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Introduction

1.1 Power System Protection

The purpose of this book is to present an introductory treatment of power system protection. This includes a study of common types of abnormal occurrences, such as faults, that can lead to power system failure, and the methods for detecting and clearing these abnormalities to restore normal operation. The method of detecting and clearing faults requires the use of special hardware, which is designed for this purpose. This book does not emphasize the hardware, as this requires timely information concerning the products marketed by various manufacturers. Instead, the emphasis will be on analytical techniques that are needed to compute the system conditions at the point of detection and the methods of making detection fast and effective. Most of these techniques are applicable to protective devices of any manufacturer and, therefore, constitute general methods for protective system analysis.

The treatment of the subject of system protection is intended primarily for the engineer or student who is learning the subject. This does not mean, however, that the presentation is elementary. It is presumed that the reader has mastered the usual requirements of the bachelors degree in electrical engineering and is familiar with the use of digital computers. It is also presumed that the reader has a working knowledge of symmetrical components, as presented in [1].

System protection has evolved, over the years, from relatively primitive devices with limited capability to complex systems that involve extensive hardware. These modern protective systems are more selective in their detection and operation and often require greater analytical effort in their application. This book is concerned with this analytical effort. We begin with a review of the basic equipment arrangements that provide the protective equipment with its raw data. We then progress to the computation of protective system quantities, beginning with simple circuit arrangements and progressing to more complex situations. This involves a treatment of the Thevenin impedance seen by the protective device at the point of application. This concept is examined in settings designed to protect lines, generators, transformers, and bus structures. Finally, we examine some special topics, including system aspects of protection, and protective system reliability.

1.2 Prevention and Control of System Failure

Most of the failure modes in a power system can be controlled to limit damage and thereby, enhance reliability. Mechanical failures are controlled by designing the system to withstand all but the unusually severe mechanical loads such as extensive ice buildup, hurricanes, and tornadoes. This

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is done in a way that tends to minimize the total transport cost of energy, which requires a balance between initial cost and maintenance. Insulation design is coordinated to minimize damage to expensive equipment due to electrical surges. Since it is not economical to design a system to withstand all possible system failures, the alternative is to design a protective system that can quickly detect abnormal conditions and take appropriate action. The type of action taken depends on the protective device and on the environmental condition that is observed by that device. The two basic types of protective systems are defined in this book as follows:

1. *Reactionary devices*. These devices are designed to recognize a certain hazard in the power system environment and to take predetermined action to remove that hazard. In most cases, the hazard is related to an abnormal system operating condition that would eventually cause failure of one or more system components. Therefore, the action is usually to isolate that portion of the system experiencing the hazard so that the rest of the system can operate normally.
2. *Safeguard devices*. These devices are designed to recognize a certain hazard in the power system environment and to take predetermined action to change that environment to a less hazardous condition.

   Each type of device will be discussed briefly.

1.2.1 Reactionary Devices

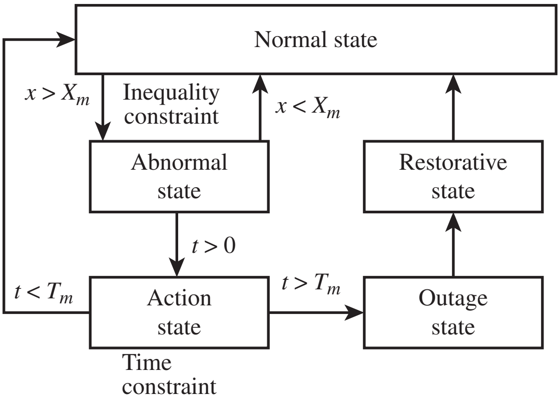
Reactionary devices are designed to detect a specific system hazard, such as a short circuit, on a system component and to remove that hazard. The power system is not designed to operate continually in the presence of hazards such as short circuits. The protective system action restores the system to the best possible operating condition under the circumstances. In many cases, after testing or inspection, the failed component can often be restored to operation. This may not be true, however, if the failed component were to continue to operate for a long time under the influence of the hazard.

The protection of the system against total failure must be adaptive in the sense that it must operate in an acceptable manner for any kind of abnormal occurrence in a reliable manner. The protective system is required to make decisions quickly, typically in a few milliseconds, and usually on the basis of limited information as to the history and state of the system at a given point of observation.

The condition of the electrical system as it experiences and recovers from a major fault or failure may be characterized in terms of a set of unique system states. Thus, we say that the system is in the *normal state* when all items of equipment that should be in operation are actually working and are operating within normal design limits. When an event occurs that causes the operation of any system component to exceed its normal operating limits, we say that the system has entered an *abnormal state*, which implies that something must be done to relieve the abnormality before a serious failure occurs. Abnormalities can be transient in nature, and, depending on the nature of the condition, it may be prudent to wait a bit before taking any action to see if the abnormality clears itself. If not, we enter an *action state*, in which certain prescribed actions must be taken, usually without further intentional delay. Following this action, the system is in an *outage state*, in which the faulted device is removed from service. Since this state is not the desired operating condition, the system is usually caused to enter a *restorative state*, wherein any required inspections or other repair actions are taken in order to again reach the *normal state*. This process is depicted in Figure 1.1.

From Figure 1.1, it is apparent that two conditions must be met in order to remove a component from normal service.

Figure 1.1 Operative states of a protection system.



To trip the device:

1. Violate the inequality constraint, $x > X_m$ *and*
2. Violate the time constraint, $t > T_m$.

It is also convenient to think of this process in terms of a decision flow chart, which might be implemented in a computer control system. Such a flow chart is shown in Figure 1.2. Usually, the system is in the normal state, and the protective device is set to assume that the normal state prevails at startup. As time is incremented, the protective device checks the observed system variables, represented by x in the flow chart, to determine if any variable exceeds its threshold value. If not, time is incremented to observe the next measured value. If the threshold is exceeded, the time threshold is checked and tripping action is withheld until the time threshold expires. When both the quantity and time thresholds are exceeded, the circuit is tripped. This type of logic is designed to prevent tripping for short, temporary disturbances that might be observed. Such disturbances are often a part of the normal operating condition of the network, and tripping should not be initiated for such events.

In some protective systems, automatic restoration is begun following a preset time delay. This concept has proven valuable since most power system disturbances are temporary, including short circuits. Once the circuit is de-energized, the abnormal condition clears itself and the circuit can be successfully restored. If this is not a part of the programmed response of the device, the circuit is “locked out” and remains in the outage state until repair personnel can determine the cause of the outage and take appropriate action. This state is shown at the bottom of the flow chart, where the system is in the outage state with no automatic escape.

1.2.2 Safeguard Devices

Safeguard devices are different from reactionary devices since safeguards are designed to change the environmental conditions that are the cause of the emergency. Examples of safeguard devices are fire sprinkler systems, apparatus supplementary cooling systems, and detectors that monitor unbalanced currents or voltages in equipment. These systems are designed to change the operating environment when protective sensors detect a specified hazardous condition. Thus, the fire sprinkler puts out the fire, and the apparatus supplementary cooling system withdraws additional heat from the operating machine to restore a normal working environment. Some safeguards are designed to alarm the operator, who makes a decision as to the severity of the hazard and may take preemptive action, such as shutting down a facility that is experiencing a hazardous condition.

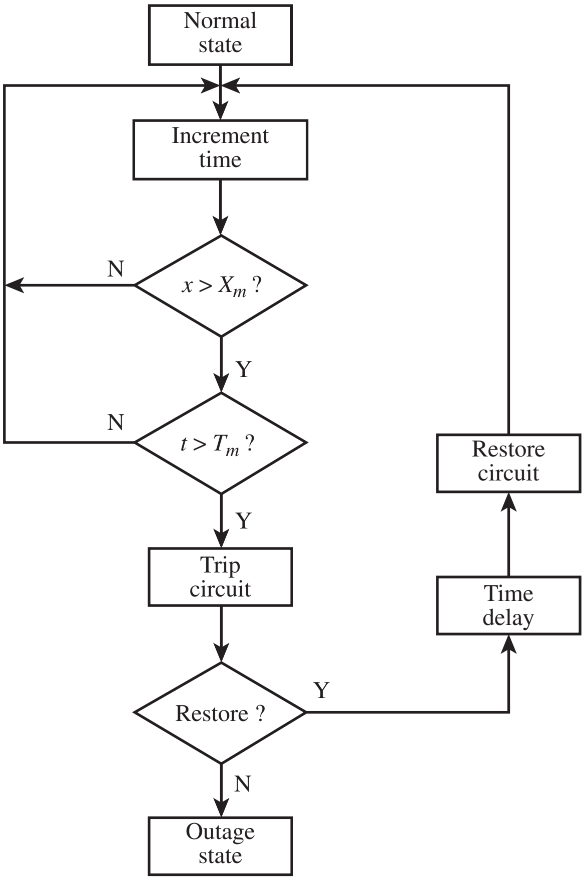


Figure 1.2 Flow chart of the tripping decision process.

Other safeguards are designed to take action, which may include removing equipment from service if other remedial actions are not effective.

Some safeguard devices are extremely important in power systems. A good example is the emergency core cooling system of a nuclear reactor, which has the capability of preventing core meltdown following a dangerous reactor failure or accident. Such safeguards must be carefully designed for very high reliability and security because of the high cost of failure.

For the most part, this book deals with reactionary protective systems, although many features of these systems are shared by safeguards as well.

1.2.3 Protective Device Operation

The protective device usually consists of several elements that are arranged to test the system condition, make decisions regarding the normality of observed variables, and take action as required. These elements are depicted graphically in Figure 1.3.

The protective system always measures certain system quantities, such as voltages and currents, and compares these system quantities, or some combination of these quantities, against a threshold setting that is computed by the protection engineer and is set into the device. If this comparison indicates an alert condition, a decision element is triggered. This may involve a timing element, to determine the permanence of the condition, and may require other checks on the system at

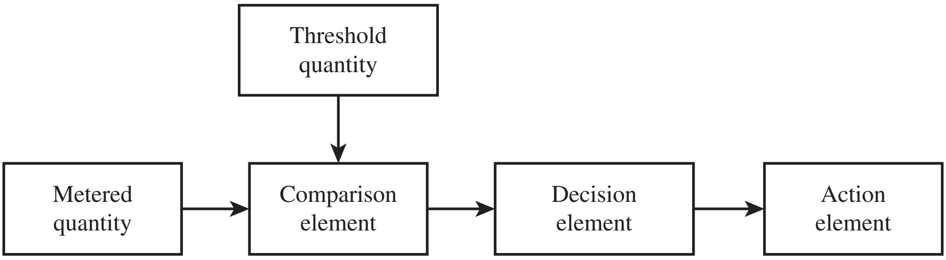


Figure 1.3 Protective device functional elements.

other points in the network. Finally, if all checks are satisfied, an action element is released to operate, which usually means that circuit breakers are instructed to open and isolate a section of the network.

The time required to take any necessary corrective action is called the *clearing time* and is defined as follows:

$$T_c = T_p + T_d + T_a \tag{1.1}$$

where

T_c = clearing time
T_p = comparison time
T_d = decision time
T_a = action time, including circuit breaker operating time

The clearing time is very important for a variety of reasons. These reasons are elaborated on in the following paragraphs.

Timing is important to facilitate coordination with other devices. Since other protective systems in the network may be time-coordinated with this protective device in order to ensure that only the necessary portions of the network are interrupted. There is an important message here, namely, that many protective devices will observe a given disturbance and many of them will find that disturbance to exceed their threshold settings. Each device should have some kind of restraint to allow those closest to the disturbance to trip first. Time is one kind of restraint that is often used. Other restraint mechanisms will be discussed later.

Fast clearing time is also important because some disturbances, such as short circuits, must be cleared promptly in order to preserve system stability. This depends on many factors, including the location and type of disturbance. However, it is a general rule that abnormal system conditions must be corrected, and speed of correction is always important.

Power quality is affected by short circuits. The voltage on faulted phases often drops below acceptable minimum values for good power quality. In some cases, the voltage on unfaulted phases may also rise above unacceptable maximum values. Therefore, short clearing times are required to minimize the negative impact of short circuits on power quality.

Short circuits also cause problems to power system equipment and expose adjacent personnel and property to hazards. Damage to faulted equipment will often be reduced if a short circuit is cleared promptly. Such prompt clearing may make the difference between repairable and unrepairable equipment. The high current flowing into the short circuit may also cause damage to unfaulted equipment supplying the fault current. Damage could be caused if the short time overload capability of the unfaulted equipment is exceeded. Further there is often arcing associated with short circuits. In many cases, the energy released by the arc is very high. The arc energy exposes nearby property and personnel to hazards. Injury due to arc flash is a well-recognized hazard to personnel working around electric power equipment. This arc flash energy is directly proportional to the duration of the short circuit.

Finally, high values of short circuit current flowing through the ground may cause significant voltage drops across short portions of grounded equipment. These voltage drops also expose personnel to hazards, commonly referred to as step and touch potential hazards. Substation equipment grounding is usually designed to maintain acceptable maximum values of step and touch potentials. However, for short circuits to ground in public areas, excessive step and touch potentials are possible. Therefore, minimizing the short circuit duration for short circuits in publicly accessible locations will minimize step and touch potential hazards to the public.

1.3 Protective System Design Considerations

A protective system should be designed to recognize certain system abnormalities which, if undetected, could lead to damage of equipment or extended loss of service. The design and specification of the system components is an important part of the protective strategy, and power systems are designed to withstand the usual operating contingencies that accompany load changes and line switching operation. The coordination of insulation is an important design consideration, and protective devices are commonly installed to protect expensive apparatus from damaging overvoltages. These problems, although a part of the overall system protection, are outside the scope of this book. Our concern here is the detection, clearing, and restoration of circuits from damaging abnormal conditions, which we usually call *faults*. This requires knowledge of the types of faults that are likely to be experienced and the kinds of protective devices that can be used to recognize faults and initiate action to clear the fault from the system. The protective system designer must develop a strategy to accomplish this within the framework of available protective equipment while optimizing the restoration of the system to the normal state.

There are several design considerations that must be weighed against cost in devising a protection strategy. We have mentioned an optimum restoration, but this does not necessarily imply the fastest possible restoration. For example, if the protective system intelligence determines that a fault is permanent, there is no point in repeating the reclosing of the circuit before a repair crew has located and repaired the difficulty. Only then can the circuit be restored to its normal state. Thus, every occurrence has a unique optimum pattern for returning to normal following a disturbance and this may involve human intervention, such as a physical repair. Normally, there is no human intervention in the protective system action, however, as this would cause the abnormal condition to persist for an extended time. In cases where this is feasible, the protective system issues an alarm, following which the operator can analyze the situation and manually take any action that is required.

The protective system should also be designed for minimum loss of load. There is no need, usually, to de-energize the entire system because of an isolated fault. The system should have *selectivity* to isolate the fault such that the minimum interruption occurs. Often this requires automatic reclosing following a circuit opening since experience has shown that the large majority of faults are temporary and that reclosures are very often successful. Minimum loss of load may also require that alternate circuits be available to serve important loads. For example, bulk transmission systems usually have the capability of serving all loads with one or more major circuit components out of service.

The protective system should also be designed with due regard for its own unreliability. This means that backup protective systems should be installed to operate in case of primary protective equipment failure so that system damage can be minimized and restoration of normal service can be achieved quickly.

It is also important that the protective system be designed such that the system can perform under normal operating conditions. The protective equipment senses system voltages and currents and, from these measurements, computes a relaying quantity which is compared to a threshold or trip value. This threshold must not be set too low or the protected circuit may be interrupted unnecessarily. Furthermore, threshold values must be periodically reviewed to make certain that these settings are satisfactory for current system loading conditions. This is an operating as well as a design problem.

The operation of protective equipment must be accurate and fast. Bulk power system reliability standards require that systems survive severe fault conditions without causing a system collapse. This in turn requires fast and reliable protective system operation. Thus, there is a direct dependency upon the protective system to achieve a given level of system reliability. This adds to the challenge of designing an effective protective system and a reliable power delivery system.

1.4 Definitions Used in System Protection

In this section, we define certain terms which are used in system protection engineering. Other, more specific terms, will be introduced later, as required.

Protective relaying is the term used to signify the science as well as the operation of protective devices, within a controlled strategy, to maximize service continuity and minimize damage to property and personnel due to the systems abnormal behavior. The strategy is not so much that of protecting the equipment from faults, as this is a design function, but rather, it is for protecting the normal system and environment from the effect of a system component which has become faulted.

Reliability of a protective system is defined as the probability that the system will function correctly when required to act. This reliability has two aspects: first, the system must operate in the presence of a fault that is within its zone of protection (Dependability), and second, it must refrain from operating unnecessarily for faults outside its protective zone or in the absence of a fault (Security) [2].

Security in protective systems is a term sometimes used to indicate the ability of a system or device to refrain from unnecessary operations. Often we use security as a generic term to indicate that the system is operating correctly.

Dependability in protective systems is a term used to indicate the degree of certainty that the system or the device will operate when necessary.

Sensitivity in protective systems is the ability of the system to identify an abnormal condition that exceeds a nominal “pickup” or detection threshold value and which initiates protective action when the sensed quantities exceed that threshold.

Selectivity in a protective system refers to the overall design of a protective strategy, wherein only those protective devices closest to a fault will operate to remove the faulted component. This implies a grading of protective device threshold, timing, or operating characteristics to obtain the desired selective operation. This restricts interruptions to only those components that are faulted.

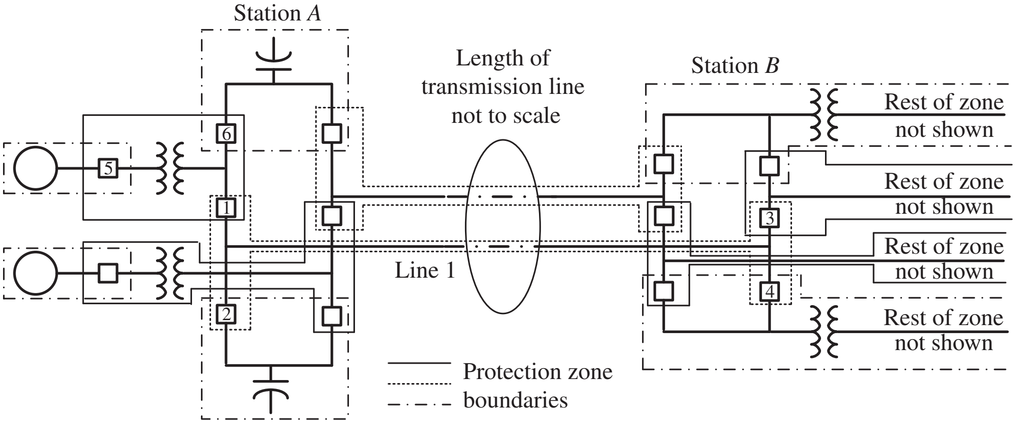


Figure 1.4 One-line diagram of a system showing primary protection zones.

Protection zones (primary protection zones) are regions of primary sensitivity. Figure 1.4 shows a small segment of a power system. The primary system is shown in heavy lines, and protection zones are enclosed by thinner lines with various styles.

Coordination of protective devices is the determination of graded settings to achieve selectivity.

Primary relays (primary sensitivity) are relays within a given protection zone that should operate for prescribed abnormalities within that zone. In Figure 1.4, for example, consider a fault on Line 1 from Station *A* to Station *B*. For this condition, relays supervising breakers 1, 2, 3, and 4 should trip before any others and these relays are called primary relays.

Backup relays are relays outside a given primary protection zone, located in an adjacent zone, which are set to operate for prescribed abnormalities within the given primary protection zone and independently of the primary relays. For example, suppose a fault on Line 1 of Figure 1.4 cannot be cleared by breaker 1 due to relay or breaker 1 malfunction. Assume that breakers 2, 3, and 4 operate normally leaving the fault connected to the equipment terminated by breakers 1, 5, and 6. Backup relays at locations 5 and 6 should be set to operate for the fault on Line 1, but only after a suitable delay that would allow breaker 1 to open first, if possible.

Local backup relays are an alternate set of relays in a primary protection zone that operate under prescribed conditions in that protection zone. Often such local backup relays are a duplicate set of primary relays set to operate independently for the same conditions as the primary set. This constitutes an OR logic trip scheme and is an effective safeguard against relay failures.

Undesired tripping (false tripping) results when a relay trips unnecessarily for a fault outside its protection zone or when there is no fault at all. This can occur when the protective system is set with too high a sensitivity. Such operation may cause an unnecessary load outage, for example, on a radial circuit, or may cause overloading of adjacent lines of a network. Thus, in some cases, unnecessary tripping is merely an inconvenience, which, although undesirable, may not cause serious damage or overloading. In other cases, where an important line is falsely tripped, it can lead to cascading outages and very serious consequences.

Failure to trip is a protective system malfunction in which the protective system fails to take appropriate action when a condition exists for which action is required. This type of failure may result in extensive damage to the faulted component if not rectified by backup protection.

Other definitions used in system protection are given in [3], which is a standard for such definitions in the United States. Many of these definitions will be introduced as needed for clarity and precision.

A summary of several important terms and definitions is also given in Appendix A.

1.5 System Disturbances

The disturbances that occur on electric networks are varied in both magnitude and character. In this section, we examine the nature of disturbances and attempt to identify those disturbances for which protective system deployment is feasible and/or necessary.

A disturbance is defined as follows by the IEEE [3].

Disturbance (General). An undesired variable applied to a system that tends to affect adversely the value of a controlled variable.

Clearly, what appears as a disturbance to one kind of apparatus may be of little consequence to another type, irrespective of the magnitude of the disturbance. Our classification is general, to begin with, and from this general classification, we shall consider which disturbance classes may require special protective system applications.

There are many possible ways to categorize disturbance types and characteristics. One reference divides disturbances into two major categories: *load* disturbances and *event* disturbances [4]. These are defined as follows:

Load disturbances: Small random fluctuations superimposed on slowly varying loads.
Event disturbances:
(a) Faults on transmission lines due to equipment malfunctions or natural phenomena such as lightning.
(b) Cascading events due to protective relay action following severe overloads or violation of operating limits.
(c) Generation outages due to loss of synchronism or malfunction.

As defined in [4], load disturbances are a part of the systems normal operating conditions. In an operating power system, frequency and voltage are always in a state of change due to load disturbances. Any departure from normal frequency and voltage, due to a load disturbance, is usually small and requires no explicit power plant or protective system response. Occasionally, however, major load disturbances do occur. These major disturbances are usually caused by important transmission or generation outages and are characterized by low, high, or widely varying frequency and voltage on the power system.

Small event disturbances are also a part of the normal power system operating environment. Event disturbances, however, imply a need for rapid response by the protective systems and can lead to larger upsets if this action fails or is delayed. Large event disturbances always require fast protective system action and may lead to complete system failure if this action is not correct and fast.

Disturbances, both large and small, may be classified as shown in Table 1.1 [5]. Usually, the system protection engineer is interested in small disturbances from the standpoint that the protective system should not act for this type of disturbance since such action would usually make the situation worse. Indeed, for this type of disturbance, the removal of additional system components is likely to make the situation worse.

Table 1.1 Disturbance cause and effect matrix.

	Type of disturbance			
	Load disturbance		System disturbance	
Event magnitude	**Cause**	**Effect**	**Cause**	**Effect**
Small	Daily load cycle	Frequency error	Load trips	Slight over frequency
	Small overload	Voltage deviation	Equipment outage	Possible load shedding
	Random load fluctuation	Spontaneous oscillation	Large load variation	Sustained system oscillations
Large	Generation overload	Frequency error	Network faults	Loss of network elements
	Winter power plant freeze up	Time error	Plant outages	Load shedding
	Inadequate reserves	Low voltage	Line outages	Unit tripping
	Circuit overloads	Loss of plant auxiliaries	Destructive natural events	Cascading/ separation/islanding
		Plant trips		Instability
		Line trips		Blackouts

Source: Weber et al. [5].

The large disturbances, on the other hand, will often require a correct response by the protective system. This means that the protective system should act promptly to remove damaged or faulted components and should not act except in carefully defined conditions. Usually, it is the system disturbances that require protective system action, for example, transmission line faults or other destructive natural phenomena, or random failure of system components. The protective system must be carefully designed to trip only for those load disturbances that would lead to permanent equipment damage and possible sustained outage. The table entries are not exhaustive and do not describe fully the conditions under which system protection must act or refrain from action. The intent of the table is simply to note that there are many types of disturbances for which normal protective system action is not the proper corrective action. Normal protective action is required in response to system *component failures*, where the prompt removal of the failed element is necessary for continued system operation. Failure of the protective systems, or improper protective system response, may lead to serious system operating conditions. There are other types of systems that are designed to respond to some of the large disturbances mentioned in Table 1.1, but these are not what we would usually call “normal” protections. These schemes are designed to recognize a particular stressed system condition and to take remedial action. Such schemes are sometimes called *system integrity protection schemes* (*SIPSs*) *or special protection schemes* (*SPSs*), or *remedial action schemes* (*RASs*), and their function is often to prevent instability or the cascading of outages that may lead to blackout.

1.6 Book Contents

The contents of this book are divided into logical units of study, and these logical units are designated as “parts” each with a defined objective.

Part 1, *Protective Devices and Controls*, provides very basic information as to the connection and intrinsic operation of system controls that are designed to remove a severe disturbance, such as a short circuit, from the operating power system. This requires the operation of some type of device that will separate the fault from the system in a timely and effective manner. The separation device may be a fuse, a circuit breaker, or other device designed for a particular application and with a given rating. The interruption of short circuits provides a severe test to the interruption device, and this will be the subject of study in this initial part of the book. The final portion of Part 1 investigates the mathematical characteristics of the power system under faulted conditions and provides analytical techniques for the analysis of any type of fault condition.

Part 2, *Protection Concepts*, investigates the mathematics of the power system under faulted conditions. Faults on radial feeders, such as those usually found in distribution systems, are presented in Chapter 6. This introduces the problems associated with the coordination of time–current devices, such as fuses or circuit reclosers. These studies are applicable to most distribution protective systems and their study introduces basic concepts regarding the necessity of recognizing faulted conditions, and clearing the fault in a timely manner, based solely on the magnitude of the fault current.

The detection of faults on transmission systems, introduced in Chapter 7, is more complex because the system is usually meshed, as opposed to the radial systems examined in Chapter 6. This means that the protective logic must be more sophisticated as the direction of current flow is dependent on the fault location. Many schemes have been devised for the protection of transmission elements, and some of these concepts are introduced here.

The remainder of Part 2 examines how a faulted condition can be viewed in the impedance or admittance planes, as functions of a complex variable. Some protective devices use measurements of both voltage and current that can be interpreted as loci in the Z or Y planes, with trip zones set as regions of those planes. This is an important concept for certain types of relays.

Part 3, *Transmission Protection*, concentrates on transmission systems, beginning with an analysis of distance protection, which utilizes Z plane loci as a measurement of distance from the relay to the fault. The mutual induction of fault currents flowing in lines parallel to the faulted lines is presented in Chapter 12. This concept can complicate fault detection and clearing involving zero sequence currents.

Pilot protection schemes are commonly used on high-voltage transmission lines to provide fast, dependable operation. Commonly used pilot schemes are described in Chapter 13. Chapter 14 investigates several topics that add complexity to transmission protection and describes methods of overcoming these complexities. One important form of complexity in transmission is the use of series compensation, which is the subject of Chapter 15.

Part 4, *Apparatus Protection*, is investigated in Chapters 16–19. This includes the protection of buses, transformers, generators, and motors. This type of protection is different than line protection since all terminals of the protected device are available to the protection equipment without the need for communication. Apparatus protection can also take advantage of the nature of the item being protected and its unique requirements. Also, since repair of items such as large transformers or generators can require weeks or even months to complete, multiple special protective schemes are often used to limit the damage of the equipment by fast recognition of a particular hazard.

Part 5, *System Aspects of Protection*, examines disturbance conditions that have widespread effects. This includes underfrequency protection, out-of-step conditions that may lead to instability, HVDC disturbances that inject abnormal effects at all terminals of the dc system, and subsynchronous oscillations that can affect one or more generators on the interconnected system.

Finally, Part 6 of the book examines the *Reliability of Protective Systems*. The subject is introduced in an elementary manner such that all required basic concepts are presented in Chapters 24 and 25 prior to their use in reliability calculations that follow. The application of reliability concepts is demonstrated through elementary examples first and is then used in the analysis of typical protection equipment. Emphasis is on the fault tree methods and Markov modeling for the study of complex systems. This leads to the reliability modeling of typical protective systems and the optimization of the scheduling of protection equipment inspections, based on probabilistic techniques.

Problems

1.1 A transmission line 100 km long is being designed as part of high reliability bulk power transmission system. Suppose that the basic line cost is $80 000/km and you are to evaluate the economics of adding two overhead ground wires which will increase the cost by 20%. However, the overhead ground wires are expected to reduce the incidence of lightning flashovers from 20 per year to 1 per year. Discuss the alternatives involved and decide whether you would recommend the added expense of the ground wires.

1.2 List all the reasonably probable abnormal occurrences you can think of that would lead to protective system operation together with your estimate of the probability of occurrence of each, in connection with the following system components:
(a) transmission line
(b) transformer
(c) generator

1.3 Distinguish among the terms power system reliability, security, and service continuity.

1.4 Consider the system portion shown in Figure P1.4.
(a) Sketch the zones of protection.
(b) Describe a possible backup scheme for failure of breaker 7 for a fault on line *BC*. Is load 1 interrupted? Or load 2?
(c) Describe a means of clearing a fault on line *BC* without a momentary interruption of load 1.
(d) Make any comment you would like about the system shown in Figure P1.4.

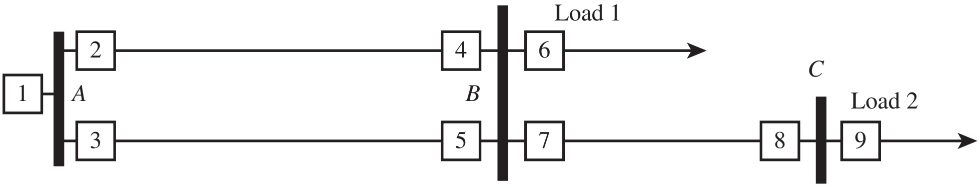


Figure P1.4

1.5 The system of Figure P1.4 is rearranged as shown in Figure P1.5 where the bus arrangement at *B* has been changed to a ring bus arrangement.
(a) Compare the cost of the two systems

(b) Compare the operation of the two systems for when a fault occurs on line *BC* with
    1 A failure of breaker 7.
    2 A failure of breaker 6.
(c) Sketch zones of protection.

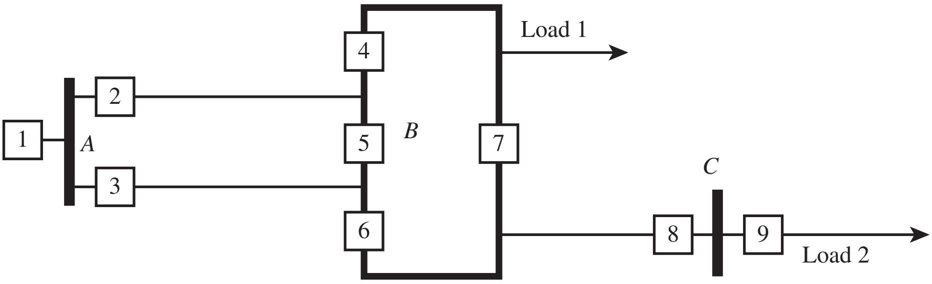


Figure P1.5

1.6 Consider a power system with several optional designs for all of its components, with the more reliable and fault resistant components having higher cost, but lower outage rates. However, the use of the lower-cost components will require more investment in protective equipment in order to assure prompt removal of faulted equipment. Is it possible to find an optimum solution to this problem, where the cost of both components and their protection is a minimum?

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