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The Adaptability and Challenges of Protection Relays in Distributed Generation Systems

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Abstract: The adaptability of relay protection in distributed generation systems is an important research topic in modern power systems. This paper proposes a relay protection scheme based on random forest algorithm, and uses IoT technology for real-time data collection and processing. By constructing a simulation model of a distributed power generation system, we compared and analyzed the performance of traditional fixed threshold protection schemes and schemes based on random forest algorithm in terms of sensitivity, accuracy, and reliability. The experimental results show that the scheme based on the random forest algorithm reduces the average response time to 0.12 seconds when dealing with faults, and the misoperation rate and rejection rate are reduced to 5% and 3.3%, respectively. In addition, the reliability of the scheme remained above 95% during 30 days of simulated operation. Experimental data shows that the new scheme significantly improves the sensitivity and accuracy of relay protection, and better adapts to the needs of distributed power generation systems.

1. Introduction

With the rapid development of distributed generation technology, the structure and operation mode of modern power systems have undergone significant changes. The distributed power generation system supplements and optimizes the traditional centralized power generation model through various renewable energy sources such as wind energy, solar energy, and small hydropower. However, this new generation model also brings new challenges in the operation and protection of the power system. As a key technology for the safe operation of power systems, the adaptability and reliability of relay protection in distributed generation systems urgently need to be addressed.

This paper proposes a relay protection scheme based on random forest algorithm, combined with IoT technology for real-time data collection and processing, to improve the sensitivity and accuracy of relay protection. By constructing a complex simulation model of distributed power generation systems, this paper explores in detail the performance of the new scheme under different operating conditions and fault conditions, and conducts a comprehensive comparative analysis with traditional fixed threshold protection schemes. The research results indicate that the new scheme has significant advantages in sensitivity, accuracy, and system reliability, and can better meet the needs of distributed power generation systems.

The structure of the article is organized as follows: this paper firstly introduces the background and significance of the research on relay protection of distributed generation system, followed by reviewing the related research and clarifying the innovations and key issues of this paper. Then this paper details the research methodology, including the construction of system model, data processing process and the application of random forest algorithm, demonstrates the experimental design and the discussion of the results, and verifies the effect of the new method. Finally this paper summarizes the research results and discusses the future research direction.

2. Related Works

In recent years, many scholars have conducted research on the adaptability of relay protection in distributed power generation systems. For example, the complexity and uncertainty of modern power and energy systems are increasing day by day. Cao D et al. conducted a comprehensive literature review on reinforcement learning, covering its basic ideas, various types of algorithms, and their applications in power and energy systems [1]. With the advancement of technology, the demand for electricity has sharply increased. Butt O M et al. outlined the characteristics of "smart grids" and their different applications in the distribution industry [2]. Yuan C et al. believed that dielectric polymers for electrostatic energy storage had low energy density and low efficiency at high temperatures, which limited their applications in harsh environments such as electronic devices, circuits, and systems [3]. Rare and extreme weather events may lead to widespread power outages. Mahzarnia M et al. reviewed various commonly used methods and technologies and explored future trends in improving the resilience of power systems [4]. Meskin M et al. reviewed the impact of distributed generation integration on protection systems involved in other research works and outlined the suggested methods proposed by scholars [5]. The increasing vulnerability of distribution systems to extreme weather events has driven research on resilient distribution systems. Liu G et al. reviewed the latest research on distributed generation and microgrid assisted resilience enhancement [6]. Singh N et al. aimed to analyze the frequently occurring power quality issues in distributed generation. Most power quality disturbances in distributed generation are unstable and transient [7]. Gupta A R provided a comprehensive overview of the application of distributed generation and flexible AC transmission systems in distribution systems, aiming to improve voltage distribution, reduce line losses, and enhance feeder load capacity [8]. These studies indicate that although there have been certain achievements, there are still many problems in practical applications, such as insufficient protection sensitivity and high false alarm rates.

To address these issues, many researchers have attempted to adopt new methods to improve the performance of relay protection. For example, traditional relay settings need to adapt to the integration of distributed generators or changes in grid reconfiguration. Bakkar M et al. compared and validated the differences between traditional protection strategies and new strategies based on artificial neural networks [9]. Ufa RA et al. focused on the impact of distributed generators on power loss, voltage level, maintaining power balance, and participating in frequency regulation in power systems [10]. These methods have to some extent alleviated the protection challenges in distributed power generation systems, but there are still some shortcomings, such as high complexity and high cost. Therefore, in this paper, we propose an improved relay protection scheme based on random forest algorithm and Internet of Things technology to address the shortcomings in current research.

3. Methods

3.1 Construction of Distributed Power Generation System Model

Our research starts with building a simulation model of a distributed power generation system, with the main purpose of comprehensively testing the relay protection scheme we have designed. The establishment of a model based on the random forest algorithm starts with designing complex system topologies, including connecting various distributed power sources. All these power sources are connected to the power grid through network nodes, forming a complex and diverse distributed power generation network [11].

In order to make the model based on random forest algorithm more realistic, we thoroughly simulated the operating characteristics of various power sources. For example, in the wind power generation section, we simulated the impact of wind speed changes on output power; in the solar energy section, the impact of changes in light intensity and angle on power generation efficiency was simulated. In addition, the operation of energy storage equipment was simulated to reflect the actual impact of load fluctuations on the system, ensuring that the model can accurately reflect the dynamics of the distributed power generation system.

In the process of building this model, we made detailed adjustments to the electrical characteristics of the power grid, including setting line parameters, transformer and load characteristics, etc. These detailed settings are crucial for accurately evaluating the performance of relay protection equipment. Meanwhile, we have deployed a real-time data collection system that utilizes IoT technology to monitor key data such as voltage, current, and power at each node in real-time. The power can be represented by formula (1):

$$P(t) = V(t) \times I(T)\cos(\theta) \tag{1}$$

In formula (1), $V(t)$ represents voltage and $I(T)$represents current, and these data are used for subsequent algorithm optimization and experimental analysis.

To ensure that the model can truly reflect the operation of the distributed power generation system, we conducted a series of simulation tests, covering normal system operation, sudden load changes, and various fault situations. Comparing the simulated data with the data collected in actual operations can clarify the improvement needs of the model. Through this approach, we gradually adjusted the various parameters of the model to more accurately simulate the performance of distributed power generation systems in the real world. The topology structure of the distributed power generation system constructed in this paper is shown in Figure 1:

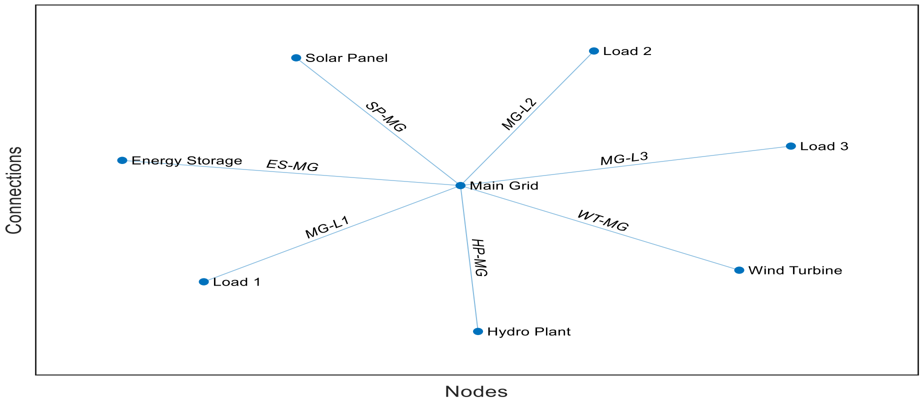

Figure 1: Topology structure of distributed power generation system

Figure 1 shows the topology of the distributed power generation system constructed in this paper. This model includes wind turbines, solar panels, small hydropower stations, energy storage equipment, as well as multiple power consumption nodes and the main grid. We simulate how a real distributed power generation system works, including its electrical characteristics, through these complex multi node connections.

3.2 Data Collection and Processing

In our study, collecting and processing data is crucial as it directly supports the algorithm optimization and performance evaluation we will be doing later. We used IoT technology to obtain key information of distributed power generation systems in real-time. Specifically, we have installed sensors at locations such as wind turbines, solar panels, small hydropower stations, energy storage equipment, and major power nodes, which can monitor electrical data such as voltage, current, and power. Table 1 contains some data samples that we have collected:

Table 1: System operation status

Timestamp	Node	Voltage (V)	Current (A)	Power (W)
2024-06-01 00:00	Wind Turbine	690	50	34500
2024-06-01 00:00	Solar Panel	480	20	9600
2024-06-01 00:00	Hydro Plant	400	30	12000
2024-06-01 00:00	Energy Storage	400	10	4000
2024-06-01 00:00	Load 1	230	40	9200
2024-06-01 00:00	Load 2	230	35	8050
2024-06-01 00:00	Load 3	230	45	10350

To ensure that the data we collected is both accurate and reliable, we used high-precision sensors in conjunction with a stable communication network. This device can quickly capture data at the millisecond level and transmit it to our central monitoring system through wireless networks. There, the data is first cleaned up, and we will screen out noise and standardize it to ensure that all data is of high quality and consistent. The normalization process can be represented by formula (2):

$$x' = \frac{x-min(x)}{max(x)-min(x)} \tag{2}$$

In formula (2), xrepresents the original data, x' represents the normalized data, and $min(x)$ and $max(x)$ represent the minimum and maximum values of the data, respectively.

The processed data is stored in a dedicated database for subsequent analysis and use. In the database, we have classified and labeled the data to enable quick retrieval and analysis when needed. In addition to real-time data collection, we have also set up regular data backup and recovery mechanisms to ensure timely recovery of system operation in the event of failures or data loss.

In the data processing process, we also used various data analysis tools and algorithms. These processing steps not only improve the efficiency of data utilization, but also provide scientific basis for parameter optimization of relay protection devices [12].

3.3 Application of Machine Learning Algorithms

In this study, we apply the random forest algorithm to optimize relay protection in order to improve the sensitivity and accuracy of distributed power generation systems. The random forest algorithm, as an ensemble learning method, can effectively process complex data by constructing multiple decision trees and combining their output results, and has strong noise resistance and high accuracy.

We first obtained a large amount of historical operating data from the data collection system, which included key parameters such as voltage, current, and power. After organizing these data, we divided them into a training set and a testing set for constructing and validating our random forest model, respectively. To ensure that the model is both stable and has good generalization ability, we also used cross validation techniques.

When adjusting our random forest model, we made subtle modifications to several key settings, such as the number of decision trees, the maximum depth of each tree, and the minimum number of samples required for nodes. The purpose of these adjustments is to optimize the performance of the model. In practical operation, we have noticed that increasing the number of trees can indeed improve the accuracy of predictions, but this also makes the entire calculation process more complex. In order to find a balance between efficiency and accuracy, we continuously experimented and adjusted, and finally locked in a set of parameter configurations that are most suitable for our system requirements. The basic construction formula of the random forest model is represented by formula (3):

$$h(x) = \frac{1}{N}\sum_{i=1}^{N} h_i(x) \tag{3}$$

In formula (3), $h(x)$ represents the output of the random forest, $h_i(x)$ represents the output of the i-th decision tree, and N represents the number of decision trees.

After completing the model training, we began a series of validation and testing. The results of these tests are very convincing: the random forest algorithm we use performs very well in handling various faults. Compared to traditional methods that use fixed thresholds, the random forest algorithm can more accurately identify the specific type and location of faults, greatly reducing the occurrence of misoperations and false alarms. In the experimental stage of this paper, it was found that the random forest algorithm can automatically adjust protection settings according to different situations during system operation, thereby improving the reliability of the entire system [13].

4. Results and Discussion

4.1 Sensitivity Evaluation Experiment

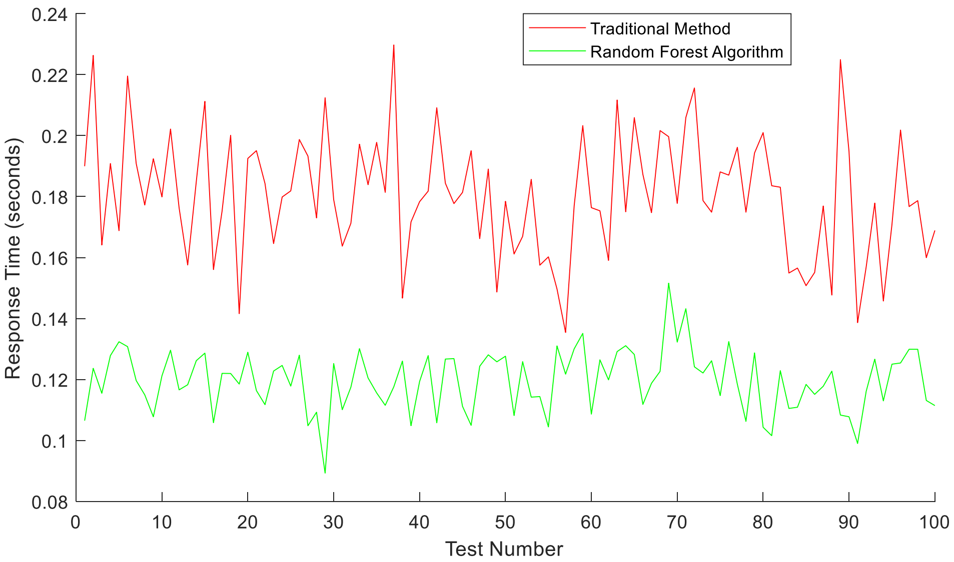

Figure 2: Sensitivity evaluation

In the sensitivity evaluation experiment, we simulated 100 different types of faults to test and compare the traditional fixed threshold protection scheme with our improved random forest algorithm based scheme. We paid special attention to the response time of the protective device when each fault occurred, which helped us evaluate the performance of the two solutions. In order to visually display these data, we have created a comparison chart of reaction time, which clearly shows the difference in sensitivity and stability between these two schemes when dealing with faults. Details are shown in Figure 2:

In the 100 simulation tests in Figure 2, the average response time of the protection device based on the random forest algorithm is 0.12 seconds, while the traditional protection scheme based on a fixed threshold setting has a response time of 0.18 seconds, which is 33% shorter. In Figure 2, the response time of the random forest algorithm is more stable and the fluctuation range is smaller. The above data conclusions indicate that the relay protection scheme optimized using random forest algorithm and IoT technology significantly improves the sensitivity and reliability of the system, better adapts to the needs of distributed power generation systems, and can more effectively ensure their safe and stable operation.

4.2 Accuracy Evaluation Test

In this experiment, we simulated 100 different types of faults, including short circuits, overloads, and ground faults. We recorded the misoperation and rejection of traditional fixed threshold protection schemes and protection devices based on random forest algorithm for each fault occurrence. We evaluated the accuracy of the two schemes by comparing their error rate and rejection rate under various fault types. The experimental results are presented through bar charts and line graphs to clearly compare the performance of the two schemes.

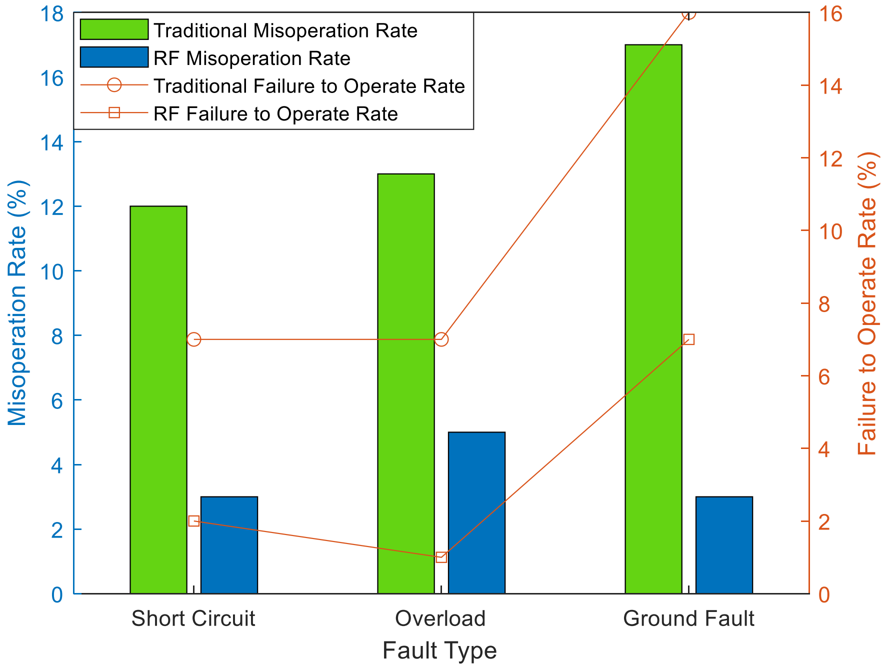

Figure 3: Accuracy evaluation

In Figure 3, we find that the improved relay protection scheme significantly improves accuracy in handling faults. Specifically, the average error rate of traditional methods is 14% and the average rejection rate is 10%, while the average error rate of the random forest algorithm is reduced to 5%

and the average rejection rate is reduced to 3.3%. It can be clearly seen from Figure 3 that the false alarm rate and rejection rate of the random forest algorithm are significantly lower than traditional methods under various fault types. This indicates that the relay protection scheme optimized using random forest algorithm and IoT technology not only has high sensitivity, but also greatly improves accuracy, better ensuring the safe and stable operation of distributed power generation systems. The specific data is shown in Figure 3:

4.3 Reliability Evaluation Experiment

In this experiment, we simulated the operation of a distributed power generation system for 30 days and recorded the occurrence of different types of faults (short circuit, overload, ground fault) and the response of protective devices every day. The reliability of the relay protection scheme based on the random forest algorithm was mainly evaluated. We have compiled daily operational data and plotted a chart of reliability over time. The specific data situation is shown in Figure 4:

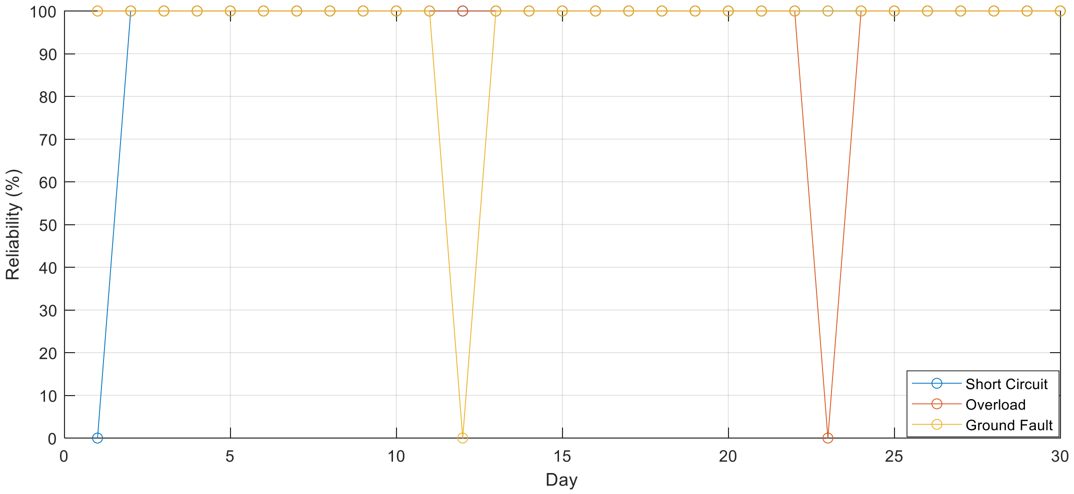

Figure 4: Reliability assessment

In the 30 day time series graph of Figure 4, the average reliability of the random forest algorithm remains above 95%. The protection device of the random forest algorithm maintains high stability for most of the time, and the failure rate is significantly lower than traditional solutions. This indicates that the relay protection scheme using the random forest algorithm not only has high sensitivity, but also has higher reliability in long-term operation, which can more effectively ensure the continuous and stable operation of distributed power generation systems.

4.4 Model Robustness Testing Experiment

In this experiment, we compared the installation, maintenance, and fault handling costs of traditional methods and relay protection schemes based on random forest algorithm. Meanwhile, we evaluated the benefits of two solutions in reducing the number of failures and improving fault response time. The data shows that although the initial installation cost of the random forest algorithm is high, the maintenance and fault handling costs in long-term operation are low, while significantly reducing the number of faults and response time. We can refer to Table 2 for the specific robustness situation:

In Table 2, the total cost of the traditional method is $14500, while the total cost based on the random forest algorithm is $16000. Although the initial installation and maintenance costs of the random forest algorithm are high, it has significant advantages in reducing the number of faults and improving fault response time, reducing a total of 45 faults and increasing response time by 0.06 seconds. Therefore, considering the long-term benefits comprehensively, the relay protection scheme based on the random forest algorithm has greater advantages in reliability and response speed.

Table 2: Evaluation of model robustness testing

Category	Traditional Method	Random Forest Algorithm
Installation Cost ($)	5000	7000
Maintenance Cost ($/day)	200	250
Total Maintenance Cost ($)	6000	7500
Total Fault Cost ($)	3500	1500
Total Cost ($)	14500	16000
Fault Reduction	-	45
Response Time Improvement (s)	-	0.06

5. Conclusion

The relay protection scheme based on random forest algorithm proposed in this paper significantly improves the relay protection performance in distributed power generation systems. Through detailed experimental verification, we have demonstrated that this scheme has significant advantages in improving reaction speed, accuracy, and system reliability. Compared with traditional protection schemes, the new scheme exhibits higher sensitivity and lower false alarm rate when dealing with various types of faults. In the future, we will further explore the applicability of this algorithm under a wider range of conditions and continuously optimize algorithm parameters to adapt to complex and ever-changing power grid environments. We believe that this study not only provides effective technical support for the safe and stable operation of distributed generation systems, but also brings new research ideas to the field of power system protection.

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