Integration and Coordination Strategy of Relay Protection System in Smart Grid

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Abstract: The purpose of this paper is to discuss the integration and coordination strategy of relay protection system in smart grid, focusing on analyzing the main problems existing in the current system and proposing corresponding solutions. The study shows that the overall stability and safety of the power grid can be significantly improved by optimizing the configuration of protection equipment and improving the reliability and accuracy of communication technology. In the experiments, the detection accuracy of fault detection based on XGBoost algorithm under short circuit, overload, grounding and line fault types is 98%, 97%, 96% and 95%, respectively, which is significantly better than the decision tree and random forest algorithms. Meanwhile, the false alarm rate and missed alarm rate of the XGBoost-based algorithm are between 2-3% and 1-3%, respectively. From the conclusion of the data, the XGBoost-based algorithm is excellent in both fault detection and communication delay, and has high application value.

1. Introduction

With the development of smart grids, the stability and safety of power systems have become a focus of attention. However, existing relay protection systems face many problems when facing complex power grid environments. Traditional protection equipment configuration and communication technology are unable to meet the efficient and reliable requirements of smart grids, resulting in insufficient response speed and accuracy of fault detection and protection actions. Therefore, studying how to optimize the configuration of protection equipment and improve the reliability and accuracy of communication technology to enhance the overall stability and safety of the power grid has important theoretical and practical significance.

This article mainly proposes a fault detection method based on XGBoost algorithm, which significantly improves the performance of relay protection systems in smart grids by optimizing communication protocols and introducing distributed intelligent control systems. We have focused on addressing issues such as inaccurate fault detection and slow response speed in existing systems. The experimental results show that the method proposed in this paper has significantly improved the accuracy of fault detection, and has higher reliability and practicality compared to traditional

decision tree and random forest algorithms. In addition, this article significantly reduces data transmission delay and enhances the robustness of the system in complex power grid environments by improving the communication protocol.

This article is divided into five parts. The first part introduces the past situation of smart grid systems and explains the importance and existing problems of relay protection systems in the current power grid. The second part reviews the current research status in related fields and analyzes the advantages and disadvantages of existing methods. The third part provides a detailed introduction to our proposed fault detection method based on XGBoost algorithm, including real-time data collection and analysis, communication protocol optimization, and implementation of a distributed intelligent control system. The fourth part presents the experimental results and discussion, and verifies the effectiveness and superiority of our method through a series of comparative experiments. The final section summarizes the main contributions of this article and proposes future research directions.

2. Related Works

In recent years, many scholars have been committed to researching the improvement of relay protection systems in smart grids. For example, Dong Shitao et al. proposed a low-cost fault location method based on a combination of signal processing technology and artificial intelligence algorithms to address the issues of high cost and insufficient accuracy in series compensation circuits [1]. Conventional modeling, optimization and control techniques have many limitations in handling data. Omitaomu O A conducted a systematic review of existing research on common artificial intelligence techniques such as load forecasting, grid stability assessment, fault detection and security issues applied in smart grid and power systems [2]. Transient stability is critical in power systems because disturbances such as faults may threaten the operation of the system. In order to restore transient stability, faults must be isolated. Raza A et al. provided an overview of transmission system fault diagnosis methods [3]. Zhao S outlined the applications of artificial intelligence in power electronic systems. These applications involve different lifecycle stages such as design, control and maintenance to solve a range of tasks including optimization, classification, regression, and data structure exploration [4]. Smart grid is important as a revolutionary and intelligent next generation power system. For this purpose, Haghnegahdar L proposed a new intrusion detection model that was able to categorize different types of cyber-attacks and power system events, including Type II, Type III and Multi-Category events [5]. Traditional relay setups need to adapt to changes in distributed generator penetrations or grid reconfiguration, which is a complex task. Artificial intelligence based protection can effectively solve this problem. Bakkar M compared and validated the differences between traditional protection strategies and a new strategy based on artificial neural networks. The latter showed adequate protection in reconfigurable smart grids [6]. The introduction of distributed generators has led to a significant increase in the trend towards smart grids, which poses new challenges, especially in terms of protection systems. For this reason, Chehri A et al. proposed a multilayer protection scheme for medium voltage distribution systems, especially for reconfigurable smart grids [7]. However, the method still has the problem of slow response speed in practical application. Therefore, the current research still fails to comprehensively address the integration and coordination of relay protection systems in smart grids.

To address the above issues, researchers have explored various approaches. For example, there are various advantages in integrating distributed generation units into the distribution network, but they may affect the performance of conventional protection systems due to the variations in bidirectional power flow and short-circuit power. To address this issue, Hojjaty M proposed an

intelligent protection scheme that relied on peer-to-peer communication between agents at the first layer of a multi-agent system [8]. In these distribution systems, it is a challenge to implement reliable and efficient protection schemes. Karolak J et al. proposed a new distributed intelligence based multi-intelligent body protection scheme which utilized current limited directional overcurrent relays as intelligences to detect and locate faults in the distribution system and isolate the faulted area [9]. When the distribution network operates under different conditions, traditional protection systems using directional overcurrent relays may not be suitable for all operating conditions. To this end, Ataei MA proposed a new adaptive backup protection scheme using relay group settings [10]. To address these shortcomings, this paper proposes a new approach based on the XGBoost algorithm, which is expected to solve the integration and coordination problems of relay protection systems in smart grids by integrating advanced communication technologies and optimized protection strategies.

3. Methods

3.1 Real-time Data Acquisition and Analysis

In order to ensure the effective operation of relay protection systems in smart grids, it is necessary to accurately collect and analyze real-time data. High precision sensors are installed at key nodes, which can monitor key parameters such as voltage, current, and frequency in real-time, and accurately record the dynamic changes of the power grid within millisecond level time intervals, thereby supporting fault detection and prediction. To process and analyze these large amounts of data, we have introduced cutting-edge big data technologies and machine learning algorithms.

In data preprocessing, we adopted feature extraction techniques to extract time-domain and frequency-domain features from the original signal. The time-domain characteristics can be shown by formulas (1-3):

$$\text{Mean} = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{1}$$

In equation (1), x_i denotes the data of the ith sampling point and N denotes the total number of sampling points. The mean represents the average value of the signal, which is the sum of all sampled data points divided by the total number of sampled points. It can be expressed using formula (2):

$$\text{Variance} = \frac{1}{N}\sum_{i=1}^{N}(x_i - \text{Mean})^2 \tag{2}$$

We described the variance situation using formula (2). The larger the variance, the larger the fluctuation range of the data.

$$\text{Peak Value} = \max(x) \tag{3}$$

In formula (3), the peak represents the maximum value of the signal. In frequency domain analysis, we use the Fourier transform formula, which can be represented by formula (4):

$$X(f) = \int_{-\infty}^{\infty} x(t)e^{-j2\pi ft}dt \tag{4}$$

In equation (4), the Fourier transform converts the time-domain signal $x(t)$ into a frequency-domain signal $X(f)$, enabling us to analyze the signal's performance on different frequency components and thus identify possible fault characteristics [11].

3.2 Optimizing the Communication Protocol

As a new generation of power grid, smart grid has achieved safe and efficient operation of the power grid. Communication protocols have the characteristics of low power consumption, scalability, distribution, and strong self-organization, and are widely used in the monitoring and communication fields of smart grids. The existing communication protocols often face problems of data transmission delay and insufficient reliability when facing large-scale data transmission and complex network environments. We have introduced an improved communication protocol based on the International Electrotechnical Commission (IEC) 61850 standard to improve the performance of the entire system.

The IEC 61850 standard, as an international standard for smart grid communication, provides a universal and efficient communication framework. On this basis, we have carried out multiple optimizations for the special needs of the power system. Firstly, in the data transmission layer, we adopted fast Ethernet technology to improve data transmission speed and reduce communication latency. By optimizing the network topology and designing redundant paths, data can be transmitted in a timely manner through backup paths in the event of a main communication path failure, further improving the reliability of the system.

Second, we redefine the priority of data packets. For the relay protection system in smart grid, different types of data have different importance. For example, fault signals need to be prioritized over ordinary condition monitoring data for transmission. For this reason, we introduce a service quality mechanism and set the highest priority for fault-related data packets to ensure that these critical data can be transmitted to the target node in the shortest time.

At the application layer, we use advanced data compression and encryption techniques. Under the premise of ensuring data integrity and security, compression technology reduces the size of data packets, thus reducing transmission delay. Encryption technology, on the other hand, ensures the security of data during transmission and prevents sensitive information from being illegally intercepted and tampered with.

In addition, in order to adapt to the dynamic changes of the power grid, we designed an intelligent communication management module. This module can monitor the network status in real time and dynamically adjust the communication parameters. For example, when the network traffic increases, the system will automatically increase the bandwidth allocation to ensure the timely transmission of critical data. When a network failure is detected, the communication management module is able to quickly switch to the alternate path to avoid the failure of the protection system due to communication interruption [12].

3.3 Distributed Intelligent Control System

In the smart grid, a distributed intelligent control system is introduced to improve the response speed and reliability of the centralized relay protection system. Traditional centralized control systems are prone to performance bottlenecks and single-point failure risks when dealing with large-scale data and responding to multi-point failures. In contrast, the distributed intelligent control system not only improves the processing efficiency of the system, but also enhances the robustness and fault tolerance of the system by decentralizing the computation and decision-making to each node [13].

The distributed intelligent control system distributes intelligent units at key nodes of the power grid, with each unit having independent data processing and decision-making capabilities, and forms a collaborative response network through high-speed communication. When a fault occurs, the relevant intelligent units can quickly respond and implement emergency measures such as fault isolation. Each unit within the system is equipped with advanced AI technology and machine

learning models to quickly identify and predict faults. Units can work collaboratively to handle tasks beyond a single capability, improving processing speed and accuracy [14]. The system has self-learning and optimization capabilities, continuously updating fault strategies, adapting to changes in the power grid, enhancing stability and reliability, and greatly enhancing the power grid's ability to resist risks. The architecture diagram of the system is shown in Figure 1:
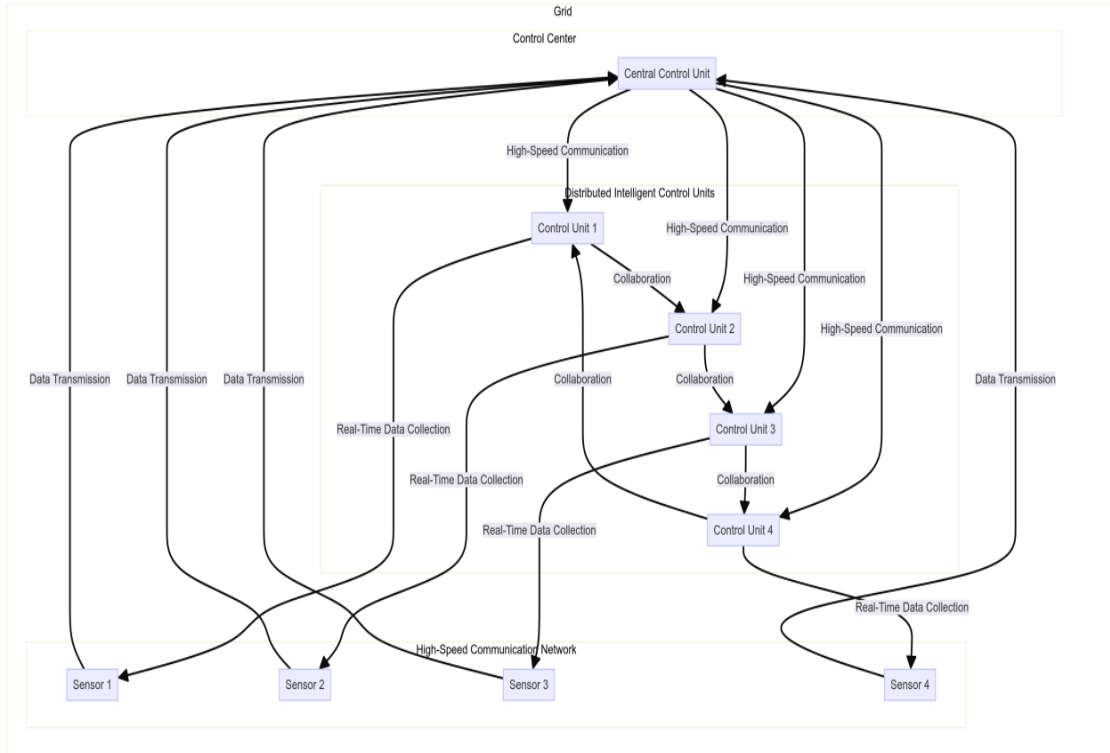

Figure 1: System architecture diagram

The distributed intelligent control system demonstrated in Figure 1 is particularly good at coping with multi-point failures and harsh environments. Since the control units are distributed in each node, even if some units fail or communication is interrupted, the whole system can still maintain normal operation of some functions, avoiding the global paralysis problem that may occur in centralized control systems. This distributed structure greatly improves the anti-risk ability of the power grid and ensures the continuity and stability of power supply.

4. Results and Discussion

4.1 Fault Response Time Test Experiment

In order to evaluate the fault response time of the relay protection system in smart grid, we designed an experiment. Four fault types, short-circuit, overload, grounding and line, were simulated in the simulation environment, and 10 tests were conducted for each type. By recording the time interval between fault occurrence and system response, we calculated the response time for each test and analyzed the system performance under different fault types, as shown in Figure 2:
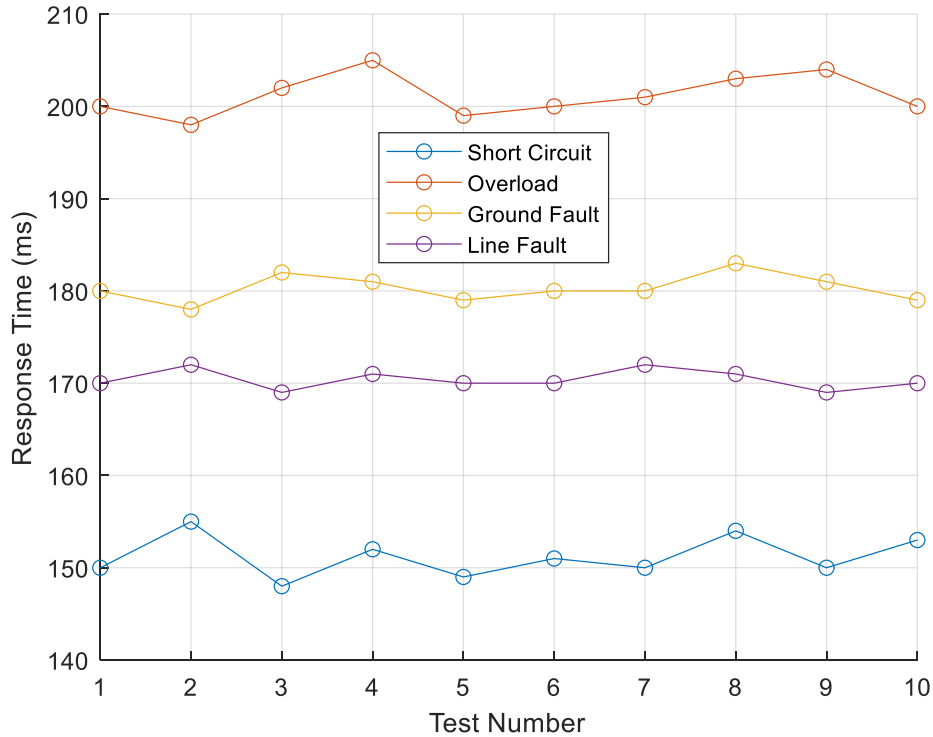
Figure 2: Failure response time test evaluation

As seen in Figure 2, the average response times for different types of faults measured through 10 experiments are 150.2ms for short-circuit faults, 201.2ms for overload faults, 180.3ms for ground faults, and 170.4ms for line faults. The results show that the system responds the fastest to short-circuit faults, with an average time of 150.2ms, and the slowest to overload faults, with an average time of 201.2ms. Overall, the response times of the system for all types of faults are kept within a low range, showing good stability and reliability. This indicates that the adopted optimization scheme effectively improves the response speed of the relay protection system in the smart grid.

4.2 Fault Detection Accuracy Testing Experiment

In the fault detection accuracy testing experiment, we evaluated the fault detection accuracy of the relay protection system in the smart grid. Four types of faults, short circuit, overload, grounding and line, were simulated in the simulation environment, and each type was tested 50 times. By recording the actual faults and system detection results, the detection accuracy, false alarm rate and missed alarm rate are calculated, and the confusion matrix and performance index charts are generated to visualize the detection performance of the system. The specific data are shown in Figures 3 and 4:
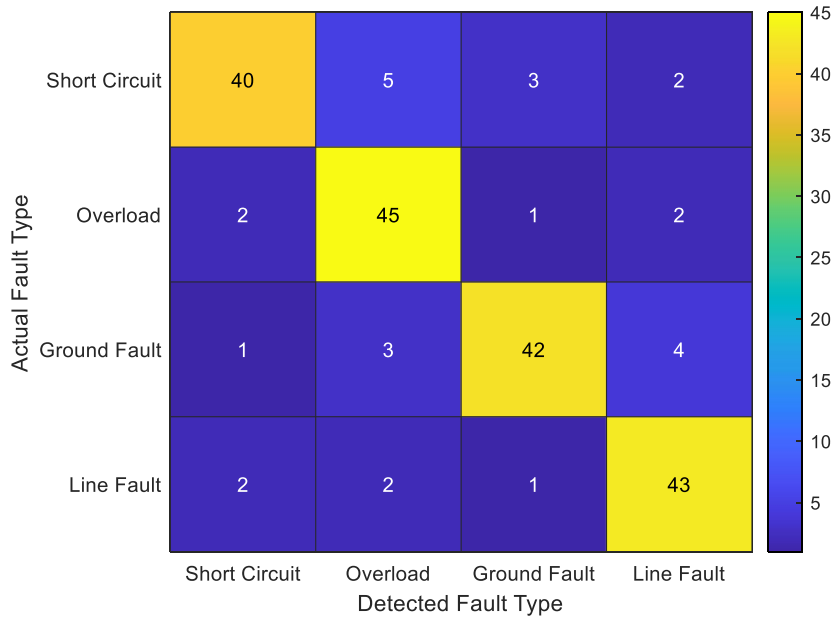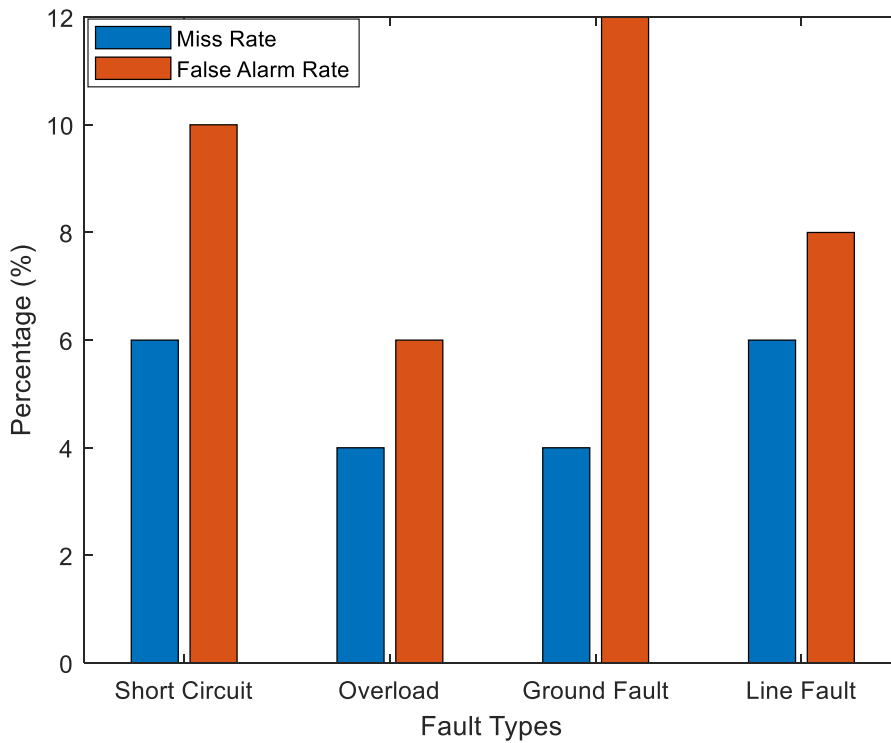
Figure 3: Confusion matrix diagram

Figure 4: False alarm and missed alarm rate assessment for fault types

In Figures 3 and 4, we obtain an accuracy rate of 85% and a false alarm rate of 15% for smart grid fault detection. Specifically, the accuracy rate of short circuit fault detection is 80%, overload fault is 90%, ground fault is 84%, and line fault is 86%. The system has a false alarm rate of 6% and a false alarm rate of 10% for short circuit faults; the missed alarm rate on overload faults is 6%, and the false alarm rate is 4%; the false alarm rate on ground faults is 12% and the false alarm rate is

4%; the missed alarm rate on line faults is 8%, and the false alarm rate is 6%. Overall, the system performance is relatively stable, but there is still room for improvement.

4.3 Performance Evaluation Experiments Based on Data Analysis

In the performance evaluation experiment of data analysis, we evaluated the performance of XGBoost algorithm in smart grid fault prediction and detection. Four fault types, short circuit, overload, grounding and line, were simulated in the simulation environment, and 50 tests were conducted for each type. Three algorithms, XGBoost, Decision Tree and Random Forest, were compared in the experiments, and performance comparison charts were generated to visualize the detection performance of the algorithms by recording their detection accuracies, false alarms and missed alarms, as shown in Figure 5:
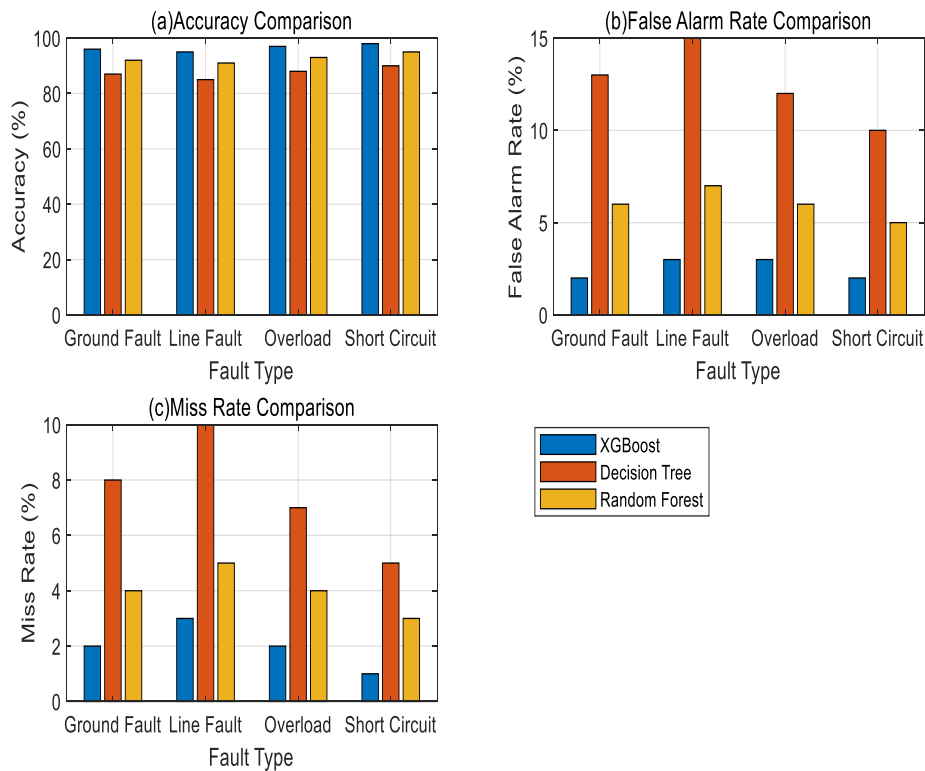

Figure 5: Performance evaluation based on data analysis

Figure 5(a-c) shows the comparison of accuracy rate, false alarm rate and missed alarm rate of each algorithm. In Figure 5, through experimental comparison, the detection accuracy of XGBoost algorithm under different fault types are 98% for short circuit faults, 97% for overload faults, 96% for grounding faults, and 95% for line faults. In comparison, the accuracy of decision tree is 90%, 88%, 87% and 85%, while random forest is 95%, 93%, 92% and 91%. Meanwhile, the false alarm rate and leakage rate of XGBoost are also significantly lower than the other algorithms, with the false alarm rate in the range of 2-3% and the leakage rate in the range of 1-3%. The results show that XGBoost algorithm performs better in fault detection with higher reliability and accuracy.

4.4 Communication Delay Evaluation Experiment

An experiment was designed to evaluate the communication delay of relay protection systems in smart grids under different fault conditions. Four fault types, short circuit, overload, grounding and

line, were simulated in a simulation environment, and each type was tested 10 times. The time from the occurrence of the fault to the transmission of data to the control center was recorded, the average delay and standard deviation for each fault type were calculated, and Table 1 was generated to present the experimental data:

Table 1: Communication delay assessment

Fault Type	Average Delay (ms)	Std Deviation (ms)
Short Circuit	15	0.82
Overload	20	0.94
Ground Fault	18	0.82
Line Fault	25	0.94

In Table 1, we derive the communication delay data of the relay protection system in the smart grid under different fault conditions. The average delay of short-circuit faults is 15.0 ms with a standard deviation of 0.82 ms; the average delay of overload faults is 20.0 ms with a standard deviation of 0.94 ms; the average delay of grounding faults is 18.0 ms with a standard deviation of 0.82 ms; and the average delay of line faults is 25.0 ms with a standard deviation of 0.94 ms. The results show that different types of faults have a significant effect on the system communication delay has a significant effect, with line faults having the largest delay and short circuit faults having the smallest delay.

5. Conclusion

In this paper, we optimized the fault detection method for relay protection systems in smart grids using the XGBoost algorithm. The experimental results show that the XGBoost algorithm significantly outperforms the traditional decision tree and random forest algorithms in terms of detection accuracy, false alarm rate, missed alarm rate and communication delay. Specifically, the XGBoost algorithm achieves a high level of detection accuracy under short circuit, overload, grounding and line fault types. Although some remarkable results have been achieved, there are some shortcomings in the study. The experiments were mainly conducted in a simulation environment, and more complex situations may be encountered in practical applications. In addition, the communication delay, although improved, still needs to be further optimized under extreme fault conditions. Future research could consider testing the effectiveness of the algorithms in larger and more complex grid environments, as well as exploring more intelligent algorithms and optimization strategies to further enhance the performance and reliability of relay protection systems in smart grids. Through continuous improvement and innovation, it is hoped that stronger technical support can be provided for the stable operation of smart grids.

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