Hierarchical Protection for Smart Grids
Hierarchical Protection for Smart Grids

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About the Author

Professor Jing Ma has been working in this area since 2003. His research mainly concentrates on power system analysis/control/protection/operation/modelling/simulation and smart grids. For more than 12 years he has carried out systematic research and practice on power system hierarchical protection, especially the approaches of local and substation area protection and studies on wide area protection. He was the first to introduce the two-terminal network and voltage drop equation to the areas of local protection, and also the first to apply limited overlapping multiple differential regions for the protection of a substation area. He has invented a variety of wide area protection strategies using electrical information and operating signals to establish a wide area protection system with high accuracy and efficiency. A series of papers has been published in authoritative journals such as IEEE Transactions on Power Systems and IEEE Transactions on Power Delivery. The work has been widely acknowledged and cited by international peers, and some of his research results have been used in many practical engineering projects to accelerate the application and spread of wide area control technology. In recent years, he has undertaken many major projects in China, such as guiding a project of the National Natural Science Foundation of China to study wide area backup protection. He set up an advanced real-time dynamic simulation laboratory for fault transient analysis of power systems, and pioneered the design and realization of the corresponding protection techniques. He has also been responsible for several projects for governments and enterprises on the study of the hierarchical protection in smart grids and was also a major member of the National Basic Research Program of China (973 Program) on the study of wide area protection and control for complicated power systems. He cooperated with China Electric Power Research Institute in guiding the study of integrated protection systems of the substation area and wide area. He has taught courses on power system protective relaying for years, and much of the material in this book has been taught to students and other professionals.
Foreword

We were pleased to have Dr Jing Ma visit us at Virginia Tech as a visiting researcher. Virginia Tech has made very significant contributions to the field of phasor measurements and wide area measurement systems and their application to practical power system problems. Dr Jing Ma was an active participant in our research in this area, and worked very well with our research team.

I am glad to see that he is now publishing a book on *Hierarchical Protection for Smart Grids*. He is very well qualified to write such a book, dealing with topics on the protection of power systems. After reviewing traditional protection topics, this book goes into protection of renewable energy systems, substation area protection, and wide area protection principles. Many new ideas are presented in these later chapters, and I am sure they will be carefully studied by serious students and researchers.

It is significant that Dr Jing Ma is working closely with power system engineers and utility companies of China. This is one of the key characteristics of a successful engineering professor: to get the opinion of practising power system engineers on the direction and results of his research.

I am well familiar with the very active research programme at the North China Electric Power University, and this work is a testament to the vibrant research traditions of this university. I expect to see other research results from Dr Jing Ma and his team in the coming years.

Following some of the major power blackouts in recent years, the efficacy of PMUs and WAMS to help identify causes and provide countermeasures for dealing with widespread disturbances on power grids has been well recognized. These measurements have provided a very accurate situational awareness of the current state of the grids, as well as their vulnerabilities. The promising applications arising out of this early work are improved monitoring, protection and control of the power grids. Within a span of about 20 years after the invention of PMUs, many research teams around the world have been developing applications of this technology, and their work will surely lead to improved performance of electric power grids in the coming years.
This book, *Hierarchical Protection for Smart Grids* presents a comprehensive view of synchronized phasor measurement technology and its applications. It combines academic rigour with pragmatic considerations in dealing with the emerging discipline of smart grid technologies. I am pleased to see the work presented in this book, and I am sure it will be a valuable reference for students, researchers and practising power system engineers of the future.

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Preface

As the construction of smart grids is being vigorously promoted, hierarchical protection has been proposed and has quickly become the focus of research. This book is the very first to conduct a comprehensive discussion on smart grid hierarchical protection and a detailed analysis of specific protection schemes.

With the integration of large-scale renewable energy and the development of AC/DC hybrid EHV/UHV interconnected power grids, it is difficult for stage protection to utilize only local information to adapt to the changeable network structure and operating mode. Meanwhile, the integration of distributed generation causes the distribution network to change from a single-source radiation network to a double-source or multi-source network, where the distribution of power flow and the size and direction of fault current change fundamentally. Thus, the original protection schemes based on a fixed setting value have major limitations in striking an effective balance between the sensitivity and selectivity of relay protection. In many blackouts in China and elsewhere, the improper operation of protection is usually one of the main causes of fault occurrence and expansion, which can eventually contribute to the collapse of a power grid.

Without the limitations of local information, hierarchical relay protection could solve the above problems in traditional protection from the global perspective of a power system. In recent years, many colleges, universities and power companies have actively participated in the exploration of hierarchical protection. A lot of progress has been made in theoretical research, together with some local engineering demonstrations, which have laid the foundation for the construction of hierarchical protection and overcoming the difficulties in traditional relay protection. On the basis of summarizing the existing research findings and learning from the experience and lessons of traditional relay protection, with research achievements of the author as the main body, this book conducts a forward-looking discussion of the key technical problems of hierarchical protection construction in particular breadth and depth – including the constitution mode of hierarchical protection, local area protection, substation area protection and wide area protection – trying to point to an evolutionary direction for the construction of hierarchical protection.

This book strives to make the explanation of basic theories understandable and the derivation of formulas rigorous and complete. On this basis, through large numbers of case studies, rigorous verification of the hierarchical protection schemes introduced in the book which fit engineering practice is conducted.
It should be noted that, since hierarchical protection is still in the ascendant, the illustrations in the book may not be the final solution. For problems that have not yet achieved a unified understanding, the author proposes distinctive options in this book, in the sincere hope that readers will be inspired to make more excellent research achievements. Due to limited space, problems that cannot be discussed in detail are included in the references for in-depth study by readers.

This book is applicable to graduate students in universities, scientific and technical personnel in research institutes and professional personnel with a degree of theoretical knowledge and practical experience, for scientific research on hierarchical protection and relevant technical innovation. Due to the limited knowledge of the author, mistakes are inevitable in the book, and any criticism and correction from readers will be welcomed.

I’d like to express sincere thanks for the great support from the National Natural Science Foundation of China (No. 51277193,50907021), National Basic Research Program of China (973 program) (No. 2012CB215200), the Chinese University Scientific Fund Project (No. 2014ZZD02), Henry Fok Education Fund (No. 141057), Beijing Metropolis Beijing Nova Program (Z141101001814012), the Excellent Talents in Beijing City (2013B009005000001) and the Fund of Fok Ying Tung Education Foundation (141057) in the process of the creation of this book.

Jing Ma
Beijing, China
2016
Introduction

In this book, the latest research results on local area protection, station area protection and wide area protection in the smart grid are introduced systematically.

This book is divided into six chapters. The first mainly introduces the basic theories of relay protection and the constitution mode of hierarchical protection. The second chapter introduces local area conventional protection such as transformer and line protection. Chapter 3 seeks to introduce the fault characteristics of renewable power generation and local area renewable energy protection. The following chapter introduces topology analysis and fault tolerance identification. Chapter 5 introduces substation area protection based on logical and electrical variables, while the final chapter introduces wide area protection based on logical and electrical variables.

Rich and novel in content, this book covers almost every aspect of smart grid hierarchical protection research. It could provide a useful reference for teachers and students of electrical engineering in colleges and universities as well as scientific and technical researchers.
1

Basic Theories of Power System Relay Protection

1.1 Introduction

As the first defence line to ensure the security of a power grid, relay protection is very important for the fast isolation of faults and the effective control of fault expansion [1,2]. However, in recent years, with the continuous integration of large-scale renewable energy sources, the structure of modern power grids has become more and more complex, and more and more problems in traditional relay protection have been exposed, such as difficulties in backup protection setting and cooperation, unexpected changes of grid structure or operating conditions which may cause protection to malfunction or refuse to operate, and cause major load transfer which easily leads to cascading, tripping and even blackout, etc.

To solve these problems, the smart grid hierarchical relay protection system was proposed. Hierarchical relay protection is based on the smart grid [3] and information sharing technology, and is composed of bay level protection, substation area protection and wide area protection. Bay level protection, which is also called local area protection, aims to realize primary protection for components in the substation through independent and decentralized configuration. Substation area protection aims to realize backup protection for components in the substation by centralizing the information of components to the substation host computer. Wide area protection aims to realize local backup protection and remote backup protection between substations through the interaction of information between relevant substation protection units.

In this chapter, first the basic theories of power system relay protection are introduced, the functions and basic requirements of relay protection are summarized, and the basic principles of relay protection are illustrated. Then, the composition mode of hierarchical relay protection is analysed in detail. The cooperation between local area protection, substation area protection and wide area protection and the protection range of each are discussed, laying the foundation for subsequent chapters in this book.

1.2 Function of Relay Protection

A power system is an energy transmission network composed of various electrical devices corresponding to electric power production, transformation, transmission, distribution and use, which are connected according to certain technical and
economic requirements. Generally, the devices through which the electric power flows are called the primary equipment of the power system: for example, the generator, transformer, circuit breaker, bus, transmission line, compensation capacitor, shunt capacitors, shunt reactors, motor and the other power consumption equipment. The devices for the monitoring, measuring, control and protection of the operating state of the primary equipment are called the secondary equipment of the power system. Through voltage and current transformers, the high voltage and large current signals of the primary equipment are converted in proportion to low voltage and small current signals for the secondary equipment [4].

The operating state of a power system can usually be described by the operating parameters. The main operating parameters include active power, reactive power, voltage, current, frequency and the angular difference between emf phasors. According to different operating conditions, the operating state of a power system can be divided into normal state, abnormal state and fault state.

When a power system is in normal operation, the primary equipment and main operating parameters are all within the allowed deviation ranges, and the power system can operate continuously to provide electric power. However, when a disturbance occurs in a power system, the balance of the main operating parameters will be broken, and the power system operating state will change.

After a power system has been disturbed, then, according to the degree of disturbance, two circumstances may result. One is that the power system transits from the original stable state to a new stable state, the deviation of operating parameters from normal values remaining within the allowed ranges – for example, an increase or decrease of load, or the regulation of the prime mover – and the system could continue in normal operation. The other is that when a fault occurs in a power system, the operation of the system will change dramatically, resulting in local failure of the power system, electrical equipment and normal power supply to electricity users, even global failure.

If there is a fault state, and no special measures are taken, it is difficult to restore the system to normal operation, which could have a major impact on industrial and agricultural production, national defence, construction or the lives of ordinary people. Many types of fault can occur in a power system, including short circuit, phase disconnection and successive occurrence of multiple faults. The most common and most dangerous faults are various forms of short circuit, including three-phase short circuit, phase-to-phase short circuit, two-phase grounding fault, single-phase grounding fault, and motor and transformer winding turn-to-turn short circuit. In addition, there may be disconnection of one phase or two phases and complex faults such as some of the above faults occurring in succession.

Since the devices in a power system are connected to each other, a fault on one device will soon affect the other parts of the system. Thus, the time to clear the faulty device must be very short, sometimes even as short as tens of milliseconds, i.e. a small number of cycles. In such a short period of time, it is impossible for the operating staff to identify the fault and clear the faulty device. Automatic devices are needed to do that, i.e. relay protection devices.

A relay protection device is an automatic device installed on the components of the whole power system, which can respond to various faults or abnormal
operating states of electrical components in the designated area quickly and accurately, and operate within the preset time limit to issue tripping signals to the circuit breaker. The term ‘relay protection’ generally refers to the relay protection technology or relay protection system composed of various relay protection devices.

The basic tasks of relay protection are [5–8]:

1) Clear the faulty components from the power system automatically, quickly and selectively, and ensure that the non-faulty parts remain in normal operation.
2) Respond to the abnormal state of the electrical devices and issue signals to inform the duty personnel, or automatically make adjustments, even issuing tripping commands.

When a power system is in normal operation, relay protection does not operate, it simply monitors the operating state of the power system and the components. Once a fault or abnormal operating state is detected, relay protection will quickly operate to isolate the fault and issue a warning to ensure the safety of the power system. Relay protection plays an important role in ensuring the safe operation of the system and its power quality, and preventing the expansion and occurrence of faults.

1.3 Basic Requirements of Relay Protection

Technically, relay protection which operates to trip switches should meet four basic requirements, i.e. reliability, selectivity, speed and sensitivity. These four basic requirements are the important criteria to analyse, evaluate and study relay protection.

1.3.1 Reliability

The reliability of relay protection refers to the capability of the relay protection to operate reliably when a fault occurs within the protection range, without any refusal to operate, and not malfunctioning in any case where protection should not operate.

Reliability is the basic requirement of relay protection. It depends on the design, manufacture and operational maintenance levels. To ensure reliability, protection schemes with performance that meets the requirements and with simple principles should be used. Reliable hardware and software with anti-jamming capability should be used to form the protection device. In addition, there should be essential automatic detection, locking and warning measures, with convenient setting, debugging and operational maintenance.

An important index for evaluating the reliability of relay protection is the correct operational rate of relay protection, which is calculated as follows:

\[ R_c = \frac{k_{\text{correct}}}{k_{\text{total}}} \times 100\% \]  (1.1)
where $R_c$ is the correct operational rate of relay protection, $k_{correct}$ is the correct operational times of relay protection, $k_{total}$ is the total operational times of relay protection, which includes the correct operational times, malfunctioning times and refusing-to-operate times.

1.3.2 Selectivity

Selectivity means that a particular fault should be cleared by the protection of the faulty device itself, and only when the protection or circuit breaker of the faulty device refuses to operate will protection of the adjacent device or the breaker failure protection be allowed to clear the fault. Thus, fault clearance can be limited to the minimum range, and the safe operation of the non-faulty part of the system is guaranteed.

To ensure selectivity, apart from using a time delay to make the backup protection and primary protection of a line cooperate correctly with each other, the correct cooperation between the backup protection of adjacent components also needs to be considered. On the one hand, the sensitivity of backup protection of the higher-level component should be lower than that of the lower-level component. On the other hand, the operational time of backup protection of the higher-level component should be longer than that of the lower-level component.

1.3.3 Speed

Speed refers to clearing the fault as quickly as possible, in order to improve the stability of the system, reduce the damage to equipment, limit the range affected by the fault and improve the effectiveness of power restoration.

The main reasons for the requirement for fast fault clearance are as follows:

1) The heating power and electrodynamic force that affect the degree of equipment damage are both proportional to the fault clearance time. The shorter the fault clearance time, the more beneficial it is to the reduction of equipment damage.

2) The longer the short circuit point arc is ignited, the more likely the fault is to expand. A single-phase grounding short circuit fault may develop into a phase-to-phase short circuit fault, or even to a three-phase short circuit fault, which is more damaging to system stability; an instantaneous short circuit fault that could be restored may develop into a permanent short circuit fault that cannot be restored.

3) It is beneficial to improving the power restoration effect of automatic devices such as auto-reclosing and standby power auto-switching, as well as the self-start and restoration of a motor.

The requirement on speed should be determined according to system stability, wiring and specific conditions of the protected device. Improving the operating speed must be on the premise that reliability is satisfied. When the requirement on operating speed is met, slightly slowing down the operating speed means more time to obtain electrical information, which is beneficial to improving the reliability of relay protection.
The fault clearance time is the sum of protection operating time and circuit breaker operating time. The operating time of fast protection is usually 0.06~0.12 s; the shortest could be 0.01~0.04 s. The circuit breaker operating time is usually 0.06~0.15 s; the shortest could be 0.02~0.06 s.

### 1.3.4 Sensitivity

Sensitivity of relay protection refers to the capability of responding to a fault or abnormal operating state in the protected range. A protection device that meets the requirement on sensitivity can respond correctly to any short circuit fault within the preset protection range under any system operating conditions, no matter what type of fault, where the fault is located, whether via fault resistance or not. This is usually measured by the sensitivity coefficient.

1) For protection that operates in response to an increase of an electrical variable, the sensitivity coefficient is:

\[
sensitivity \ coefficient = \frac{I_{\text{f min}}}{I_{\text{set}}} \times 100\%
\]  

where \(I_{\text{set}}\) is the setting value of the relay protection, \(I_{\text{f min}}\) is the minimum short circuit current calculated value when a metallic short circuit occurs within the protection zone.

2) For protection that operates in response to a decrease of an electrical variable, the sensitivity coefficient is:

\[
sensitivity \ coefficient = \frac{I_{\text{set}}}{I_{\text{f max}}} \times 100\%
\]

where \(I_{\text{set}}\) is the setting value of the relay protection, \(I_{\text{f max}}\) is the maximum calculated short circuit current value when a metallic short circuit occurs within the protection zone.

The four requirements form the basis of the analysis, evaluation and research on relay protection. The emphasis on each of the four requirements should be ‘modest’ and balanced, and meet power system safe operational standards, otherwise adverse effects will result. Usually, selectivity and speed are contradictory; sensitivity and reliability are contradictory; anti refusing-to-operate and anti malfunction are contradictory. Therefore, the four requirements should be in dialectical unity in the configuration of protection, according to the actual operating conditions of a power system and the function of the protected equipment. The scientific research, design, manufacture and operation of relay protection are mostly centred on how to deal with the dialectical unity between the four requirements. It is of vital importance that protection devices are configured with the same principle on components at different locations in the power system and that they cooperate; it should be possible to maximize the way of configuring the corresponding relay protection for the same power component installed at different locations in a power system to preserve the operational efficiency of the protected power system. These issues fully demonstrate the scientific nature of relay
protection theoretical research and the technical nature of relay protection engineering practice.

1.4 Basic Principles of Relay Protection

1.4.1 Over-Current Protection

When three-phase and phase-to-phase short circuit faults occur at any point in a power system, the approximate formula for calculating the power frequency periodic component of the short circuit current on the line between the fault point and the power source is:

$$I_k = \frac{E_\phi}{Z_\Sigma} = K_\phi \frac{E_\phi}{Z_S + Z_k}$$

(1.4)

where $E_\phi$ is the phase emf of the system equivalent power source, $Z_k$ is the impedance between the fault point and the relaying point, $Z_S$ is the impedance between the relaying point and the system equivalent power source, $K_\phi$ is the short circuit type coefficient; for three-phase short circuit $K_\phi = 1$, for phase-to-phase short circuit $K_\phi = \frac{\sqrt{3}}{2}$. As there is a change in (a) the startup mode of a power system, (b) the topology of the network between the relaying point and the power source and (c) the load level, $E_\phi$ and $Z_S$ will both change. As the distance between the fault point and relaying point and the short circuit type differ, the values of $Z_k$ and $K_\phi$ will also differ, and so will the short circuit current.

Within the protection range, the amplitude of the short circuit current is always bigger than that of the load current. Over-current protection distinguishes between the normal operating state and the short circuit state according to the amplitude of the current at the relaying point. The principle is simple and reliable, and is easy to implement. The operating equation of over-current protection is:

$$I > I_{set}, \text{ fault occurs within the protection range, tripping}$$

(1.5)

where $I$ is the current at the relaying point and $I_{set}$ is the setting value of over-current protection. The amplitude of current at the relaying point is closely related to $Z_S$, $E_\phi$ and $K_\phi$, and varies with the distance between the fault point and the equivalent power source. The longer the distance, the smaller the current.

1.4.2 Directional Current Protection

Over-current protection only uses the increase of current amplitude after phase-to-phase short circuit to distinguish between faulty and normal operating states. It is difficult to apply this principle to multi-source networks. For the double-source system shown in Figure 1.1, since there are power sources on both sides, circuit breakers and protection devices are installed at both ends of line AB.

Suppose the capacities of the two power sources are different, and the fault current at relay B in the case of a k1 fault is smaller than the fault current at relay B in the case of a k2 fault. In order to protect line AB, the setting value of over-current
protection at relay B must be smaller than the fault current at relay B in the case of a k2 fault, thus when a fault occurs at k2, over-current protection at relay B will malfunction. This problem could be solved by adding directional protection at relay B.

Directional protection can identify the direction of short circuit power flow, and it operates only when the power flows from bus to line (forward direction). Combined with over-current protection, directional current protection uses not only the amplitude of the current, but also the direction of power flow, and thus it can clear the fault quickly and selectively.

Directional current protection identifies the direction of the fault by measuring the angular difference between current and voltage. Since the line is inductive, when a fault occurs in the forward direction, the short circuit current at the relay will lag behind the bus voltage by a phase angle $\phi_k$ (i.e. the impedance angle of line from bus to fault point), and $0^\circ < \phi_k \leq 90^\circ$. The output of power direction component varies with the angular difference between the input voltage and current. For the power direction component to be the most sensitive to the most common short circuit faults, the maximum sensitivity angle should be $\phi_{sen} = \phi_k$. And to ensure that the directional component can operate reliably when the fault resistance causes line impedance angle $\phi_k$ to vary $0^\circ$~$90^\circ$, the operating angle should be in a certain range, and is usually equal to $\phi_k$. The operating equation of directional current protection can be expressed as:

$$\phi_{sen} + 90^\circ > \text{arg} \frac{\hat{U}_m}{\hat{I}_m} > \phi_{sen} - 90^\circ$$

where $\hat{U}_m$ is the measured voltage of protection, and $\hat{I}_m$ is the measured current of protection.

The direction component should operate reliably when various kinds of faults occur in the forward direction, and should not operate when a fault occurs in the reverse direction. Rather, it should be sensitive to faults in the forward direction [9].

### 1.4.3 Distance Protection

The protection range and sensitivity of current protection are greatly affected by variations in system operating mode. In order to meet the requirements of a complex network, relay protection principles with better performance must be applied, among which is distance protection. Distance protection has a relatively stable protection range and can identify the direction of the short circuit point, so it is widely applied in power systems [10,11].

![Double-source system](image-url)
Current protection only uses the single feature of current increase in a short circuit fault, while distance protection uses the dual features of voltage decrease and current increase in a short circuit fault. Calculating the ratio of measured voltage to measured current reflects the distance from the fault point to the relaying point, and then distance protection will operate if the calculated value is smaller than the setting value.

In distance protection, the measured impedance \( Z_m \) is the ratio of measured voltage \( U_m \) to measured current \( I_m \) at the relaying point, i.e.

\[
Z_m = \frac{U_m}{I_m}
\]  

where \( Z_m \) is a vector, which could be expressed in the form of polar coordinates, or in the form of rectangular coordinates on the complex plane.

When the power system is in normal operation, \( U_m \) is approximately the rated voltage, \( I_m \) is the load current and \( Z_m \) is the load impedance. The magnitude of the load impedance is relatively large, and the impedance angle is the power factor angle, which is relatively small; thus the impedance is mostly resistive. When a fault occurs in a power system, \( U_m \) decreases, \( I_m \) increases and \( Z_m \) becomes the line impedance between the fault point and the relaying point, the magnitude of which is relatively small, and the impedance angle is the line impedance angle (relatively large). According to the variation of magnitude and phase angle of \( Z_m \), distance protection could identify whether a fault has occurred or not.

In an ideal case, when metallic short circuit faults occur at different locations, the measured impedance is the complex variable on the line AB in Figure 1.2. Note, however, that the secondary side measured impedance is affected by the errors of current and voltage transformers and transmission line impedance angle, as well as the fault resistance. Usually, the protection range of an impedance component is expanded to the form of a circle, as shown in Figure 1.2, the circular area being referred to as the operational characteristics. When the measured impedance falls in the range of the operational characteristics, distance protection will operate. In Figure 1.2, \( Z_{set} \) is the diameter of the circle, which represents the setting impedance of distance protection, and \( \phi_{set} \) is the maximum sensitivity angle.

**Figure 1.2** Operational characteristics of distance protection.
Although distance protection is not affected by the system operating mode, for
distance protection in a high-voltage system, the reliability will be affected by a
variety of unfavourable factors, including system oscillation, overload and fault
resistance. These factors will cause distance protection to malfunction or refuse
to operate, posing a hidden threat to the safe operation of a large-scale complex
power grid. Thus, corresponding countermeasures need to be studied to eliminate
or reduce the impact of these factors.

The main protection principles in traditional protection have been introduced
above. In a single-source network, over-current protection could achieve a good
protection effect. In a loop network or double-source network, directional protec-
tion should be added to complement over-current protection. In high-voltage and
extra-high-voltage (EHV) power grids, distance protection is less effective, so a
system operating mode should be applied. However, although the performance
of distance protection is good, when oscillation or overload occurs in the system,
or when there is fault resistance, using distance protection also runs the risk of
incorrect operation.

1.5 Hierarchical Relay Protection

Due to constraints such as the microcomputer protection hardware device, CPU
processing ability and specialization, traditional relay protection has used the
decentralized and independent configuration mode, and has achieved successful
operation in practice over quite a long period of time. However, with the devel-
OPMENT of power systems, the structure and operating mode of power grids has
become more and more complex, and more and more problems with traditional
relay protection have been discovered.

1) The complicated cooperation between protection components, and long oper-
ating time delay have adverse effects on system stability.
2) Problems include: difficulty of setting up, lack of adaptability to variation of
system operating mode and protection mismatch and lack of sensitivity.
3) They are incapable of distinguishing between internal faults and overload
caused by power flow transfer, which easily leads to cascading tripping and
blackout, greatly endangering the safety of the power grid.

With the development of smart grids and information sharing technology, relay
protection can get more information from more extensive sources, which brings
new opportunities for solving the problems of traditional relay protection. In
recent years, scholars have put forward a novel hierarchical relay protection sys-
tem which is composed of substation bay layer local protection (hereinafter
referred to as local area protection), substation layer protection (hereinafter
referred to as substation area protection) and wide area layer protection (hereina-
fter referred to as wide area protection). Thus, a vertically hierarchical relay pro-
tection system may be realized, and through the combination of time and the
coordination of the operational information between areas, the performance of
relay protection could be improved. Different levels of the hierarchical relay pro-
tection system are illustrated as follows.
1.5.1 Local Area Protection

Local area protection is oriented to a single protected object. By retaining conventional primary protection and simplifying the backup protection, with the aim of isolating the fault component quickly and accurately, local area protection can realize fast and reliable protection of components using the information about the protected object itself to make independent decisions. Local area protection is not dependent on external communication channels, thus, even if the communication channel is damaged, it can still complete its protection function. Local area protection mainly includes line protection, main transformer protection and bus protection.

There are two main reasons for retaining local area protection. On the one hand, local area protection is the implementation layer for hierarchical protection. In view of the reliability and speed requirements of the main protection, substation area protection or wide area protection are difficult to use to replace the main protection or integrated main protection. Thus, currently, substation area protection and wide area protection are mainly for backup protection. On the other hand, substation area protection and wide area protection are both dependent on the reliability of the communication system. When communication fails, the backup functions of both will fail. Therefore, local area protection must be retained as the last ‘life defence line’ of a power system to provide the last backup measure for fault clearance in the case of communication system failure.

Apart from completing its own protection function, local area protection also communicates with the substation area protection to provide organizational information, including protection information, measurement and control information, fault information and electric power information, which are generated by relevant functional equipment in the bay layer, as the data source for device function application and information transmission in the substation control layer. The information is transmitted in the substation in the form of messages, according to the data interface model defined by the IEC 61850 standard [12–15]. The substation is divided into the substation control layer, bay layer and process layer. The information exchange between bay layer and process layer is mainly through the process layer network, including the sampling value information and switch status information. The information exchange between bay layer and substation control layer is mainly through the substation control layer network, including protection operation messages, operation of device and warning and operation and control commands.

In summary, local area protection retains the conventional main protection function, simplifies the backup protection function and improves the performance of conventional backup protection with complicated setting and coordination. Meanwhile, as a node of substation area protection, local area protection is integrated into the substation area protection system and cooperates with substation area protection to realize substation level protection. Local area protection is the cornerstone of hierarchical protection, providing data support for and executing the decisions of substation area protection.

With transmission of power from west to east China, the construction of an EHV power grid and the integration of large-scale renewable energy, local area protection using only the information of a single component will experience many
problems. For conventional local area protection, the excitation inrush current of parallel transformer no-load input can cause transformer differential protection to malfunction; the strong zero-sequence mutual inductance coupling between double-circuit lines on the same tower, and complicated cross-line faults will directly affect the operational characteristics and performance of distance protection or directional protection. For local area renewable energy protection, such as the new energy station protection of centralized power generation, if the transient regulation and weak feed characteristics of a new energy current converter are not considered, the collector line protection may malfunction and the sensitivity of outgoing transmission line protection may be reduced.

This book will discuss in detail the problems in conventional local area protection and the new local area energy protection and will introduce corresponding solutions in order to improve the function of local area protection and lay a solid foundation for the construction of hierarchical protection.

1.5.2 Substation Area Protection

Substation area protection is mainly responsible for the protection of components inside the station and backup protection of the tie line between stations. According to the multi-source electrical variable and logical variable information shared by the generic object oriented substation event (GOOSE) network and the sampled value (SV) network [16], the substation host computer could accurately identify substation faults and quickly clear them.

The biggest advantage of substation area protection over traditional protection is that it utilizes multi-source information to make comprehensive decisions and judgements. The comprehensive information from the station, and from adjacent stations, includes direct information such as voltage, current, circuit breaker and switch state and intermediate information or indirect information such as the operational result. By using the redundant direct information and indirect information, the coordination between different protection devices can be optimized, and the contradiction between the selectivity and speed of protection can be alleviated.

Substation area protection could also simplify the setting and cooperation of backup protection. In modern power grids where the network topology is ever more complex, for local backup protection and remote backup protection based on local information, due to limited information acquisition, the protection ranges overlap with one another, and cooperation is very complicated with a large amount of setting value calculation. When the communication is normal, substation area protection can correctly isolate the fault after collecting the information in the station and making a simple identification according to the substation network topology. Therefore, substation area protection could not only effectively improve the performance of protection, but also significantly simplify the setting and coordination of backup protection.

Currently, substation area protection mainly has the following two forms:

1) Distributed substation area protection – This protection algorithm is mainly aimed at distributed buses. By decentralizing traditional centralized bus protection into some bus protection units, each protection unit collecting the
current in each loop, converting it into digital form which is then uploaded to the network, and acquiring the current information of all the other loops from the network, distributed bus protection could identify whether the fault is at the bus according to the calculation results based on the principle of bus differential protection. If the fault is identified to be at a particular bus, then only the circuit breaker in the loop where the protection unit is will be tripped. If one protection unit malfunctions, then only the corresponding loop is wrongly tripped. The other loops connected to the bus will not all be cleared. Thus, compared with traditional centralized bus protection, distributed bus protection is more reliable. However, the design of a distributed substation protection system is complicated, the hardware cost is high and the economic efficiency is poor.

2) Centralized substation area protection – In substation centralized protection, all information is centralized to a computer system for centralized processing. Substation area protection collects all the information about electrical variables and state variables through the process layer network, and the central decision-making point of the protection system analyses and calculates the information within the substation protection range, thus realizing comprehensive judgement and decision-making of protection. The system structure is convenient for data transmission and sharing, and could realize protection of multiple bay layers in the station. Compared with distributed substation area protection, substation centralized protection could acquire more information, locate the fault from the whole station level, simplify the cooperation of protection operating time and also improve the selectivity and reliability of protection, which is beneficial for intelligent protection decision-making.

1.5.3 Wide Area Protection

Wide area relay protection is mainly responsible for protection of the tie line between substations and remote backup protection of substation components. According to the node current, voltage and circuit breaker state shared through the data network, the wide area host computer calculates the basic information of the fault and realizes the function of wide area protection. The advantage of wide area protection over traditional protection based on single-end variables is mainly reflected in that, wide area protection uses not only the information of the protected device, but also the information of other relevant devices, the network topology information and model parameter information. Thus, the function of the existing protection can be optimized, and the selectivity of protection can be improved. Wide area protection uses wide area information to identify the fault directly, without considering the cooperation between different protection devices, which simplifies the setting of the protection, and the speed is improved. When the line information is missing, wide area protection can make up for the missing information by analysing and utilizing the wide area information, thus the reliability of protection can be improved.

According to the information collection range of the regional protection system, the information transmission mode, and the position and function of information processing and decision-making unit, the basic structure of a wide area