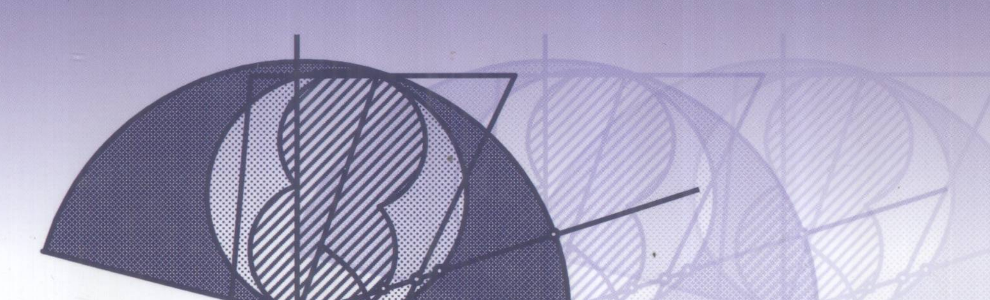
Power System Relaying

Third Edition

Stanley H. Horowitz
Arun G. Phadke



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POWER SYSTEM RELAYING

Preface to the third edition

The second edition of our book, issued in 1995, continued to receive favorable response from our colleagues and is being used as a textbook by universities and in industry courses worldwide. The first edition presented the fundamental theory of protective relaying as applied to individual system components. This concept was continued throughout the second edition. In addition, the second edition added material on generating plant auxiliary systems, distribution protection concepts and the application of electronic inductive and capacitive devices to regulate system voltage. The second edition also presented additional material covering monitoring power system performance and fault analysis. The application of synchronized sampling and advanced timing technologies using the Global Positioning Satellite (GPS) system was explained.

This third edition takes the problem of power system protection an additional step forward by introducing power system phenomena which influence protective relays and for which protective schemes, applications and settings must be considered and implemented. The consideration of power system stability and the associated application of relays to mitigate its harmful effects are presented in detail. New concepts such as undervoltage load shedding, adaptive relaying, hidden failures and the Internet standard COMTRADE and its uses are presented. The history of notable blackouts, particularly as affected by relays, is presented to enable students to appreciate the impact that protection systems have on the overall system reliability.

As mentioned previously, we are gratified with the response that the first and second editions have received as both a textbook and a reference book. Recent changes in the electric power industry have resulted in power system protection assuming a vital role in maintaining power system reliability and security. It is the authors' hope that the additions embodied in this third edition will enable all electric power system engineers, designers and operators to better integrate these concepts and to understand the complex interaction of relaying and system performance.

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Blacksburg

Preface to the second edition

The first edition, issued in 1992, has been used as a textbook by universities and in industry courses throughout the world. Although not intended as a reference book for practicing protection engineers, it has been widely used as one. As a result of this experience and of the dialog between the authors and teachers, students and engineers using the first edition, it was decided to issue a second edition, incorporating material which would be of significant value. The theory and fundamentals of relaying constituted the major part of the first edition and it remains so in the second edition. In addition, the second edition includes concepts and practices that add another dimension to the study of power system protection.

A chapter has been added covering monitoring power system performance and fault analysis. Examples of oscillographic records introduce the student to the means by which disturbances can be analyzed and corrective action and maintenance initiated. The application of synchronized sampling for technologies such as the GPS satellite is explained. This chapter extends the basic performance of protective relays to include typical power system operating problems and analysis. A section covering power plant auxiliary systems has been added to the chapter on the protection of rotating machinery. Distribution protection concepts have been expanded to bridge the gap between the protection of distribution and transmission systems. The emerging technology of static var compensators to provide inductive and capacitive elements to regulate system voltage has been added to the chapter on bus protection. The subject index has been significantly revised to facilitate reference from both the equipment and the operating perspective.

We are gratified with the response that the first edition has received as a text and reference book. The authors thank the instructors and students whose comments generated many of the ideas included in this second edition. We hope that the book will continue to be beneficial and of interest to students, teachers and power system engineers.

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Preface to the first edition

This book is primarily intended to be a textbook on protection, suitable for final year undergraduate students wishing to specialize in the field of electric power engineering. It is assumed that the student is familiar with techniques of power system analysis, such as three-phase systems, symmetrical components, short-circuit calculations, load flow and transients in power systems. The reader is also assumed to be familiar with calculus, matrix algebra, and Laplace and Fourier transforms and Fourier series. Typically, this is the background of a student who is taking power option courses at a US university. The book is also suitable for a first year graduate course in power system engineering.

An important part of the book is the large number of examples and problems included in each chapter. Some of the problems are decidedly difficult. However, no problems are unrealistic, and, difficult or not, our aim is always to educate the reader, help the student realize that many of the problems that will be faced in practice will require careful analysis, consideration and some approximations.

The book is not a reference book, although we hope it may be of interest to practicing relay engineers as well. We offer derivations of several important results, which are normally taken for granted in many relaying textbooks. It is our belief that by studying the theory behind these results, students may gain an insight into the phenomena involved, and point themselves in the direction of newer solutions which may not have been considered. The emphasis throughout the book is on giving the reader an understanding of power system protection principles. The numerous practical details of relay system design are covered to a limited extent only, as required to support the underlying theory. Subjects which are the province of the specialist are left out. The engineer interested in such detail should consult the many excellent reference works on the subject, and the technical literature of various relay manufacturers.

The authors owe a great debt to published books and papers on the subject of power system protection. These works are referred to at appropriate places in the text. We would like to single out the book by the late C. R. Mason, *The Art and Science of Protective Relaying*, for special praise. We, and many generations of power engineers, have learned relaying from this book. It is a model of clarity, and its treatment of the protection practices of that day is outstanding.

Our training as relay engineers has been enhanced by our association with the Power System Relaying Committee of the Institute of Electrical and Electronics Engineers (IEEE), and the Study Committee SC34 of the Conférence Internationale des Grands Réseaux Electriques des Hautes Tensions (CIGRE). Much of our technical work has been under the auspices of these organizations. The activities of the two organizations, and our interaction with the international relaying community, have resulted in an appreciation of the differing practices throughout the world. We have tried to introduce an awareness of these differences in this book. Our long association with the American Electric Power (AEP) Service Corporation has helped sustain our interest in electric power engineering, and particularly in the field of protective relaying. We have learned much from our friends in AEP. AEP has a well-deserved reputation for pioneering in many phases of electric

power engineering, and particularly in power system protection. We were fortunate to be a part of many important relaying research and development efforts conducted at AEP. We have tried to inject this experience of fundamental theory and practical implementation throughout this text. Our colleagues in the educational community have also been instrumental in getting us started on this project, and we hope they find this book useful. No doubt some errors remain, and we will be grateful if readers bring these errors to our attention.

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Introduction to protective relaying

1.1 What is relaying?

In order to understand the function of protective relaying systems, one must be familiar with the nature and the modes of operation of an electric power system. Electric energy is one of the fundamental resources of modern industrial society. Electric power is available to the user instantly, at the correct voltage and frequency, and exactly in the amount that is needed. This remarkable performance is achieved through careful planning, design, installation and operation of a very complex network of generators, transformers, and transmission and distribution lines. To the user of electricity, the power system appears to be in a steady state: imperturbable, constant and infinite in capacity. Yet, the power system is subject to constant disturbances created by random load changes, by faults created by natural causes and sometimes as a result of equipment or operator failure. In spite of these constant perturbations, the power system maintains its quasi-steady state because of two basic factors: the large size of the power system in relation to the size of individual loads or generators, and correct and quick remedial action taken by the protective relaying equipment.

Relaying is the branch of electric power engineering concerned with the principles of design and operation of equipment (called 'relays' or 'protective relays') that detects abnormal power system conditions, and initiates corrective action as quickly as possible in order to return the power system to its normal state. The quickness of response is an essential element of protective relaying systems – response times of the order of a few milliseconds are often required. Consequently, human intervention in the protection system operation is not possible. The response must be automatic, quick and should cause a minimum amount of disruption to the power system. As the principles of protective relaying are developed in this book, the reader will perceive that the entire subject is governed by these general requirements: correct diagnosis of trouble, quickness of response and minimum disturbance to the power system. To accomplish these goals, we must examine all possible types of fault or abnormal conditions which may occur in the power system. We must analyze the required response to each of these events, and design protective equipment which will provide such a response. We must further examine the possibility that protective relaying equipment itself may fail to operate correctly, and provide for a backup protective function. It should be clear that extensive and sophisticated equipment is needed to accomplish these tasks.

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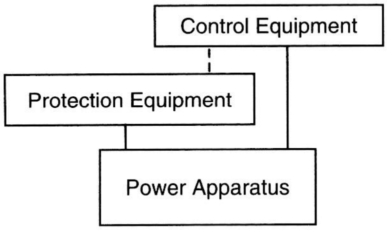


Figure 1.1 Three-layered structure of power systems

1.2 Power system structural considerations

1.2.1 Multilayered structure of power systems

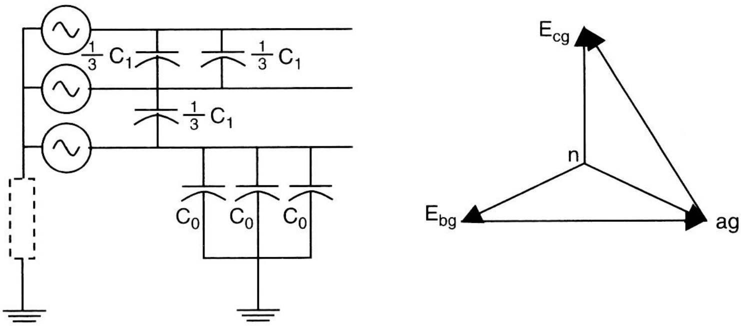
A power system is made up of interconnected equipment which can be said to belong to one of three layers from the point of view of the functions performed. This is illustrated in Figure 1.1.

At the basic level is the power apparatus which generates, transforms and distributes the electric power to the loads. Next, there is the layer of control equipment. This equipment helps maintain the power system at its normal voltage and frequency, generates sufficient power to meet the load and maintains optimum economy and security in the interconnected network. The control equipment is organized in a hierarchy of its own, consisting of local and central control functions. Finally, there is the protection equipment layer. The response time of protection functions is generally faster than that of the control functions. Protection acts to open and close circuit breakers, thus changing the structure of the power system, whereas the control functions act continuously to adjust system variables, such as the voltages, currents and power flow on the network. Oftentimes, the distinction between a control function and a protection function becomes blurred. This is becoming even more of a problem with the recent advent of computer-based protection systems in substations. For our purposes, we may arbitrarily define all functions which lead to operation of power switches or circuit breakers to be the tasks of protective relays, while all actions which change the operating state (voltages, currents, power flows) of the power system without changing its structure to be the domain of control functions.

1.2.2 Neutral grounding of power systems

Neutrals of power transformers and generators can be grounded in a variety of ways, depending upon the needs of the affected portion of the power system. As grounding practices affect fault current levels, they have a direct bearing upon relay system designs. In this section, we will examine the types of grounding system in use in modern power systems and the reasons for each of the grounding choices. Influence of grounding practices on relay system design will be considered at appropriate places throughout the remainder of this book.

It is obvious that there is no ground fault current in a truly ungrounded system. This is the main reason for operating the power system ungrounded. As the vast majority of faults on a power system are ground faults, service interruptions due to faults on an ungrounded system are greatly reduced. However, as the number of transmission lines connected to the power system grows, the capacitive coupling of the feeder conductors with ground provides a path to ground, and a ground fault on such a system produces a capacitive fault current. This is illustrated in Figure 1.2(a). The coupling capacitors to ground C_0 provide the return path for the fault current. The interphase capacitors $\frac{1}{3}C_1$ play no role in this fault. When the size of the capacitance becomes sufficiently large, the capacitive ground fault current becomes self-sustaining, and does not clear by itself. It then becomes



(a) (b)

Figure 1.2 Neutral grounding impedance. (a) System diagram. (b) Phasor diagram showing neutral shift on ground fault

necessary to open the circuit breakers to clear the fault, and the relaying problem becomes one of detecting such low magnitudes of fault currents. In order to produce a sufficient fault current, a resistance is introduced between the neutral and the ground – inside the box shown by a dotted line in Figure 1.2(a). One of the design considerations in selecting the grounding resistance is the thermal capacity of the resistance to handle a sustained ground fault.

Ungrounded systems produce good service continuity, but are subjected to high overvoltages on the unfaulted phases when a ground fault occurs. It is clear from the phasor diagram of Figure 1.2(b) that when a ground fault occurs on phase a, the steady-state voltages of phases b and c become $\sqrt{3}$ times their normal value. Transient overvoltages become correspondingly higher. This places additional stress on the insulation of all connected equipment. As the insulation level of lower voltage systems is primarily influenced by lightning-induced phenomena, it is possible to accept the fault-induced overvoltages as they are lower than the lightning-induced overvoltages. However, as the system voltages increase to higher than about 100 kV, the fault-induced overvoltages begin to assume a critical role in insulation design, especially of power transformers. At high voltages, it is therefore common to use solidly grounded neutrals (more precisely 'effectively grounded'). Such systems have high ground fault currents, and each ground fault must be cleared by circuit breakers. As high-voltage systems are generally heavily interconnected, with several alternative paths to load centers, operation of circuit breakers for ground faults does not lead to a reduced service continuity.

In certain heavily meshed systems, particularly at 69 kV and 138 kV, the ground fault current could become excessive because of very low zero sequence impedance at some buses. If ground fault current is beyond the capability of the circuit breakers, it becomes necessary to insert an inductance in the neutral in order to limit the ground fault current to a safe value. As the network Thévenin impedance is primarily inductive, a neutral inductance is much more effective (than resistance) in reducing the fault current. Also, there is no significant power loss in the neutral reactor during ground faults.

In several lower voltage networks, a very effective alternative to ungrounded operation can be found if the capacitive fault current causes ground faults to be self-sustaining. This is the use of a Petersen coil, also known as the ground fault neutralizer (GFN). Consider the symmetrical component representation of a ground fault on a power system, which is grounded through a grounding reactance of X_n (Figure 1.3). If $3X_n$ is made equal to X_{c0} (the zero sequence capacitive reactance of the connected network), the parallel resonant circuit formed by these two elements creates an open circuit in the fault path, and the ground fault current is once again zero. No circuit breaker operation is necessary upon the occurrence of such a fault, and service reliability

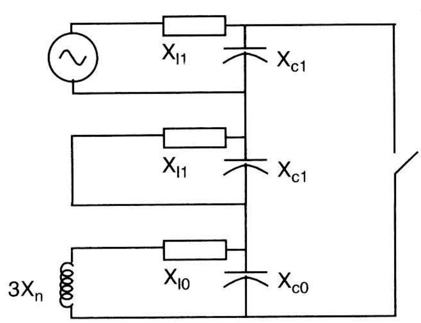


Figure 1.3 Symmetrical component representation for ground fault with grounding reactor

is essentially the same as that of a truly ungrounded system. The overvoltages produced on the unfaulted conductors are comparable to those of ungrounded systems, and consequently GFN use is limited to system voltages below 100 kV. In practice, GFNs must be tuned to the entire connected zero sequence capacitance on the network, and thus if some lines are out of service, the GFN reactance must be adjusted accordingly. Petersen coils have found much greater use in several European countries than in the USA.

1.3 Power system bus configurations

The manner in which the power apparatus is connected together in substations and switching stations, and the general layout of the power network, has a profound influence on protective relaying. It is therefore necessary to review the alternatives, and the underlying reasons for selecting a particular configuration. A radial system is a single-source arrangement with multiple loads, and is generally associated with a distribution system (defined as a system operating at voltages below 100 kV) or an industrial complex (Figure 1.4).

Such a system is most economical to build; but from the reliability point of view, the loss of the single source will result in the loss of service to all of the users. Opening main line reclosers or other sectionalizing devices for faults on the line sections will disconnect the loads downstream of

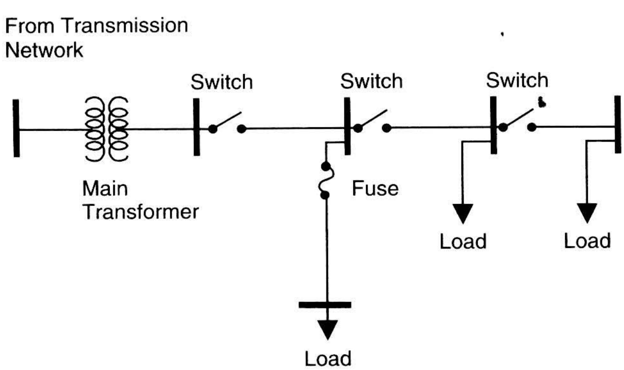


Figure 1.4 Radial power system