$

Here, t represents time. This formula is used to calculate the probability of fault-free operation of a device during time t and is a standard method of assessing the reliability of a relay protection device at a given time.

3.3 FMEA Methods

(1) Identify failure modes

The detailed failure mode impact analysis was conducted to identify various possible types of faults. Among them, hardware failures include wire breakage, short circuit, aging of components, etc; software failures include program errors, data processing errors, etc; system level failures include communication interruptions, configuration errors, etc.

(2) Evaluate the impact of failures

The influence of various failure modes on the stability of the system, the time required for failure recovery and the resulting economic losses are analyzed. The evaluation work depends on the detailed simulation of the system and the analysis of historical data. On this basis, we also need to consider the detectability and repairability of the fault, so as to put forward an effective countermeasure.

The top event probabilities1 in fault tree analysis P_{d}[11] are as follows:

$$P_{\mathrm{d}} = 1 - \prod_{i=1}^{n}(1 - P_i) \tag{3}$$

Where P_i is the probability of occurrence of a single basic event and n is the total number of basic events. This formula is used to calculate the probability that multiple independent events together lead to the occurrence of a top event, and is a common method for calculating the probability of failure of complex systems in fault tree analysis.

3.4 Design and Implementation of Enhancement Strategies

(1) Design of enhancement strategy

This paper puts forward a targeted promotion strategy. These include increasing hardware redundancy, updating and optimizing software algorithms, improving system fault tolerance, and strengthening staff training and emergency response capabilities [12].

(2) Implement and validate the enhancement strategy

In this paper, the proposed lifting scheme is applied in practice, and tests and field tests are conducted to validate the proposed scheme. The specific research content is as follows: under the real operating environment, the proposed scheme is tested and evaluated for its effect on reducing the probability of failure, shortening the recovery time of failure, and improving the overall stability performance of the system. During the execution process, the execution situation during the execution process is collected and analyzed, and a careful comparison is made to ensure the correctness of the execution strategy. On this basis, improvement measures are proposed to ensure the safe, stable and reliable operation of the power grid.

The system effectiveness E is as follows.

$$E = \frac{\sum \mathrm{c_s}}{\sum \mathrm{z_x}} \tag{4}$$

This formula is used to assess the efficiency of a microcomputer relay protection device in fault response, where successful response time $\mathrm{c_s}$ is the time it takes for the device to successfully recognize and act on a fault, and total response time $\mathrm{z_x}$ is the total time it takes for the device to respond to all faults. This metric helps to measure the effectiveness of the device in responding to faults after the implementation of the enhancement strategy [13].

4. Results and Discussion

4.1 Experimental Setup

All experiments were conducted in a simulated power network environment that emulated a typical urban power grid including power stations, substations and distributed loads. In each experiment, microcomputer relays were configured at key nodes to monitor and protect the operation of the grid. The main parameters of the experiments include real-time data of power signals such as current, voltage, and frequency, as well as environmental factors such as temperature and humidity. Fault injection techniques are used to simulate different types of network faults such as short circuits, open circuits and equipment failures.

4.2 Analysis of Results

(1) Basic test

The basic test results are shown in Table 1.

Table 1: Basic test results

Fault type	Fault detection rate (%)	Mean failure response time(ms)
Short circuit	80	250
Open circuit	75	280
Overload	90	200
Ground	65	320
Equipment	70	260
Other complex	55	350

First, in terms of the fault detection rate, the overload fault has the highest detection rate of 90%, indicating that the device is more capable of recognizing overload faults. The detection rates of short-circuit faults and equipment faults were also high, at 80% and 70%, respectively. However, ground faults and other complex faults had lower detection rates, which may indicate that these fault types are more difficult for the device to recognize.

Second, in terms of average fault response time, the response time for overload faults is the shortest at 200 ms, showing that the device can react quickly after detecting an overload fault. Short circuit faults and equipment faults also have shorter response times, but ground faults and other complex faults have longer response times, which may affect the timeliness of fault handling.

In summary, the microcomputer relay protection device exhibits different detection rates and response times for different types of faults in the baseline test. In order to improve the overall performance, ground faults and other complex faults need to be further optimized and debugged to enhance their recognition ability and response rate. At the same time, it is also important to maintain a high detection rate and short response time for common faults such as overloads and short circuits.

(2) Hardware redundancy experiment results

The results of the hardware redundancy experiment are shown in Table 2.

First, from the point of view of fault detection rate, after hardware redundancy, the detection rate of all kinds of faults is significantly improved. Whether it is short-circuit faults, open-circuit faults, overload faults, grounding faults, equipment faults or complex faults, the detection rate is significantly improved, especially for short-circuit faults and overload faults, whose detection rate is close to or more than 95%. This indicates that the hardware redundancy strategy is very effective in improving the fault detection capability.

Second, in terms of system recovery time, the system recovery time after hardware redundancy is significantly shortened. Taking the short-circuit fault as an example, the original recovery time is 5 seconds, while it is shortened to 2 seconds after adding hardware redundancy. Recovery times for other fault types are also reduced to varying degrees, which means that when a fault occurs, the system is able to return to normal operation more quickly and reduce downtime due to the fault.

Table 2: Hardware redundancy experiment results

Fault type	Original fault detection rate (%)	Fault detection rate after hardware redundancy (%)	Original system recovery time (s)	System recovery time after hardware redundancy (s)
Short circuit	80	95	5	2
Open circuit	75	90	6	2.5
Overload	90	98	4	1.5
Ground	65	85	8	3
Equipment	70	92	7	2.8
Other complex	55	80	10	4

Comprehensive analysis of the above, increasing hardware redundancy at critical nodes is an effective strategy that not only improves the fault detection rate of the microcomputer relay protection device, but also shortens the system recovery time, thus enhancing the stability and reliability of the power system. This is of great significance in ensuring the continuous operation of the power system and reducing fault losses.

(3) Software optimization experiment results

The results of software optimization experiments are shown in Figure 1 (Figure 1(a) shows the original accuracy and the accuracy after software optimization, and Figure 1(b) shows the original response speed and the response speed after software optimization).

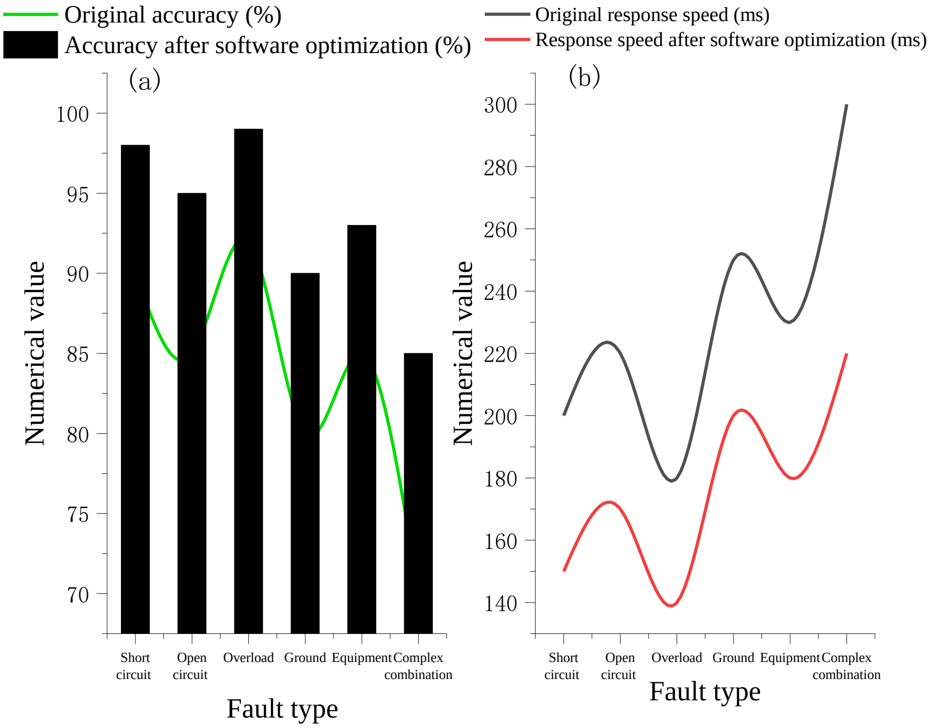

Figure 1: Experimental results of software optimization

First, in terms of processing accuracy, the software optimization has significantly improved the processing accuracy of various fault types. The accuracy of short-circuit faults, open-circuit faults, overload faults, grounding faults, equipment faults and complex combination faults are all improved, among which the processing accuracy of short-circuit faults and overload faults is close to perfect. This indicates that the new software algorithms and fault diagnosis logic are more accurate and can recognize and handle various fault types more effectively.

Secondly, the response speed has been greatly improved through software optimization. It is of great significance to reduce the response time from 300 ms to 220 ms for all kinds of faults, especially for complex compound faults. Fast response capability means that the system can respond in a shorter time, so it can protect the power grid more timely.

Generally speaking, the optimization of software can not only improve the fault handling accuracy of microcomputer relay protection device, but also make the response of microcomputer relay protection device faster, which can effectively reduce the potential safety hazards when accidents occur. The optimization of the software has achieved good results, which is of great help to improve the performance of microcomputer protection.

(4) Operator response experiment

The results of the operator response experiment are shown in Figure 2.

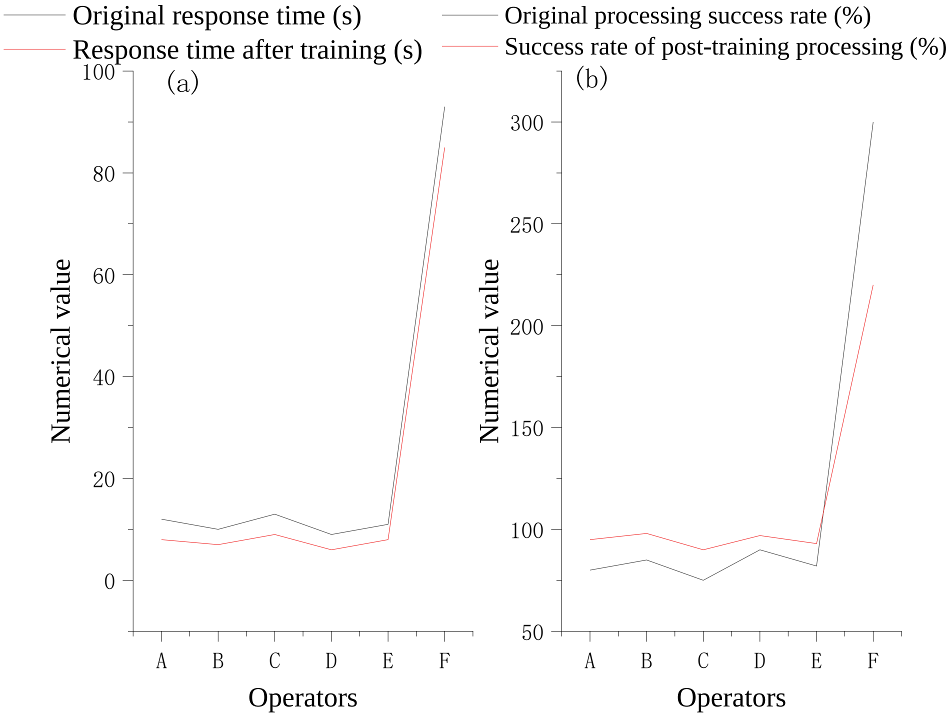

Figure 2: Results of operator response experiment

First, as for the response time, the response time of all operators has been reduced after training. For example, the response time of operator A is shortened from 12 seconds to 8 seconds. Reduced response time means that in an emergency, operators can respond more quickly, which may reduce potential losses or risks.

Second, there was also a significant improvement in the processing success rate. The processing success rate of all operators after training exceeded the original level, and the improvement was large. Operator B's processing success rate even reached 98%, which is a very high level, showing that the training not only improved the response speed, but also enhanced the operational skills and decision-making ability, which made them more comfortable and accurate in handling the faults.

In summary, emergency response training has a significant effect on improving the response speed and handling success rate of operators. This not only improves the professional ability of operators, but also provides a strong guarantee for responding to emergencies.

(5) Results of the comprehensive strategy experiment

The results of the comprehensive strategy experiment are shown in Table 3.

Table 3: Results of the comprehensive strategy experiment

Strategy/Indicators	Raw data	Data after implementing the strategy
Hardware redundancy		
Fault detection rate	85%	97%
System recovery time (s)	5	2
Software optimization		
Accuracy of fault handling	90%	98%
Fault response speed (ms)	200	120
Operator training		
Response time (s)	11	7
Processing success rate	82%	96%
Overall performance		
Average fault detection rate	85%	97%
Mean failure response time (ms)	200ms (including personnel response)	125ms (including personnel response)
Average processing success rate	82%	96%

Firstly, the hardware redundancy technology is adopted, which improves the accuracy of error detection from 85% to 97%, showing a great improvement and a high ability of error identification. At the same time, the time required for system recovery was reduced from 5 seconds to 2 seconds, which greatly accelerated the speed of system recovery.

Secondly, by optimizing the software, the accuracy of error handling is improved from 90% to 98%, which shows high accuracy and reliability. The experimental results show that this method can effectively improve the response ability of the system to faults.

The training strategy for operators has also achieved remarkable results. The reaction speed is reduced from 11 seconds to 7 seconds, which shows that the operator can handle the fault quickly and efficiently. The results show that the important role of training strategies in improving employees' working ability and efficiency has increased from 82% to 96%.

Generally speaking, by taking measures such as hardware redundancy, software optimization and operator training, the average fault detection rate, average fault response time and average processing success rate can be effectively improved. This method has high application value on the premise of ensuring the system running stably, reliably, efficiently and accurately. On the premise of ensuring the safety and stability of the power grid, the above measures are very necessary.

(6) Long-term operation test

The results of the long-term operation test are shown in Figure 3.

First of all, from the first 5 months of failures to 0.2 in 12 months, we find that the number of failures is significantly reduced. This improvement not only reduces the maintenance cost, but also improves the overall security level of the power grid.

Secondly, the improvement of trouble-free working condition rate is more obvious. The baseline data is 85% and the twelfth month is 99%, which shows that the system is in a trouble-free state in most cases. This high reliability ensures the continuous and stable operation of the power grid and reduces the risk of power failure caused by accidents. This improvement is attributed to the previous comprehensive improvement strategy, including hardware redundancy, software optimization and operator training. The redundancy of hardware ensures that when the equipment fails, it can be quickly switched to the backup equipment, thus shortening the time of failure. By optimizing the software, the response ability of the system to complex errors is improved and the reliability of the system is improved. In addition, the training of operators can also improve their ability to deal with emergencies and reduce accidents caused by human errors.

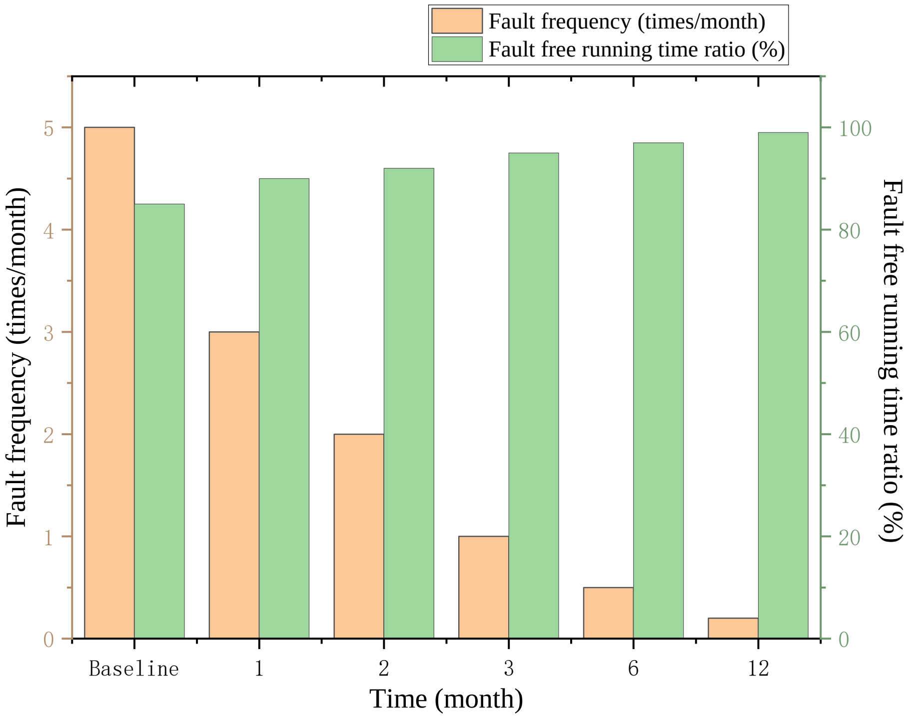

Figure 3: Long-term operational test results

On the whole, after a long period of test, the microcomputer relay protection device has high reliability and stability. The research results of this project will provide a strong guarantee for the safe and stable operation of China's power grid. In the future work, the system needs to be continuously improved to improve its performance and reliability.

5. Conclusion

In this study, FTA and FMEA methods are used to systematically diagnose and analyze the reliability of microcomputer relay protection devices, and the potential failure modes of the devices and their effects on power systems are identified. By collecting and preprocessing the actual data, a fault tree model is constructed and the effects of different fault modes are evaluated. Based on these analyses, specific promotion strategies are put forward, including hardware redundancy, software optimization and operator training, and the effectiveness of these strategies is verified through a series of experiments. The research results show that the implementation of the lifting strategy significantly improves the reliability of the microcomputer relay protection device. Specifically, hardware redundancy enhances the fault detection ability and recovery ability of the system, software optimization reduces the fault response time, and effective training of operators improves the success rate of fault handling. The implementation of the comprehensive strategy further improves the overall stability and reliability of the system, and verifies the effectiveness of the multi-dimensional improvement strategy.

Although this study has achieved positive results, there are still some limitations. First of all, data collection mainly depends on the existing fault records, which may not completely cover all potential fault modes, especially in extremely rare cases. Secondly, although the fault simulation experiment is carried out in the control environment, the complexity of the actual power grid environment may lead to the difference between the experimental results and the actual application. In addition, the cost-benefit analysis of the promotion strategy is not discussed in detail in this study, which is an important factor to determine the feasibility of the strategy. Future research can be further expanded from several aspects: First, more advanced data analysis tools can be developed to identify and predict more complex and hidden failure modes. Secondly, it is suggested to carry out more extensive field tests to verify the effect of the lifting strategy under various operating conditions and adapt to the actual complexity of the power system. In addition, a detailed cost-benefit analysis of the promotion strategy will help power grid operators to make more reasonable decisions in actual operation. Finally, considering the rapid development of technology, future research should pay attention to the application potential of emerging technologies, such as artificial intelligence and machine learning, in improving the reliability of microcomputer relay protection devices. These technologies can provide more efficient and intelligent solutions for fault diagnosis and treatment.

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