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Introduction

The power system is a complex network of generators, transformers, transmission lines, distribution feeders, loads, and other electrical components. The purpose of this network is to deliver electrical power from generators to loads through transmission lines and distribution feeders. Today, electrical power is a necessity of everyday life and is expected to be present whenever we flip the light switch, charge our phones, and turn on other gadgets. Unfortunately, this expected service may not always be available, particularly when there is a fault on the power system.

Faults are abnormal conditions on the power system that disrupt the normal flow of electrical power from generators to loads. Lightning, animal contact, tree contact, and adverse weather such as strong winds and winter storms are some of the major reasons for power system faults. Utilities take many preventive steps such as installing shield wires and surge arresters to divert the energy of lightning strikes, putting up animal guards, and trimming trees at periodic intervals to minimize the chances of a fault. In spite of all these measures, faults are inevitable on the power system. So when they occur, all efforts must be made to locate the fault as quickly as possible, make repairs, and restore power. This is why fault location is so important and critical to improving power system reliability.

We begin this chapter by explaining the types of faults that can occur on the power system and their root cause. We then move our focus to fault-locating algorithms. We discuss their aim and importance, their principles, their implementation in the field, and their evaluation criteria. Finally, we discuss how to choose the best fault-locating algorithm from among the many algorithms that have been proposed in the literature.

1.1 Power System Faults

Faults are abnormal conditions on the power system that cause voltage, current, frequency, and power to deviate from their nominal values. Protective relays are typically used to detect and isolate these faults as quickly as possible to return the power system back to normal operating conditions. The Institute of Electrical and Electronics Engineers (IEEE) defines a protective relay as “a device whose function is to detect defective lines or apparatus or other power system conditions of an abnormal or dangerous nature and to initiate appropriate control action” [1]. Protective relays use current transformers (CTs) and potential

Fault Location on Transmission and Distribution Lines: Principles and Applications, First Edition.
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transformers (PTs) to monitor the state of the power system. When a fault is detected, they send a trip command to circuit breakers, which then open to isolate the fault. In low-voltage distribution systems, fuses are often used instead of protective relays and circuit breakers to detect and isolate faults that create an overcurrent condition. A fuse is defined by IEEE as “an overcurrent protective device with a circuit-opening fusible part that is heated and severed by the passage of the overcurrent through it.”

Faults experienced by the power system can be of two types, series faults and shunt faults. Series faults usually occur when there is an open circuit on one or two phase conductors during load conditions. Because the open circuit occurs in series with the phase conductor, these faults are known as series faults. Series faults can be caused by broken jumpers or when all three poles of a circuit breaker pole are unable to close during a manual or an automatic close operation. They can also be caused by a blown fuse. For example, Fig. 1.1 shows a distribution transformer being protected by high-side fuses. If one or two high-side fuse blows due to an overcurrent condition, it will result in a series fault. During a series fault, the current in the faulted phase decreases due to loss in load while the healthy phase continues to carry load current. The voltage and frequency of the faulted phase also increase as compared to the healthy phase. While series faults do not result in high magnitude currents to flow in the faulted phases, they make the power system unbalanced, causing unbalanced currents to flow in the power system. The heat generated by the unbalanced currents can damage transformers and motors. References [2–4] explain how protective relays can be set up to detect and isolate series faults.

Shunt faults occur when there is a shunt connection between one or more phase conductors to the ground or between each other. The shunt connection creates a short-circuit condition allowing current to flow through an alternate, lower impedance path. The lower impedance causes the current in the faulted phase to dramatically increase while the voltage of the faulted phase decreases. Because shunt faults are more common and more damaging than series faults, this book will focus on locating shunt faults.

There are four types of shunt faults (see Fig. 1.2). Single line-to-ground faults (also referred to as single phase-to-ground faults) occur when one of the three phase conductors makes contact with the ground wire or the grounded piece of an equipment. Seventy to eighty percent of all faults are single line-to-ground faults, making this the most common fault type [5]. Line-to-line faults (also referred to as phase-to-phase faults) occur when two phase conductors make contact with each other. Double line-to-ground faults (also referred to as double phase-to-ground faults) occur when two phase conductors make contact with each other and the ground wire or the grounded piece of an equipment. Three-phase faults occur when all three phase conductors make contact with each other,

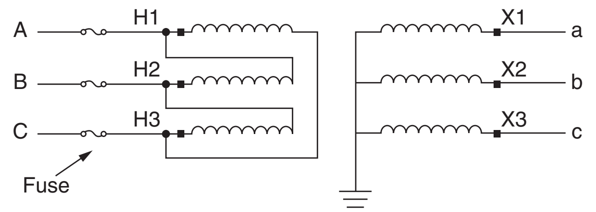

Figure 1.1 A distribution delta/wye-grounded transformer being protected by high-side fuses. A blown fuse will result in a series fault.

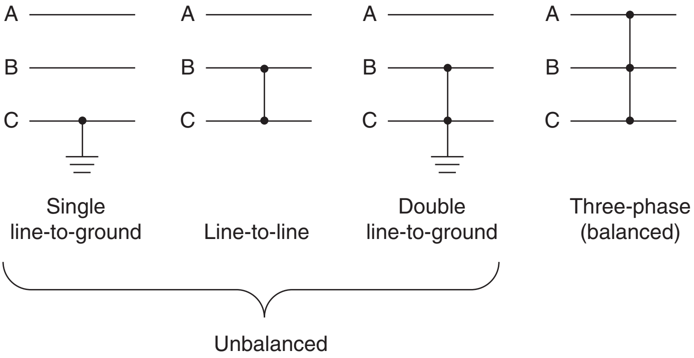

Figure 1.2 The four types of shunt faults.

with or without ground connection. This fault type is quite rare and is most often the result of human errors. Three-phase faults are referred to as balanced faults as the fault involves all three phases. The other fault types involve one or two phases and make the power system unbalanced. As a result, they are referred to as unbalanced faults.

Shunt faults can be permanent (leading to sustained outages) or temporary (leading to momentary outages). Permanent faults occur when there is permanent damage to a power system equipment and require line crew to make repairs before reenergization. Temporary faults occur due to lightning, animal contact, flying debris, and other temporary sources of fault. Such faults clear out on their own after the fault arc gets extinguished. When the arc gets extinguished by itself without the operation of any protective device, the fault is referred to as a self-clearing fault. These faults generally occur when insulation breaks down near the voltage peak but clear out on their own within a quarter cycle. The frequency of self-clearing faults increase over time and eventually lead to permanent faults [6]. Fault arcs can also get extinguished by the operation of a relay and circuit breaker. After a short open time delay, which allows the arc to get extinguished, the relay sends a reclose command to the circuit breaker to resume normal operation. Most faults on underground cables are permanent faults. In contrast, most faults on overhead systems are temporary faults [7].

Shunt faults can cause significant thermal damage to power system equipment. Thermal energy during a fault is proportional to the magnitude and duration of the fault current. If this thermal energy exceeds the thermal limit of power transformers, motors, and other power system equipment, they get damaged due to insulation failure. In addition, strong mechanical forces developed by the high magnitude current can break and physically damage power system equipment. In fact, [8] reports that transformers, a critical asset in the substation, most often fail due to mechanical and thermal stress caused by external through faults. Shunt faults are also a safety concern. Sparks from faults can start forest fires. Faults inside oil-filled transformers can lead to fires and explosions, creating dangerous working conditions for personnel inside the substation. Arc flash events in a switchgear can lead to dangerous and possibly fatal conditions due to heat, ultraviolet radiation, shrapnel, noise, and pressure from the blast [9]. Shunt faults if not cleared before the critical clearing time can make the power system unstable, leading to cascading outages [10]. Finally, shunt faults can cause voltage sags or swells on other healthy feeders. A voltage sag is defined as an event in which the rms voltage drops to a value between 0.1 and 0.9 per unit for a duration

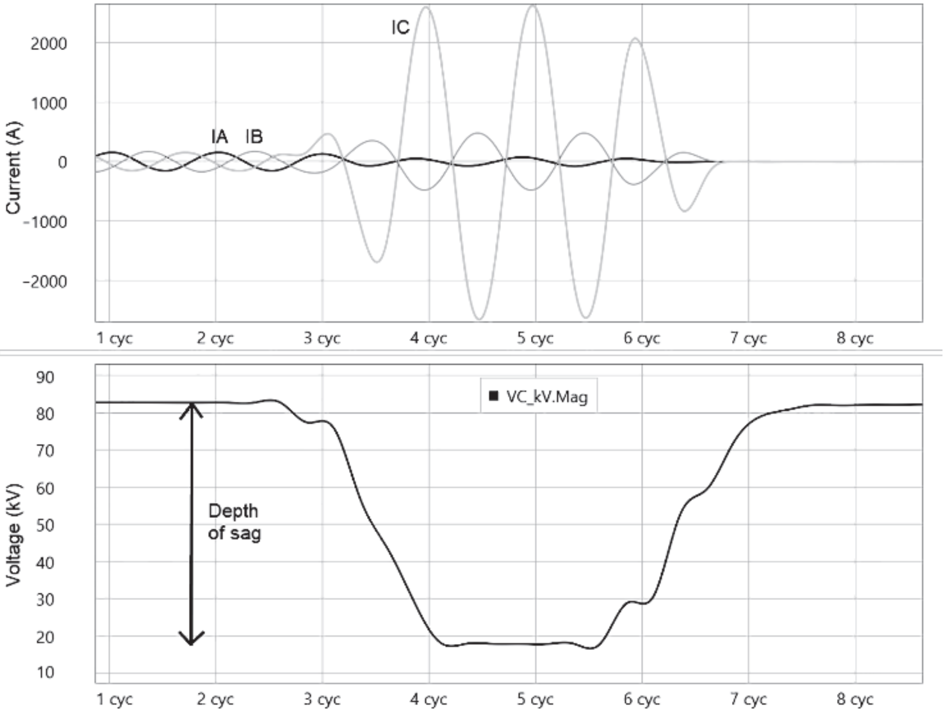

Figure 1.3 Voltage sag due to a single line-to-ground fault on a 138 kV line.

between a half cycle to one minute. An example of voltage sag during a single line-to-ground fault is shown in Fig. 1.3. Voltage sag is a power quality event that can shut down sensitive equipment in industrial plants, resulting in a revenue loss of several million dollars. Voltage swell is defined as an event in which the rms voltage increases to a value between 1.1 and 1.8 per unit for a duration between a half cycle to one minute. This can occur when single line-to-ground faults occur on an ungrounded system. Voltage of the unfaulted phases swells to 1.73 per unit and stresses the insulators. For all the reasons listed above, shunt faults must be detected and isolated as fast as possible. The latest generation of protective relays can detect faults in as fast as 2 ms [11]. The breaker takes an additional two or three cycles to open. The fast clearing time limits the damage to power system equipment, reduces the impact of the fault on the rest of the power system, and increases personnel safety.

1.2 What Causes Shunt Faults?

This section discusses the most common causes of shunt faults on the power system.

Lightning

Lightning is a major cause of shunt faults on the power system. Data collected by Texas Reliability Entity shown summarized in Fig. 1.4 is a case in point. You can see that lightning

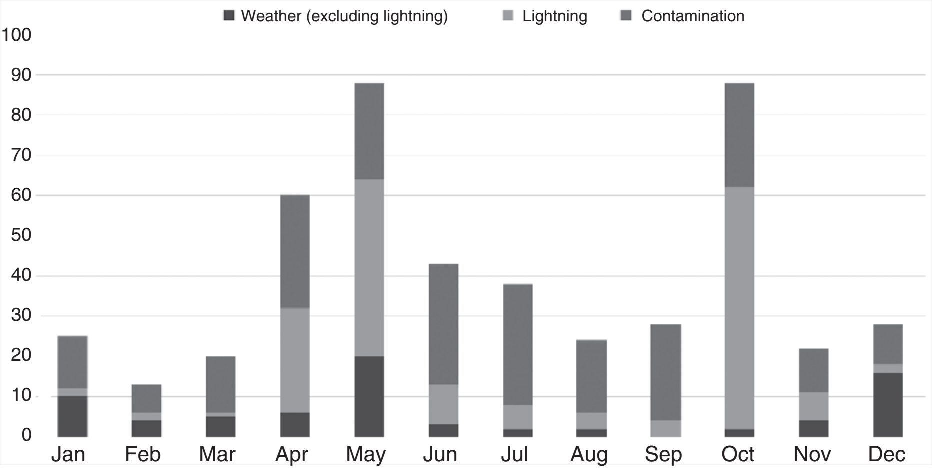

Figure 1.4 Shunt faults on 345 kV transmission lines in Texas in 2015 categorized by root cause [18].

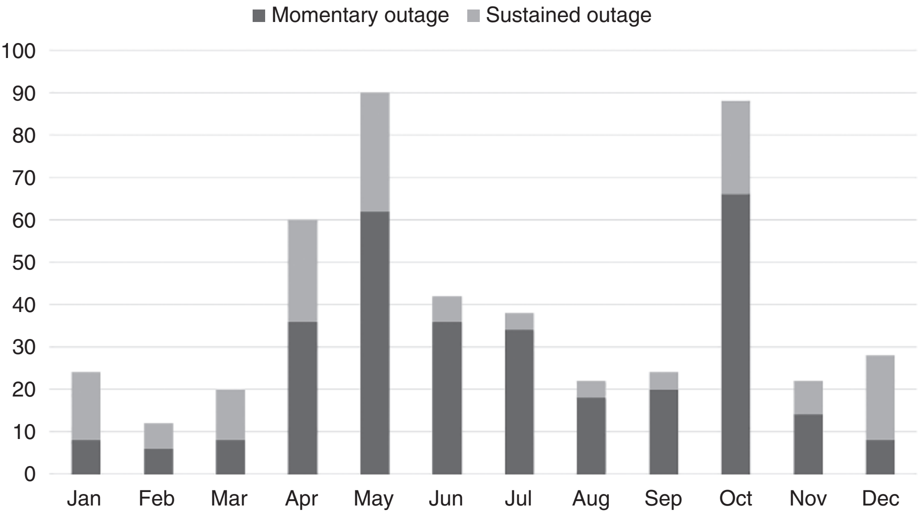

Figure 1.5 A comparison of the number of sustained and momentary outages on 345 kV transmission lines in Texas in 2015 [18].

was responsible for a large number of faults on 345 kV transmission lines in Texas in 2015, particularly during the months of April, May, and October. Figure 1.5 shows how many of the same shunt faults resulted in sustained and momentary outages. During the months of April, May, and October, when lightning activity had dramatically increased, the number of momentary outages was much greater than the number of sustained outages. The data establishes a strong correlation between lightning and momentary outages, indicating that most faults due to lightning are temporary faults.

Figure 1.6 Location of NLDN sensors to detect lightning [14].

Lightning activity in the US is monitored by the National Lightning Detection Network (NLDN). This network, owned and operated by Vaisala, has over a hundred sensors across the US as shown in Fig. 1.6. During a lightning strike, sensors that get triggered send the information they captured about the strike via satellite to a central location in Tucson, Arizona. There, data from different sensors are combined to establish date, time, peak current magnitude, type, and location of the lightning strike [13]. The data is then made available to the National Weather Service and utilities that subscribe to this service. These utilities can make use of this information to determine whether lightning was in the area when a particular fault occurred on their system and whether it was the root cause of the fault.

Lightning occurs when a thundercloud (also referred to as a cumulonimbus cloud) develops areas of positive and negative charges as shown in Fig. 1.7. Lightning discharge can occur between the positively charged and the negatively charged regions inside the cloud and are referred to as intracloud lightning. It can also occur between the positively charged

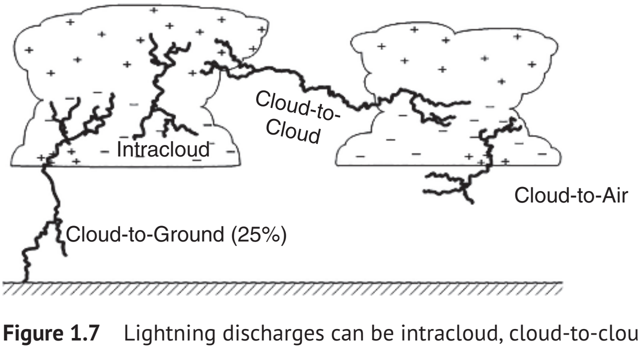

Figure 1.7 Lightning discharges can be intracloud, cloud-to-cloud (intercloud), cloud-to-air, and cloud-to-ground [14].

area of one thundercloud and the negatively charged area of another thundercloud and is referred to as cloud-to-cloud or intercloud lightning. Lightning can also occur between a thundercloud and air, referred to as a cloud-to-air lightning discharge, and between a thundercloud and the earth, referred to as a cloud-to-ground discharge. Cloud-to-ground discharges constitute about twenty-five percent of all lightning discharges and are the ones responsible for creating shunt faults on the power system.

Figure 1.8 shows four different ways by which a cloud-to-ground lightning strike can occur. A downward negative lightning strike starts when negative charges at the lower parts of the cloud start ionizing the air. This results in a column of negative charges, known as the leader, moving down toward the ground. As the leader approaches the ground, it induces streamers of opposite charges to move up from the ground. When the leader and streamer make contact with each other, the path becomes complete, a cloud-to-ground strike occurs, and a huge amount of negative charge is transferred to the ground. A downward positive lighting strike occurs the same way as the previous one, except that the leader is initiated by positive charges in the cloud. Upward lightning strikes occur when leaders are initiated by tall objects on the ground with sharp corners. When the leader reaches the cloud, a cloud-to-ground lightning strike occurs. When the leader is positive, it is called upward positive lightning. When the leader is negative, it is called upward negative lightning. Out of the four types, downward negative cloud-to-ground lightning strikes are more common.

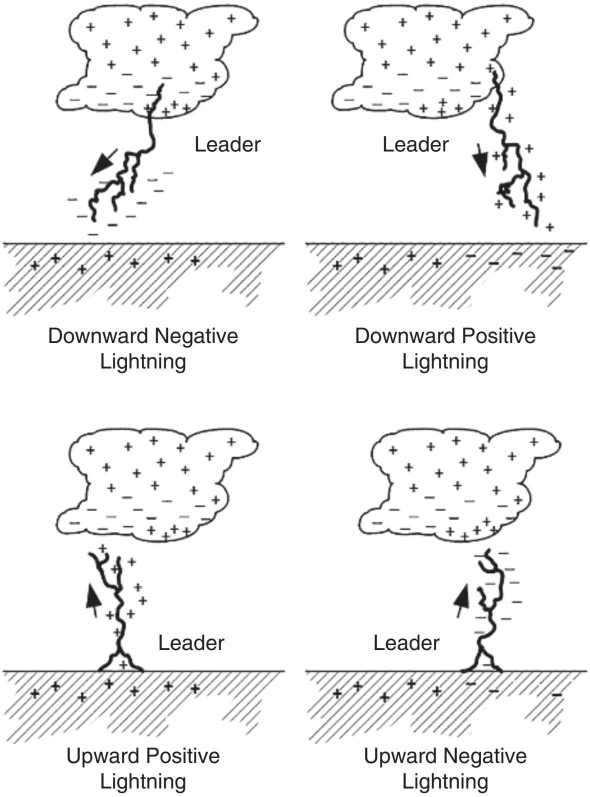

Figure 1.8 Types of cloud-to-ground lightning [14].

Figure 1.9 Overvoltage due to lightning strike on a 69 kV transmission line resulted in a flashover and a phase-to-ground fault. The insulator string was found to be damaged with multiple ceramic disks missing. (*Photo: Courtesy of Mr. Genardo Corpuz, Lower Colorado River Authority, USA.*)

A cloud-to-ground lightning strike can create faults when it directly strikes a phase conductor and injects a huge current surge into the line. The current surge is accompanied by a voltage surge. If the voltage surge exceeds the insulator critical flashover voltage, a flashover will occur, resulting in a shunt fault. Lightning can also strike a tower and create faults. When the injected current surge travels through the tower to the ground, a voltage rise develops across the tower crossarm due to the surge impedance of the tower and the tower footing resistance. If the voltage rise is large enough, a flashover will occur from the tower to the conductor across the insulator string. This flashover, commonly referred to as backflash, will create a shunt fault. Figure 1.9, Figure 1.10, and Figure 1.11 show the damage to utility assets due to flashover during lightning.

To protect power system equipment from lightning at substations, lighting masts (shown in Fig. 1.12) and lightning arresters are used. Line arresters are used in parallel with transmission line insulators to prevent the voltage from increasing beyond the line insulation level. To reduce the possibility of direct lightning strikes to transmission lines, ground wires (shield wires) are often placed above the phase conductors (shown in Fig. 1.13). Shield wires also reduce the possibility a backflash as the injected current is divided into three parts (tower and each direction on the shield wire). Pole ground is improved by driving a metal rod further down into the ground.

Animals

Animals such as birds, snakes, monkeys, cats, and squirrels are notorious for creating faults on the power system. Figure 1.14 shows a monkey that died after making contact with

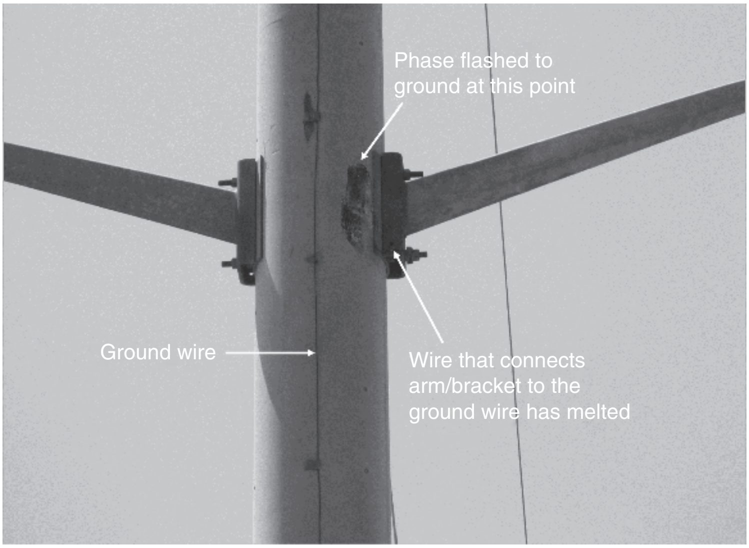

Figure 1.10 Another example of a fault due to lightning strike on a 138 kV transmission line. The resulting overvoltage caused a flashover and an A-G fault. Notice the damage to the concrete tower at the point of the flashover. Part of the wire that connects the bracket/tower arm to the ground wire has either melted or blown away. (*Photo: Courtesy of Mr. Genardo Corpuz, Lower Colorado River Authority, USA.*)

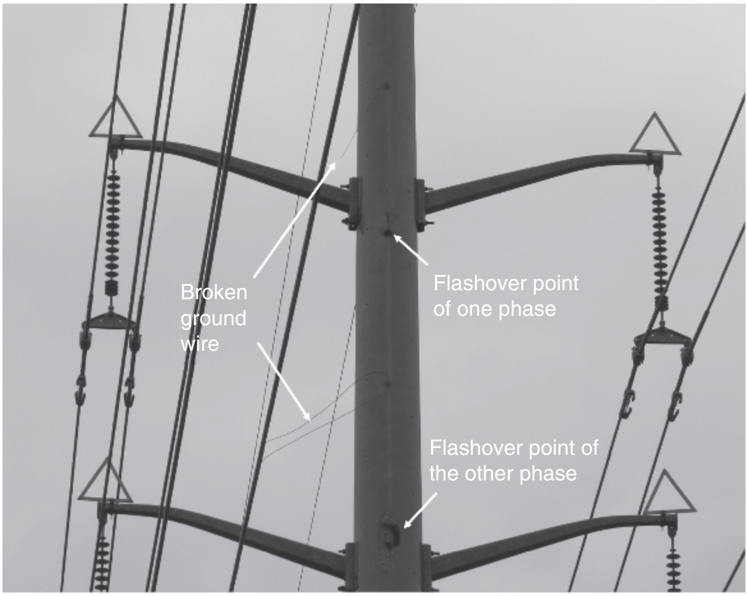

Figure 1.11 Similar to the previous example, lightning struck a 138 kV transmission line. Phase A and phase C flashed to the ground wire and created a line-to-line fault through the ground wire. Notice the evidence of damage to the concrete tower when one of the phases flashed over to the ground wire. (*Photo: Courtesy of Mr. Genardo Corpuz, Lower Colorado River Authority, USA.*)

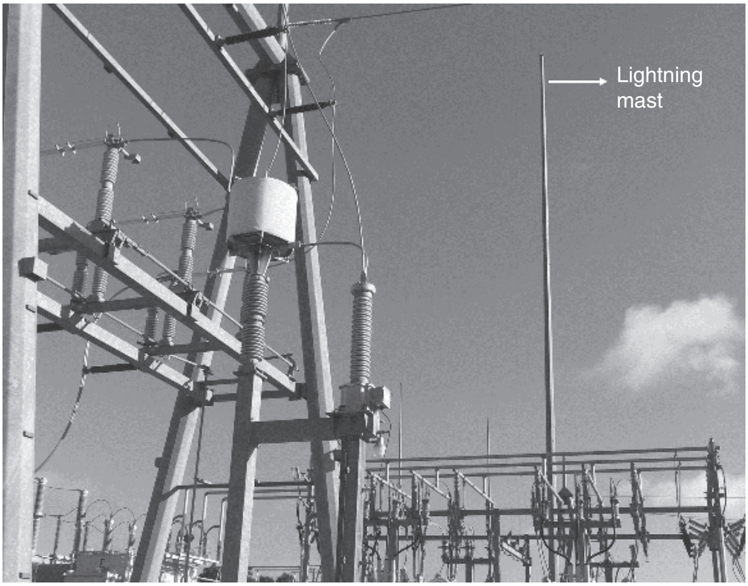

Figure 1.12 Lightning mast at a substation.

Figure 1.13 Shield wire on a single-circuit 345 kV transmission line. (*Photo: Courtesy of Mr. Genardo Corpuz, Lower Colorado River Authority, USA.*)

energized equipment in a substation and creating a fault. Figure 1.15 shows the damage to a 22 kV breaker when a bird flapped its wings, touched both B and C phases, and created a BC fault. Birds build nests on transmission towers, on distribution poles, and in substations. These nests can cause a short circuit by making contact with multiple conductors. They can also attract other animals such as snakes and raccoons that in turn cause faults. Bird droppings contaminate insulators and can result in a flashover. Woodpeckers can cause structural damage to wooden poles. Horses, bears, bison, and cattle can also degrade the structural integrity of poles by rubbing against guy-wires, causing the poles to lean and conductors to sag. Squirrels can climb utility poles and create faults by bridging the gap between phase conductors and the grounded equipment. Small animals such as rats and mice can chew on the insulation of underground cables and create faults. To reduce the number of

Figure 1.14 A monkey that made contact with energized equipment in a substation and created a fault. (*Photo: Courtesy of Mr. Emmanuel Raubenheimer, Eskom, South Africa.*)

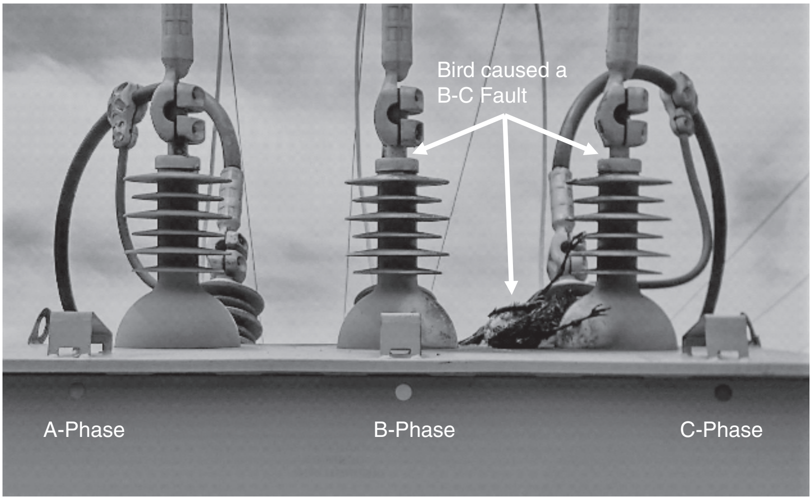

Figure 1.15 A bird flapped its wings and bridged the gap between phase B and phase C bushing on the bus side of a 22 kV breaker, creating a BC fault. The fault current magnitude was about 2 kA. The line-to-line fault later evolved into a three-phase fault. It also flashed across the breaker and created a B-G fault on the 22 kV distribution feeder, just in front of the breaker. Flash marks are clearly visible on the clamps and on the bushings of the breaker. (*Photo: Courtesy of Mr. Emmanuel Raubenheimer, Eskom, South Africa.*)

Figure 1.16 Bird spikes to prevent birds from perching.

faults due to birds, some utilities install bird spikes such as the one shown in Fig. 1.16 to discourage birds from perching or roosting. Another preventive step is to wash the insulators at periodic intervals to remove bird droppings and other contaminants. Animal guards such as the one shown in Fig. 1.17 are also installed around energized equipment to restrict animal contact.

Figure 1.17 Animal guard around the top of the transformer low voltage bushing.

Trees

Trees are responsible for a large number of power system faults. In fact, a tree was responsible for the fault that triggered the Northeast blackout of 2003, one of the major blackouts in North America's history [15]. Trees can cause faults in a number of ways. Those uprooted by heavy winds or hurricanes can tear down lines, knock down poles, or damage insulators when falling down. Overgrown vegetation can bridge phase conductors. Tree limbs broken during heavy winds can fly into a line and bridge phase conductors. Tree branches blown by the wind can push two conductors together. Lines may sag during heavy load conditions and on doing so may make contact with the underlying vegetation. Electric utilities typically have a vegetation management program to trim trees and prevent tree-related outages and wildfires. They may also modify spacing between phase conductors to increase the resistance to flashover.

Other Causes

Power system faults can be caused by accidents such as when vehicles crash into poles or when drones, kites, shiny foil balloons, and hot air balloons make contact with energized conductors. Such an unfortunate event occurred on July 30, 2017, when a hot-air balloon struck high-voltage conductors, killing all sixteen people aboard [16]. A fault can also occur due to human errors such as forgetting to remove the grounding chains after maintenance and closing the breaker. Faults can also occur during acts of vandalism. They include thieves stealing conductor wire to later sell as scrap metal or people shooting at insulators with a rifle. An example of vandalism occurred on April 16, 2013, when there was a sniper attack on the Metcalf transmission substation owned by Pacific Gas and Electric [17]. Snipers opened fire on seventeen transformers, causing severe damage and forcing grid officials to reroute power from nearby power plants to avoid a blackout. In addition, contaminants can also weaken the insulators over time, resulting in a flashover and a short-circuit fault. This is a problem particularly in coastal areas where contaminants such as dust and salt or in agricultural areas where contaminants such as pesticide and fertilizer build up over time, eventually leading to a fault. Strong winds can cause power lines to swing into one another and create faults. Severe winds during hurricanes and tornadoes can even break power lines and utility poles, creating significant damage to the power system infrastructure. Snow and ice are also a major cause of faults. Their weight can cause power lines to snap or tree limbs to break and fall into utility lines. Power system equipment can also fail internally and create a fault. The internal fault may be the result of an insulation failure due to age, overvoltage, and other factors. Figure 1.18 show when a regulator failed in a substation and caused significant damage. Figure 1.19 shows another example when there was a fault inside a capacitor bank due to overvoltage.

Figure 1.18 Internal fault within a voltage regulator at a substation. (*Photo: Courtesy of Mr. Long Tran, South Texas Electric Cooperative, USA.*)

Figure 1.19 Internal fault inside a capacitor bank in a substation due to overvoltage. (*Photo: Courtesy of Mr. Long Tran, South Texas Electric Cooperative, USA.*)

1.3 Aim and Importance of Fault Location

The purpose of the power system is to deliver electric power from generators in power plants to industrial plants and residential customers through an interconnected network of transmission lines and distribution feeders. Figure 1.20 shows a turbine and generator inside a steam power plant. Steam produced by heating water is used to rotate the turbine. This turbine coupled to an electric generator transforms the mechanical power to electrical power with a voltage between 5 and 34.5 kV. To transport electrical power over long distances with minimum loss, the voltage is stepped up to between 69 and 765 kV using step-up transformers as shown in Fig. 1.21. The electrical power at a stepped-up voltage is

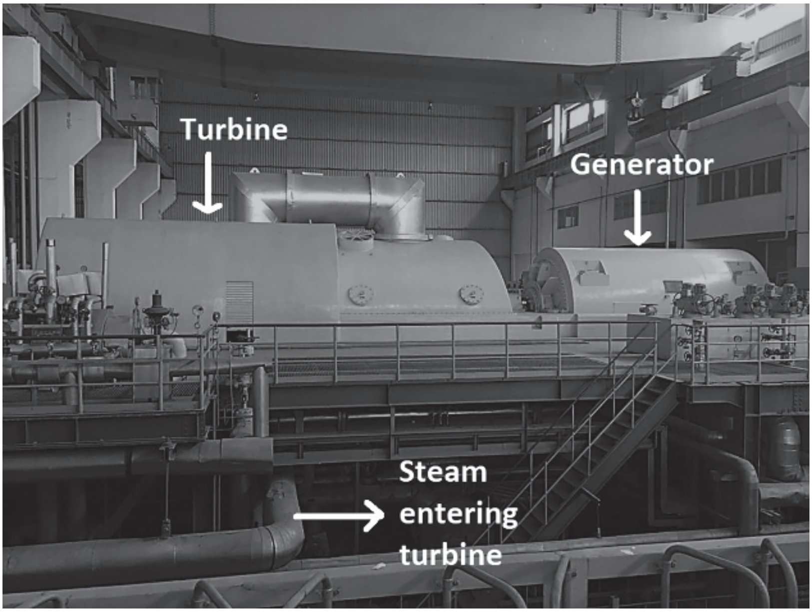

Figure 1.20 Turbine and generator in a 125 MW steam power plant. (*Photo: Courtesy of Mr. Dip Kumar Das, Development Consultants Private Limited, India.*)

Figure 1.21 Generator step-up transformer is transforming the low voltage output from the steam turbine generator to 132 kV and interconnecting the power station to the transmission network. (*Photo: Courtesy of Mr. Dip Kumar Das, Development Consultants Private Limited, India.*)

then transported by transmission lines. Closer to load centers, the voltage is stepped down to the low-voltage level of the load and delivered to various individual users.

When a permanent fault occurs, this normal flow of power is interrupted. Loads downstream from the fault experience an outage. Unless power is rerouted through other lines, the outage time will equal the time taken to find the fault plus the time taken to make repairs. If power is rerouted, the other lines supporting the additional load may get overloaded since power systems today operate close to their operating limits. This can set off a series of cascading trips, leading to a blackout. Data collected by NERC shows that between 2015 and 2019, 200 kV circuits had an average unavailability rate of 0.09% due to automatic outages caused by protective relay operation during an unplanned transmission incident (see Figure 1.22). This means that at any given time, there was a 0.09% chance that a 200 kV transmission circuit was unavailable due to a sustained automatic outage [12]. Figure 1.23 shows the outage data by duration in Texas [18]. As you can see, fifty-eight percent of the outages lasted longer than two hours. As a result, it is critical to find permanent faults as quickly as possible and restore normal operation. In addition to permanent faults, it is equally important to locate temporary faults. While they may not have resulted in a sustained outage, locating them and taking immediate action can help the utility avoid a permanent fault and outage later.

Faults inside generating power plants, substations, or load centers are localized and are hence easier and quicker to locate. In contrast, faults on transmission and distribution lines are much more difficult to find as they cover large distances. Reference [19] reports that there are 707,000 miles of high-voltage transmission lines and 6.5 million miles of distribution lines in the US. In the aftermath of a fault, the traditional approach for fault location has been to patrol the line length and look for visible evidence of a fault.

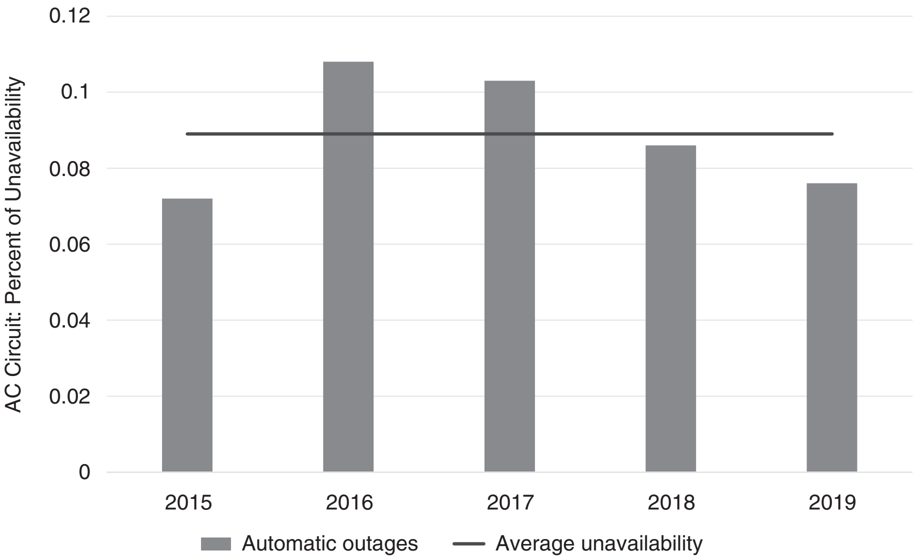

Figure 1.22 Percent unavailability of 200 kV transmission circuits due to automatic outages from 2015 to 2019 [12].

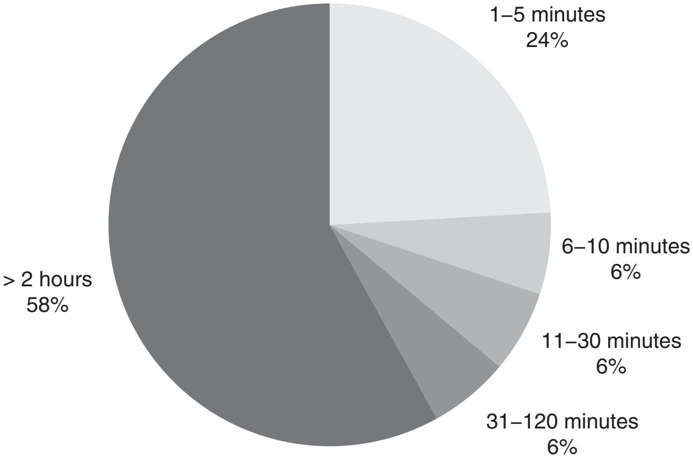

Figure 1.23 2015 345 kV automatic outage data by duration in Texas [18].

This manual approach is labor intensive and time consuming. Calls from customers reporting an outage can sometimes help narrow down the location of the fault. To make matters worse, rough terrains, remote areas, or bad weather may interfere with line patrol efforts and can delay repair work. Utilities may be forced to consider other expensive alternatives such as deploying helicopters to locate the fault. Furthermore, faults that leave behind a trail of evidence are easy to find. However, some faults are difficult to find. Figure 1.24 shows one such scenario where a flashed insulator is not easily visible from the ground. Figure 1.25 shows a zoomed-in view of the blown-out insulator. In addition, temporary faults may not leave a visible mark or indication as to the cause and location of the fault and can go unnoticed during inspection patrols. Knowing where to look for the fault can save field crew significant time and help them restore power back quickly. In addition to helping field crew locate the fault, fault location provide valuable operational benefits. For example, knowing the fault location is critical to establishing whether a protective relay operated correctly or not during a fault. It can also help catch CT and PT wiring errors and help validate relay settings, all of which are important to avoid undesired relay operations. These additional benefits are discussed in detail in Chapter 7.

1.4 Types of Fault-Locating Algorithms

The subject of using electrical signals for fault location has been of interest since the early 1900s [20–22]. Today, fault-locating algorithms can be classified into two major categories, impedance-based and traveling-wave algorithms.

Impedance-based fault-locating algorithms use Ohm's law to calculate fault location. Voltage during the fault is divided by current during the fault to estimate the line impedance between the measurement point and the shunt fault. Line impedance to the fault is not as useful as knowing the distance to the fault in miles (or kilometers). Therefore, these

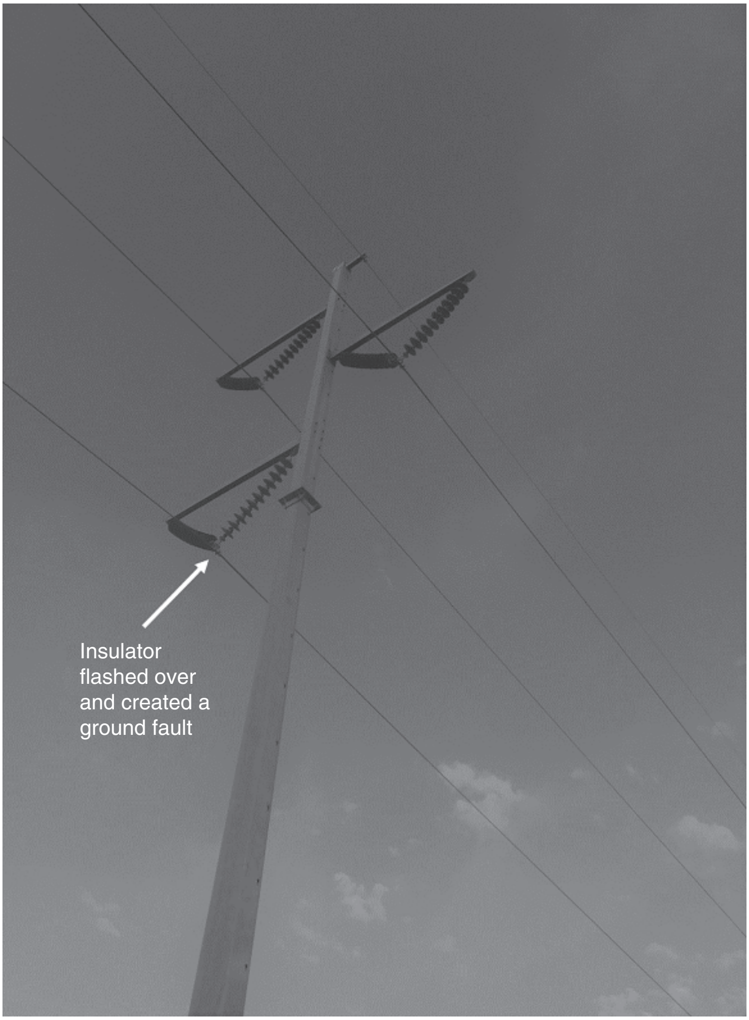

Figure 1.24 Faults are not always immediately obvious during line patrol. For example, an insulator flashover at this structure resulted in a phase-to-ground fault. The flashed insulator is not visible from the ground. (*Photo: Courtesy of Mr. Genardo Corpuz, Lower Colorado River Authority, USA.*)

algorithms use the line impedance in ohms per unit length (length in miles or kilometers) to convert line impedance to the fault to a distance estimate (same unit as the line length). Since line impedance is usually defined at the system frequency, the voltage and current used for fault location are also at the system frequency. Impedance-based fault-locating algorithms can be applied to locate faults on both transmission and distribution lines.

Traveling-wave fault-locating algorithms, on the other hand, use the velocity equation to calculate fault location. A fault causes a sudden change in voltage at the fault point. This generates high frequency voltage and current surges, also known as traveling waves, which travel at either direction from the fault. These waves travel at almost the speed of light on

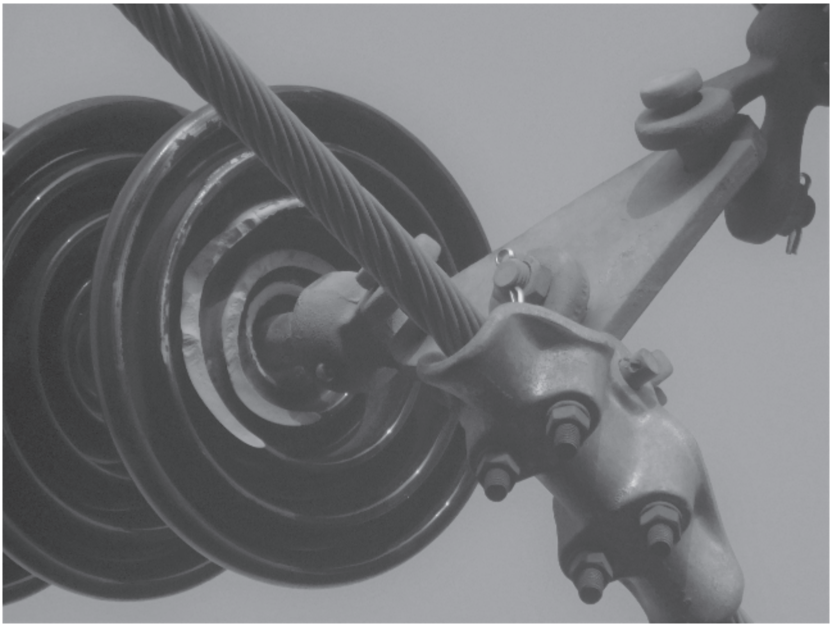

Figure 1.25 A zoom-in view of the flashed and blown-out insulator. (*Photo: Courtesy of Mr. Genardo Corpuz, Lower Colorado River Authority, USA.*)

overhead lines and eventually die out due to multiple reflections. Multiplying the velocity of the waves with the time taken by the waves to travel from the fault point to the measurement point gives the distance to the fault from the measurement point. Traveling-wave fault-locating algorithms can be presently used to locate faults on transmission lines only (69 kV and above).

In addition to impedance-based and traveling-wave algorithms, artificial neural networks, fuzzy logic, and other knowledge-based approaches are also being studied extensively for fault location [23–25]. Since this category is in the research stage and not commercially available, this book will focus on impedance-based and traveling-wave algorithms.

1.5 How are Fault-Locating Algorithms Implemented?

Fault-locating algorithms are implemented in microprocessor-based relays, digital fault recorders, stand-alone fault locators, and fault analysis software. In this section, we discuss their implementation.

(a) Microprocessor-Based Protective Relays

There have been significant advancements in the field of protective relaying. The earliest relays were electromechanical relays. They used the measured voltage, current, or both to create electromechanical forces. During a fault, these forces would actuate a movable

Figure 1.26 Electromechanical relay for overcurrent protection.

element within the relay to close the trip output contact. A target on the relay would indicate when the relay tripped. Other than this, the relay did not provide any other information about the fault. Figure 1.26 shows an example electromechanical relay designed for overcurrent protection.

Today, most protective relays are microprocessor-based relays, also referred to as numerical or digital relays. These relays use analog-to-digital converters to digitize the current and voltage analog signals. The digitized data is then used by numerical protection algorithms saved inside the microprocessor to detect faults and take action by closing the relay trip output contact. Microprocessor-based relays are multifunctional devices, meaning the relay is capable of providing several protection functions. For example, the microprocessor-based relay shown in Fig. 1.27 is a feeder protection relay. It can provide overcurrent, under- and overvoltage, under- and overfrequency, directional, breaker failure, reclosing, and other protective functions. In addition to protecting the power system, microprocessor-based relays also capture event records during a fault and provide fault location to assist operators understand the fault, analyze the relay operation, and restore service quickly. References [26–28] discuss all the advantages of using microprocessor-based relays over electromechanical relays. For the purposes of this book, we will focus on the fault location feature of microprocessor-based relays.

Fault location is a standard feature available in most microprocessor-based relays. An impedance-based fault-locating algorithm is used to calculate fault location from event reports saved after a fault. Figure 1.28 shows an example event report captured during a

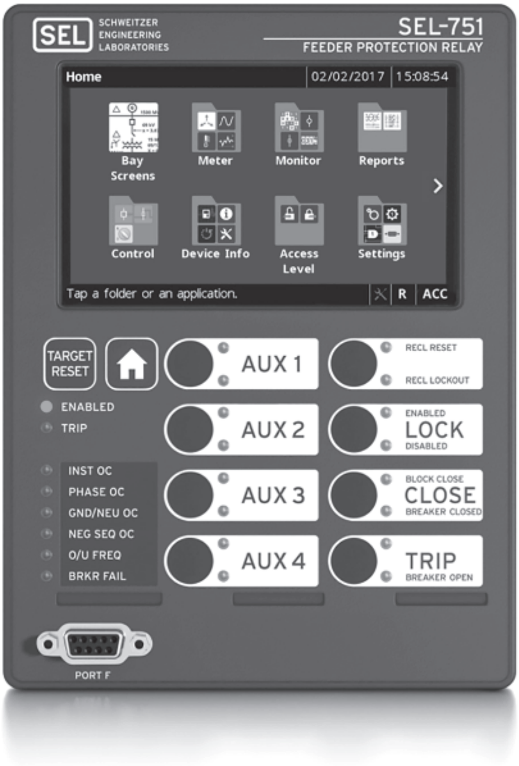

Figure 1.27 Microprocessor-based multifunctional feeder protection relay and fault locator. (*Photo: Courtesy of Schweitzer Engineering Laboratories.*)

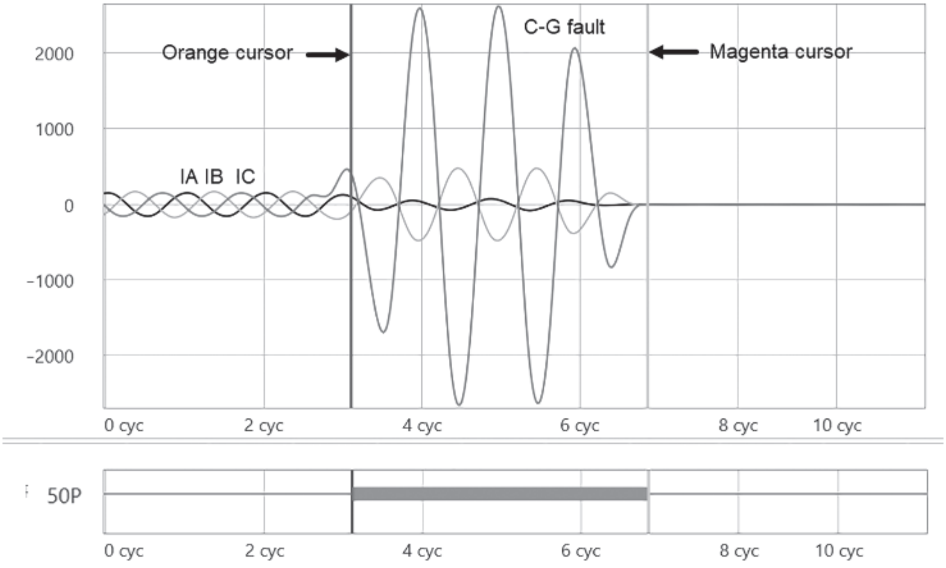

Figure 1.28 Event report captured by a microprocessor-based relay during a fault.

fault. It is a snapshot of the measured voltage and current analog signals, as well as the response of relay protection elements for a length of time set by the user (eleven cycles in this example). The fault-locating algorithm in the relay first establishes the window of time for which the fault was present on the power system. One method to establish this window is to look at the response of overcurrent, distance, and other fault detector elements in the relay during the fault [29]. For instance, in the example event report, the phase instantaneous overcurrent element (50P) picked up at the location of the orange cursor. It dropped out at the location of the magenta cursor. The relay interprets the orange cursor to be the start of the fault and the magenta cursor to be the end of the fault. Data between these two cursors is, therefore, valid for fault location. Since currents are most stable in the middle of the window, fault-locating algorithms in these relays use voltage and current data in the middle of the window to calculate fault location.

In addition to impedance-based fault location, some microprocessor-based relays also implement traveling-wave fault location. They have special hardware to capture traveling waves measured by conventional CTs and PTs. Traveling waves are not just created by internal faults on the line. They are created by anything that causes a sudden change in voltage such as lightning strikes or switching operations. Therefore, relays implementing traveling-wave fault location first determine if the captured traveling wave is due to an internal fault on the line. They usually do this by looking for a trip output from the relay within a couple of cycles from the instant the first traveling wave was recorded. This is because internal faults on the line will cause the relay to trip [33].

(b) Digital Fault Recorders (DFRs)

Digital fault recorders (DFRs) are microprocessor-based devices that record three-phase voltage and current waveforms, as well as the sequence of events following a disturbance on the power system. The recording capabilities of a DFR may seem similar to a microprocessor-based protective relay. However, there are some differences between the two with respect to sampling rate and how long of a record they save [30]. DFRs typically record current and voltage waveforms at a higher sampling rate than most protective relays. For example, [31] records waveforms at 256 samples per cycle and [32] records waveforms at 200 samples per cycle. In contrast, a typical relay records data at 4, 16, or 32 samples per cycle although the latest generation of microprocessor-based relays record data at a resolution of 1 MHz [33]. The higher sampling rate allows the visualization of high frequency transients such as lightning strikes, breaker restrikes, and switching events. DFRs also record data over a longer length of time (typically several minutes) than most protective relays (typically several cycles). In addition to recording waveforms during a fault, some DFRs can also locate faults. For example, [32] locates faults using impedance-based algorithms.

(c) Stand-Alone Fault Locators

Stand-alone fault locators provide a fault location after a line trip. An example of such a device has been described in [34]. It is a traveling-wave fault locator that can provide fault location for eight different circuits. Installing this particular fault locator does not require a line outage. It uses split-core linear couplers that are placed around the secondary wiring of conventional CTs to capture the traveling waves for fault location. The trip output from a protective relay can be wired into the digital input of the fault locator. A change of state of the digital input would indicate an internal fault on the line and would trigger the fault locator.

(d) Fault Analysis Software

Fault analysis software such as [35] automatically collects waveform event reports from microprocessor-based protective relays or DFRs after a fault, runs fault location algorithms, and notifies personnel about an event along with fault location results via email or SMS text messages.

1.6 Evaluation of Fault-Locating Algorithms

Fault-locating algorithms are evaluated by their error percent. This is typically calculated relative to line length as [36]:

$$e = \frac{|m_{est} - m_{act}|}{LL} \times 100 \tag{1.1}$$

where m_{est} is the fault location estimate, m_{act} is the actual fault location, and LL is the line length. All three must have the same unit of distance, typically miles or kilometers. A lower error percent is desirable as this means that the estimated fault location is closer to the actual fault location. This allows field crew to find the fault faster, leading to shorter outage times. In addition to measuring the performance of fault-locating algorithms, knowing the error percent of a specific fault-locating algorithm for a particular line can help field crew build a search radius around the fault location estimate. For example, suppose that a fault has occurred on a hundred-mile-long line. The fault is estimated to be located at forty-five miles from the substation. Past experience indicates that the fault-locating error on this line is five percent of the line length. The error works out to be five miles in this example. Therefore, field crew should broaden their search around the estimated fault location by five miles.

Commercial fault-locating devices may also be evaluated on how fast they can calculate fault location. Traditionally, the purpose of fault-locating algorithms was to help field crew search for the fault. Therefore, it was perfectly acceptable if this data was available within a couple of minutes after the fault had occurred. Some applications, however, use the fault location estimate to make protection decisions. An example of such an application is the decision to autoreclose on hybrid lines. Hybrid line consists of both overhead and underground line sections. Faults on overhead line sections can be momentary or permanent while faults on underground line sections are typically permanent. Protective relays can use the fault location data to identify whether a fault is on the underground or on the overhead line section. If the fault is determined to be on the overhead line section, reclosing is allowed. On the other hand, if the fault is on the underground section, reclosing would be blocked. Such applications require the fault location to be computed and be available faster than that required for traditional applications.

1.7 The Best Fault-Locating Algorithm

Under impedance-based and traveling-wave categories, several fault-locating algorithms have been developed. While all algorithms have the same objective, which is to find the fault with the highest accuracy, each of them make different assumptions and use different data to arrive at this result. What is the best fault-locating algorithm? Unfortunately, there is no one-size-fits-all answer. The correct answer is that it depends. It depends on the data available for fault location, the system to which the algorithm will be applied to, and the characteristics of the fault (such as whether it involves the ground or whether it evolves from one fault type to the other). The purpose of this book is to explain the theory and principles behind many of the common fault-locating algorithms, identify the input data they need, and discuss error sources. This will allow the user to make an informed decision about the best fault-locating algorithm for their system.

1.8 Summary

The key takeaways from this chapter are as follows:

- The power system can experience two types of faults, series faults and shunt faults.
- Series faults occur when there is an open circuit on one or two phase conductors during load conditions. The current in the faulted phase decreases due to loss in load while the current in the healthy phase (or phases) equal the load current. This unbalance can damage transformers and motors. Series faults are caused by blown fuses or broken jumpers on one or two phases. They can also be caused when one or two poles of a circuit breaker are unable to close during a manual or automatic close operation.
- Shunt faults occur when there is a shunt connection between one or more phase conductors to the ground or between each other. The current in the faulted phase dramatically increases while the voltage of the faulted phase sags. These faults need to be detected and isolated as fast as possible to limit the thermal and mechanical stress to power system equipment, prevent the power system from becoming unstable, avoid shutting down industrial plants with equipment sensitive to voltage sags, and increase personnel safety. Shunt faults are caused by lightning, animals, tree contact, equipment failure, extreme winds or snow, vehicle accidents, vandalism, or human error. They can be single line-to-ground, line-to-line, double line-to-ground, or three-phase faults. Single line-to-ground faults are the most common fault type.
- Fault-locating algorithms are used to locate shunt faults on transmission and distribution lines to expedite service restoration and repair after a permanent fault. They can be classified into impedance-based and traveling-wave algorithms. These algorithms can be implemented in microprocessor-based relays, digital fault recorders, stand-alone fault locating devices, or fault analysis software.
- Fault-locating algorithms are required to be accurate. In some applications where the fault location information is used to make a protective decision such as reclosing, how fast fault location is calculated becomes another important requirement.
- Under impedance-based and traveling-wave categories, several algorithms have been developed. The best method for fault location depends on your application, the available data, and the characteristics of the fault.