

# Development Status and Prospects of Relay Protection Technology in Smart Grids

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**Abstract.** With the rapid development of smart grids, ensuring system stability, security, and efficiency has become a key challenge. Relay protection technology plays a vital role in fault detection, isolation, and recovery, evolving with intelligent algorithms, digital equipment, and automated coordination to enhance grid reliability. This paper explores the development of relay protection technology in smart grids, analyzing its applications in intelligent algorithms, digital devices, and automated coordination. Practical case studies demonstrate its effectiveness, while key challenges such as system stability, information security, and cross-regional coordination are discussed. Finally, the paper examines future trends and potential advancements in relay protection technology.

**Keywords:** Smart Grid; Relay Protection; Automation; Adaptive Protection; Distributed Generation.

## 1. Introduction

With the rapid development of smart grids, relay protection technology, as a core component ensuring the safety of power systems, is undergoing profound changes and innovations. This paper systematically reviews the co-evolution of smart grids and relay protection technology: early traditional grids relied on one-way transmission and centralized generation, with relay protection technology primarily based on electromagnetic relays. With the advent of communication technologies and the proliferation of distributed energy resources, smart grids have gradually achieved multi-source information fusion and real-time control, and relay protection technology has also moved towards digitalization and intelligence. Currently, significant achievements in global smart grid construction have laid the foundation for the advancement of relay protection technology.

At the technical application level, relay protection in smart grids has achieved breakthroughs through wide-area protection, automatic setting systems, and digital technologies. Digital technologies, adhering to the IEC 61850 standard, enable multi-device coordination through GOOSE messages, effectively addressing the fluctuations caused by the integration of distributed generation [1]. Case studies demonstrate that these technologies have significantly improved fault isolation accuracy and system reliability [2].

However, relay protection in smart grids still faces multiple challenges. The volatility of distributed generation leads to voltage instability, and the complexity of short-circuit current distribution increases the risk of transient instability [3]. Cybersecurity threats reveal the potential for data tampering and device control loss. Cross-regional coordination is hindered by standard differences and communication delays, which can lead to protection misoperations. In the future, artificial intelligence and big data technologies will drive the deep development of adaptive relay protection. The adoption of 5G communication and standardization efforts are expected to resolve coordination issues, ultimately achieving precise fault prediction and optimized protection strategies, thereby providing robust support for the construction of new power systems.

## **2. Development of Smart Grids and Relay Protection**

### **2.1. Evolution and Current Status of Smart Grids**

The development of smart grids has been a gradual process. Early traditional grids primarily operated on a one-way transmission and centralized generation model, with limited monitoring and control capabilities. With the advancement of communication technologies, Supervisory Control and Data Acquisition systems (SCADA) were gradually applied to grids, enabling remote monitoring and control of some operational parameters. Subsequently, the rise of distributed energy resources, such as solar photovoltaic and wind power, demanded higher compatibility and flexibility from grids, giving birth to the concept of smart grids.

Currently, many countries and regions worldwide are actively promoting smart grid construction. The United States, through initiatives like GridWise, has significantly enhanced the intelligence level of its grids. In China, State Grid and Southern Grid have also made remarkable achievements in smart grid construction. By the end of 2024, China had built over 10,000 smart substations and achieved a smart meter coverage rate of over 90%, essentially realizing comprehensive real-time monitoring and management of electricity consumers.

### **2.2. Evolution and Current Status of Relay Protection Technology**

The development of relay protection technology has gone through several stages. In the early days, the implementation of relay protection functions mainly relied on electromagnetic relay devices, which detected faults by simply comparing electrical quantities such as current and voltage, with relatively limited functions. In the mid-20th century, with the development of semiconductor technology, relay protection devices based on transistors gradually replaced electromagnetic relays, improving the logical decision-making ability and response speed. In the latter half of the 20th century, relay protection devices based on integrated circuits further enhanced the reliability and accuracy of the protection devices. With the advent of the information revolution in the 21st century and in the era of smart grids, relay protection technology has undergone significant changes, rapidly developing towards intelligence, digitization and automation.

## **3. Technical Analysis of Relay Protection Functions in Smart Grids**

In the operation of smart grid systems, relay protection serves as a crucial protective mechanism. It intelligently monitors and controls various aspects of the grid system, providing effective protection and ensuring the safe and stable transmission and supply of electrical energy.

### **3.1. Wide-Area Protection Technology**

Wide-area protection technology is primarily based on the application of subset unit grids. It utilizes wide-area communication networks to collect real-time electrical quantity information from multiple nodes across the grid, enabling rapid and accurate fault identification and isolation through comprehensive analysis. The fundamental principle relies on synchronized phasor measurement data obtained from Wide-Area Measurement Systems (WAMS), which, through distributed computing and intelligent decision-making algorithms, determine fault locations and extents. By deeply analyzing and processing grid faults, it collects and organizes equipment status information, leveraging computer technology to systematically analyze and predict data, thereby identifying fault locations and providing critical information for maintenance. Wide-area protection technology consists of two main components: security automatic control technology and relay protection technology [4]. Security automatic control technology primarily handles grid faults and provides solutions, while relay protection technology diagnoses faults and offers references for maintenance personnel, thereby eliminating faults and enhancing grid relay protection capabilities.

### 3.2. Automatic Setting Systems

In the development of modern grids, power generation equipment exhibits significant distributed characteristics. The integration of new energy generation systems, such as photovoltaic and wind power systems, introduces notable fluctuations in power output, significantly affecting grid power flow distribution and reducing grid reliability. Traditional relay protection devices are set with specific values based on existing power system operating conditions. When system operations change, relay protection devices may misoperate because the preset values no longer suit the new operating environment, requiring manual recalibration. This increases the operational time for system changes, reduces power system efficiency, and can lead to misoperations[5]. In smart grids, as shown in Figure 1, the system automatically identifies the operating mode of the regional power system based on telemetry-collected operational information, transmitting this information to the relay protection system via telemetry to enable automatic adjustment of relay protection device settings, thereby avoiding system errors caused by manual misoperations[6].

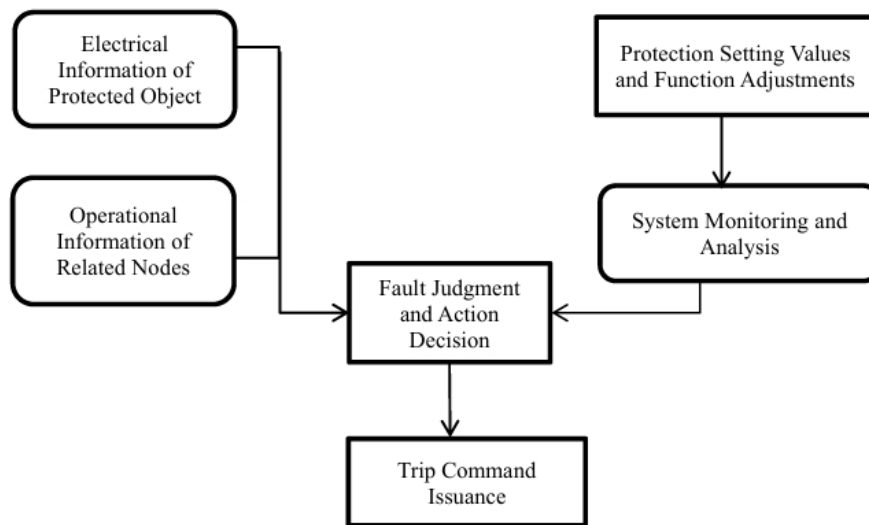


Figure 1: Structure of Automatic Setting System

### 3.3. Digital Relay Protection Technology

In traditional substations, protection devices, monitoring and control devices, and other equipment are connected to traditional transformers and primary equipment via secondary cables (as shown in Figure 2).

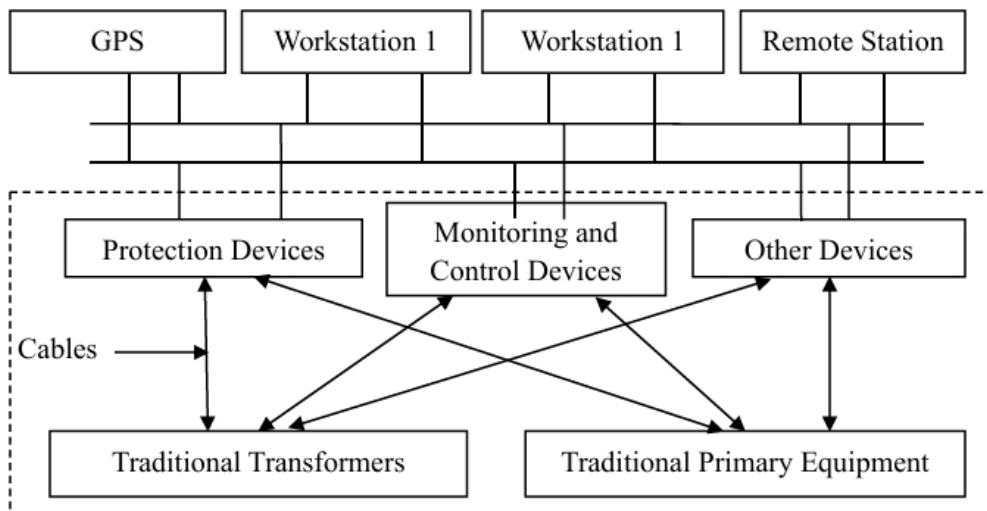
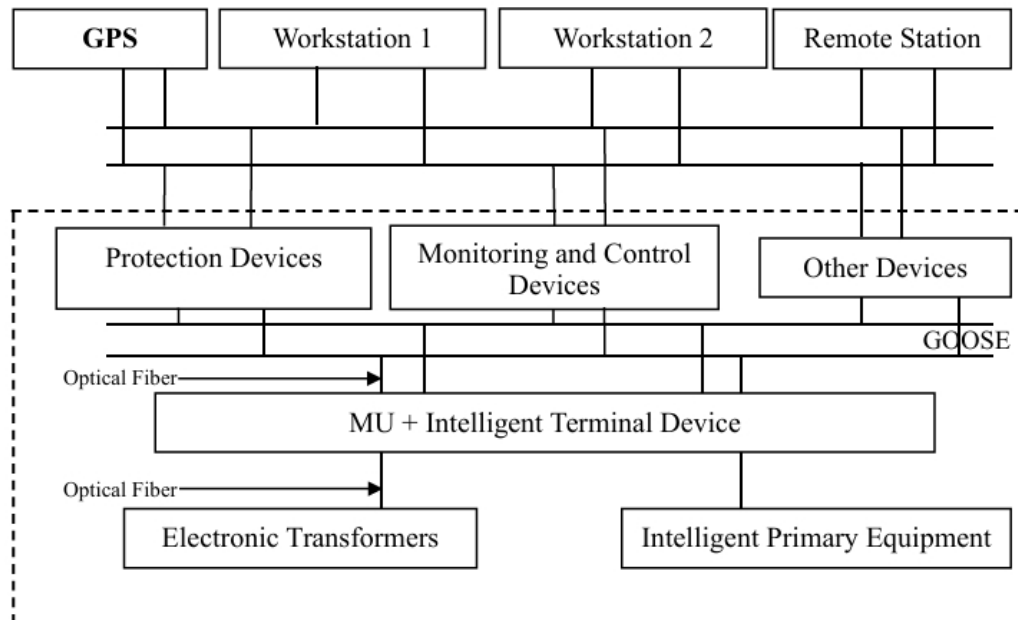


Figure 2: Traditional substation structure

In smart substations, as shown in Figure 3, the principle is based on digital signal processing technology, computer technology, and communication technology. By collecting, processing, and analyzing power system parameters, it real-time judges grid status and performs protection actions. Compared to traditional substation relay protection, digital relay protection devices offer higher precision, stronger functionality, flexible configuration, superior reliability, and ease of remote monitoring.



**Figure 3:** Structure of Smart Substation

The digital protection system, based on the IEC 61850 international standard adopted in 2002, plays a significant role in modern smart grids. This system, through unified communication protocols and data models, enables interoperability among devices from different manufacturers within substations. Comprising MMS services, GOOSE services, and SMV services, the system, by adhering to the IEC 61850 standard, facilitates data sharing and collaborative work on a single platform. In complex electrical faults, the protection devices can quickly obtain the operating status information from the surrounding equipment, achieve coordinated actions of multiple protection devices through information sharing and decision-making, precisely isolate the faulty part, and ensure the safe and stable operation of the power grid. The information exchange between relay protection devices relies on GOOSE message transmission [7]. In recent years, with the development of Internet of Things technology, the fault detection technology for distribution site equipment based on the Internet of Things has been proposed. Managers can monitor various parameters of distribution network operating equipment through mobile terminals, which makes the operation and maintenance of smart grid more convenient[8].

### 3.4. Automated Protection Coordination Technology

#### 3.4.1 Application of Wide-Area Protection Systems

For example, a regional grid implemented a wide-area protection system (WAPS). During a severe short-circuit fault, the WAPS accurately identified the fault location within 50ms and coordinated the actions of relevant protection devices, successfully isolating the fault and preventing cascading failures. Before the implementation of the WAPS, the average handling time for similar faults was over 150ms, significantly increasing the risk of accident escalation.

#### 3.4.2 Automated Protection Setting Calculation Systems

Automated protection setting calculation systems automatically compute and optimize relay protection settings based on real-time grid operating conditions and equipment parameters. For

instance, a provincial grid's automated protection setting calculation system can real-time acquire parameters of generators, transformers, transmission lines, and other equipment, as well as grid topology and operating condition information. Using built-in calculation models and optimization algorithms, it can complete protection setting calculations for complex grid operating conditions within 30 minutes, with an accuracy rate exceeding 99%. Compared to traditional manual calculations, this significantly improves the efficiency and accuracy of setting calculations, effectively ensuring the safety and reliability of grid operations.

## **4. Challenges Facing Relay Protection Technology in Smart Grids**

### **4.1. System Stability Issues**

The integration of distributed generation poses numerous challenges to system stability. In terms of voltage stability, distributed energy resources (such as solar photovoltaic and wind power) exhibit intermittent and fluctuating output. For example, in a distribution network with 5MW of distributed photovoltaic capacity, sudden weather changes causing rapid variations in light intensity can reduce the output power from 5MW to below 1MW in a short period, leading to voltage fluctuations of up to  $\pm 12\%$ , far exceeding the normal operating range of  $\pm 5\%$ , severely affecting the normal operation and lifespan of user equipment [9].

In terms of transient stability, the integration of distributed generation alters the distribution and magnitude of short-circuit currents in the grid. For instance, after integrating a significant amount of distributed wind power, the characteristics of short-circuit currents during faults change markedly. Previously, the short-circuit current level in the region was around 10kA during faults. After integrating distributed wind power, the short-circuit current may increase or decrease, and its distribution becomes more complex, leading to reduced transient stability and increased risk of system instability. The complex and variable operating modes of smart grids, coupled with the uncertainties introduced by distributed generation, increase the likelihood of relay protection misoperations and failures to operate [3]. Additionally, while rapid protection actions can quickly isolate faults, they may also cause overvoltages and increased mechanical stress on equipment.

### **4.2. Network Security Threats**

Smart grid information and communication networks face various cyber-attack methods. Malware intrusions can disrupt communication or tamper with data in relay protection devices. For example, in 2015, Ukraine's power system suffered a large-scale cyber-attack, resulting in power outages for approximately 2.3 million users. Attackers spread malware through phishing emails, successfully infiltrating the internal networks of power companies and gaining control over the system. Hackers installed malware to control the operating system, remotely operating the grid's control system to cut off power supply. Another notable case is the 2017 "CrashOverride" attack on the U.S. power system, where hackers infiltrated the network of a power company through phishing emails and gained control over relay protection devices. Although this attack did not cause widespread outages, it revealed significant cybersecurity threats to relay protection devices and control systems in power systems. Some encryption algorithms used in current relay protection systems are at risk of being cracked. For example, some older substation protection devices use the DES encryption algorithm, which has known vulnerabilities, allowing data to be tampered with during transmission, leading to misoperations. Additionally, authentication mechanisms can be bypassed, failing to ensure information security [10]. Strengthening information security measures, such as increasing encryption strength and complex authentication processes, may increase data transmission delays and processing times, affecting the rapid response of relay protection devices and potentially delaying fault isolation.

### **4.3. Cross-Regional Protection Coordination Issues**

#### **4.3.1 Differences in Operational Characteristics of Regional Grids**

Regional grids exhibit significant differences in structure, load characteristics, and power distribution. For example, in China, the western region's grid has long and widely distributed transmission lines with a relatively weak structure, while the eastern region's grid has shorter transmission lines and higher load density with a more robust structure. These differences result in varying requirements for relay protection setting calculations and values across regions. In terms of load characteristics, industrial areas experience large fluctuations in industrial loads with high demands for power quality, while adjacent residential areas have relatively stable residential loads. With the proliferation of electric vehicle charging stations, the impact of load fluctuations is becoming more pronounced, complicating cross-regional protection coordination.

#### **4.3.2 Standardization Challenges in Cross-Regional Protection Coordination**

Due to differences in protection setting calculation principles, methods, and standards across regional grids, contradictions often arise in coordinating protection settings for cross-regional tie lines. Moreover, the development of relay protection standards often lags behind technological advancements. The rapid development of smart grid technologies is not always matched by timely updates and revisions of standards, leaving some advanced technologies without adequate support. For example, differences in distance protection setting calculation methods and sensitivity requirements between two sides of a cross-regional tie line can lead to misoperations and failures to operate when system operating conditions change, affecting the safe and stable operation of the grid. Additionally, cross-regional information exchange faces issues such as communication delays, inconsistent data formats, and information security challenges. Different regional grids may use different data formats and communication protocols, complicating information sharing and collaborative processing.

## **5. Future Development Trends of Relay Protection Technology in Smart Grids**

### **5.1. Digitalization**

The present intelligent grid system promotes the realization of relay protection digitalization in data measurement interface and optical fiber information transmission. With the introduction of electric transformers, data measurement interfaces improve the digital measuring capability of relay protections. Optical fiber grids facilitate more secure data transmission through data communication using light. It also improves the quality and speed of data sending and receiving by means of optical fiber grids.

### **5.2. Networking**

In recent years, network technology has been widely applied in many fields. Combining relay protection technology with network technology, the benefit of networks is used to optimize or update the security of the information transmission between relay protection and protect the speed of data transmission while optimizing the efficiency and scope of relay protection so that we can provide reliable power supply services for users in a safe and stable manner [11]. In order to obtain sufficient data to ensure the transmission of protection devices, 5G network technology plays an important role in the wide-area protection solution developed for the power system, which helps solve the reliability problem caused by protection delay [13]. The existing protection solutions have no mature technical foundation, and the main application direction should rely on trusted party privacy protection or smart grid's privacy protection based on decentralization as one-way solution, making it easier to implement on the premise of protecting the private key without sacrificing the function [14].

### 5.3. Intelligence

Existing relay protection of grid systems mainly realize real-time control and protection functions of operational lines but face difficulties due to different levels of intelligence among protection devices: some have traditional hardware protections only; others provide better protection abilities through intelligent equipment, like adaptable protection and remote monitoring & controlling. As a result, standardizing these protection devices within smart grids is challenging, and their protection range is limited with possible errors in the setting values during the relaying protection processes. Hence, realizing the intelligent development of setting is necessary. After completing the intelligent setting process, all parts of data from grid systems could be collected and protected, greatly improving the efficiency of grid systems.[15].

### 5.4. Standardization

Smart grids are complex systems encompassing power systems, communication networks, data management, and device interoperability. The existing IEC 61850 international standard system enables data sharing and collaborative work on a single platform. With the widespread application of smart grid technologies, countries and regions are actively promoting the standardization of relay protection in smart grids. Organizations such as the International Electrotechnical Commission (IEC), the International Organization for Standardization (ISO), and the Standardization Administration of China (SAC) are developing or refining relevant standards. These standards primarily address relay protection devices, communication protocols, information exchange, and data security, aiming to ensure compatibility and interoperability among different manufacturers and systems. The promotion of 5G communication standards will further enhance the efficiency of IoT transmission, facilitating the standardization of communication protocols [16].

## 6. Conclusion

As the cornerstone of modern power system development, smart grids are driving a profound transformation in relay protection technology. Both have evolved from traditional models to intelligent, digital, and automated systems, with the transition to smart grids becoming an inevitable trend that significantly enhances operational efficiency. Looking ahead, the deep integration of artificial intelligence with relay protection will accelerate its advancement. Smart grids are expected to achieve breakthroughs in fault diagnosis accuracy and early fault warning, enabling more adaptive protection strategies and enhanced regional coordination. Additionally, big data analytics, leveraging the vast multi-source data generated by smart grids, will play a crucial role in fault prediction, protection optimization, and decision-making, further strengthening the intelligence and precision of relay protection systems.

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