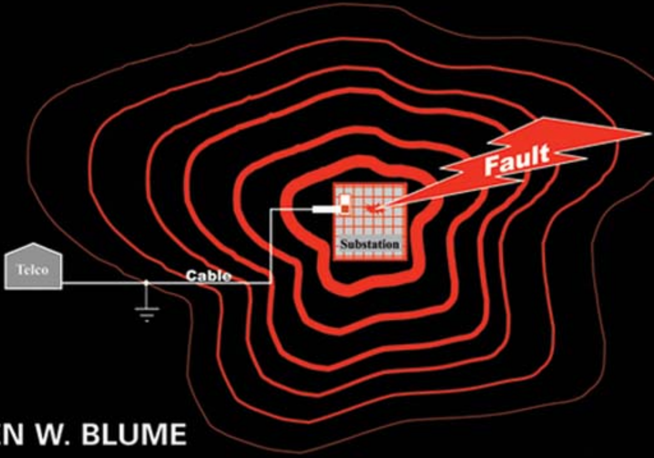
High Voltage Protection for Telecommunications



STEVEN W. BLUME

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Preface

ABOUT THE BOOK

This book is intended to help electric power and telephone company personnel and individuals interested in properly protecting critical telecommunications circuits and equipment located in high voltage (HV) environments and to improve service reliability while maintaining safe working conditions. Critical telecommunications circuits are often located in HV environments such as electric utility power plants, substations, cell sites on power towers, and standalone telecommunications facilities such as 911 call centers and mountaintop telecommunications sites. The need for highly reliable telecommunications circuits during power faults and lightning strikes when controlling our nation's electric power grids, communicating via wireless phones, and conversing with public safety support individuals at 911 call centers has never been higher. The utilization of information provided in this book should help provide higher reliable telecommunications circuits and improve the safety of personnel working in HV environments. Several industry standards and best practices are referenced throughout this book. These standards and practices are based on power and telecommunications company experience, field testing, workgroup committees, equipment manufacturers' support, and the advice of construction contractors and industry experts/consultants. This book is very comprehensive in that it combines several detailed references into a practical general purpose applications reference guide.

There is a power and telecommunications industry concern that a high percentage of people knowledgeable in this subject area have either retired or are approaching retirement, and these industries are losing valuable expertise for proper application solutions. This book is intended for individuals new to this subject area who want a working knowledge of the concepts, design techniques, and industry's best practices. Likewise, subject area professionals require knowledge of the dos and don'ts regarding the special electrical phenomena that affect telecommunications circuits that are required to be reliable and safe to maintain.

The target audience is managers, engineers, planners, and technicians involved in protecting critical telecommunications circuits from the adverse effects of electric power faults and lightning strikes. Personnel in public safety, natural gas, water, public utilities, and others involved in assuring that critical telecommunications circuits are reliable under lightning conditions should find benefit from reading this book.

What is not covered in this book are the details surrounding each type of telecommunications circuit such as digital subscriber line (DSL), high speed DSL, T1, plain old telephone service, the difference between two-wire and four-wire circuits, and so on. This information is readily available on the Internet and from other resources such as the following:

- *Subscriber Loop Signaling and Transmission Handbook—Analog* by Whitman D. Reeve
- *Subscriber Loop Signaling and Transmission Handbook—Digital* by Whitman D. Reeve

Also not included in this book are the vendor-specific details of their proprietary HV isolation equipment and details contained in the referenced industry standards. The focus here is to explain how such critical circuits are protected from lightning strikes and power faults, plus the safe handling of such circuits should a power fault or lightning strike occur at the time of construction or maintenance.

This book provides a helpful reference to implement concepts correctly and to recognize situations to avoid. The reader should also be aware that sophisticated computer programs and consulting services are readily available for guidance with unique circumstances that may not be covered in this book. This book does provide the knowledge and background necessary to work closely with consultants or to understand the principles of sophisticated computer programs.

CHAPTER SUMMARIES

A brief overview of each chapter is presented below to summarize the flow of technical information and to help identify what and where specific topics are covered in this book.

Chapter 1 presents an overview of high voltage protection for telecommunications (HVPT). The book starts out with a brief yet informative discussion of the impending problems that can occur when critical telecommunications circuits exist in HV environments. The purpose of this chapter is to quickly familiarize the reader with the important issues, industry standard solutions, and safety aspects affecting telecommunications reliability during lightning and power fault situations.

Chapter 2 discusses the fundamentals of electric power systems to help readers who are unfamiliar with HV equipment become better acquainted with HVPT applications. A basic model of the overall electric power system is presented to establish a fundamental understanding of how power systems work and the electrical phenomena that can interrupt critical telecommunications circuits and, if the system is not properly protected, cause equipment damage and injury to personnel. This chapter explains how substation ground grids, protective relaying, fault clearing devices, lightning arresters, and telecommunications equipment are used to clear power faults to minimize equipment damage and maximize electric service reliability.

Chapter 3 elaborates on the concepts of ground potential rise (GPR) and zone of influence (ZOI). These two concepts are fundamental to this subject area, and proper protection design, installation, and maintenance depend on a solid understanding of these concepts. The definitions, causes, boundary conditions, and calculations of GPR and ZOI are discussed in this chapter.

The critical telecommunications circuits found in HV environments are discussed in Chapter 4. The various classes and types of critical telecommunications circuits used by power and telecommunications companies and public service providers where HV protection is necessary are also discussed. Examples of situations which require HV protection are the critical electric power systems control centers and associated protective relaying applications, telephone companies that are using telecommunications circuits involving wireless radio equipment mounted on HV electric power towers, and 911 call centers, which have their respective requirements for critical circuit reliability. The standard service performance objectives (SPOs) and standard levels of protection are discussed in this chapter.

Chapter 5 presents discussions about the actual HV protection equipment used in these critical circuit situations. The concepts behind modern telecommunications protection schemes and equipment used to resolve GPR problems are also discussed, as well as references to industry standards and typical manufacture equipment offerings.

Chapter 6 discusses proper installation and testing procedures of high voltage interface (HVI) equipment. The design and installation objectives, both theoretical and physical, for reliable HV isolation are the focus points of this chapter. Proper design and installation is paramount; however, attention is given to the dos, don'ts, and common installation deficiencies. Photographs of actual installed equipment configurations are included in this chapter to give the reader a practical perspective.

Safety in working with HV equipment is the main topic of Chapter 7. The safety of personnel who work with HV protection equipment is a paramount concern for supervisors and managers responsible for technicians and field personnel. For example, telephone company personnel who work in electric power substations must be aware of all safety rules and procedures and proper use, inspection, and testing of personal protective equipment (PPE) before entering a substation or power plant. The reader will be made aware of these safety concerns and how and when to properly use PPE.

DISCLAIMER

This book is not intended to ensure safety of personnel nor to ensure that equipment will not be damaged should a power fault or lightning strike event occur. The advice, suggestions, and recommendations contained in this book are presented for general educational purposes only and to increase safety awareness regarding HV protection for telecommunications. The information presented in this book is based on applicable industry standards and best practices. This book is not intended to be a legal or other expert advice resource and should not be used in place of highly qualified professional consultants. The information in this book is considered accurate and helpful but is not to be considered exhaustive and complete. The responsibility for safe and reliable equipment in HV environments always remains the responsibility of the parties doing the work.

Steven W. Blume

Acknowledgments

I would personally like to thank several people who have contributed to the success of my career and the success of this book. To my wife Maureen who has been supporting me for over 40 years, thank you for your guidance, understanding, encouragement, and so much more. Thank you Bill Ackerman, Dick Knight, Percy Pool, Tim Conser, Larry Young, Ernie Duckworth, Chuck Keller, and Rich Minetto for your unbiased technical support, help, and encouragement over the several years we have worked together in this field. I would also like to thank Positron Inc. and RLH Industries, Inc. for their photo contributions and equipment expertise.

S.W.B.

About the Author

Steven W. Blume is a registered professional engineer with over 40 years' experience in the areas of electric power systems and telecommunications. He holds a master's degree specializing in electrical power systems and a bachelor's degree specializing in telecommunications technologies. He has worked in both the telecommunications industry (City of Los Angeles Police and Fire critical telecommunications) and electric power industry (Sierra Pacific Power Company [now NV Energy]) in planning, design, operations, and construction of high voltage power facilities and telecommunications systems. Steve has been teaching high voltage protection for telecommunications (HVPT) courses for over 15 years. His combined knowledge, experience, and recognized ability to explain complex subjects in the simple-to-understand terms presented in this book will be useful to those interested in gaining a working knowledge in HVPT applications.

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CHAPTER 1

Overview of High Voltage Protection for Telecommunications

LEARNING OBJECTIVES

- Discuss the purpose of high voltage (HV) isolation protection equipment
- Describe ground potential rise (GPR) and how it can damage telecommunications equipment and expose people to unsafe working conditions
- Describe what is meant by zone of influence (ZOI) and the 300-V point
- Explain the problems encountered if HV isolation equipment is not used
- Explain where to install HV isolation equipment
- Describe the two main types of HV isolation equipment (copper vs. fiber) and the corresponding IEEE recommended practices for proper design and installation
- Explain how copper versus fiber HV isolation equipment works

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BASIC PURPOSE AND APPLICATIONS

Copper wire-line telecommunication facilities (as opposed to fiber optics, radio, microwave, satellite, and power line carrier systems) that are used in electric supply locations (ESLs) often require special high voltage (HV) protection equipment to provide safety to personnel, to prevent damage to equipment, and to assure the reliable operation of the telecommunications circuits themselves. There are various means of properly protecting telecommunications facilities equipment and personnel. The goal of high voltage protection for telecommunications (HVPT) is to provide the design engineer with safe, reliable, and cost-effective installations when exposed to unexpected HV events such as power faults and lightning strikes. Power faults are HV flashovers of insulation, the breakdown of equipment used in HV systems, or when something happens to HV equipment causing it to discharge large amounts of electrical energy into its surroundings. When personnel are working in HV environments such as electric power substations, power plants, cell sites on power towers, and other potentially dangerous locations where an HV event is possible, properly protecting critical telecommunications facilities is essential. Copper telecommunications cables can transfer dangerous potentials from remote locations due to their insulated jackets and remote connections. All dielectric optical fiber systems, on the other hand, offer electrical isolation due to the nonconductive properties of glass. This chapter summarizes the potential problems with telecommunications circuits in HV environments, the industry solutions, and the recommended methods to work in these environments safely.

The first point to make in explaining the potential problem associated with these facilities is to clarify the difference between HV "isolation" of telecommunications circuits and HV "protectors" used on telecommunications circuits. The terms are almost synonymous when it comes to protecting telecommunications circuits from HV conditions. Both terms apply to HV exposure conditions where circuits need to protect themselves from damage. However, the term HV "protectors" refers to circuit protection equipment that is used to limit the voltage across telecommunications circuit conductors by shunting the energy to the earth grounding electrodes (i.e., circuit protectors such as gas tubes and carbon blocks as discussed in more detail later in this book). The term HV isolation is used to describe circuit protection from HV damage by isolating the copper conductors from the damaging HV potentials. Shunt "protectors" are usually applicable to HVs 1000 V or less, and HV "isolation" devices are applicable to exposure HVs above 1000 V. Hence, both HV protectors and HV isolation equipment may be required at HV environments such as power substations, personal communications system (PCS) cell sites located on electric power towers, stand-alone mountaintop telecommunications antenna towers, and 911 emergency call centers. One of the main purposes of this book is to explain when and where to use shunt protectors and/or HV isolation equipment.

THE HV PROTECTION CHALLENGE

Electrical disturbances that cause damage to telecommunications equipment and possible injuries to personnel are commonly lumped into two categories, "power faults" and "lightning strikes." Power faults typically occur when HV power lines come in contact with earth-grounded equipment and/or substation HV power equipment failures. Power faults and lightning strikes cause high currents to flow through metallic paths to earth-grounded objects. The portion of faulted current that flows through the earth itself, returning to voltage sources, can have harmful effects on telecommunications cables and equipment. For example, Figure 1.1 shows a basic cable and equipment scenario *not* under a fault condition. The telephone company termination side (referred to as "central office" or "CO" side) is on the left, and the power company equipment side (referred to as "substation") is located

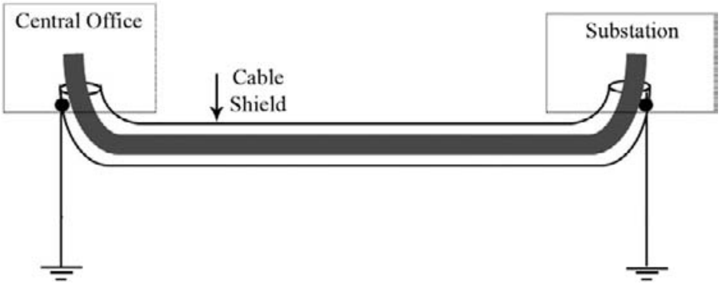

Figure 1.1 Basic cable configuration.

on the right. Notice that the cable shield is grounded on both ends (grounded is the term used to describe how the connection is made between the metal cable shield and the metal conductors buried in the earth). For the sake of illustration, intermediate grounds of the cable shield are not shown. In this case, the earth serves as a natural conductive body that can potentially conduct electrical current should a voltage appear between the grounded objects. In the normal state, the earth has zero potential between these two grounded objects, and no current is flowing through the cable shield.

During a power fault or lightning strike situation, the earth's electrical potential (voltage) rises and causes anything metal that is buried in the earth at or near that location to also rise in potential. When the earth's potential rises, referred to as "ground potential rise" (GPR), the voltage of these grounded cable shields also rises and can be significantly different. These GPR voltages can differ on the order of tens of thousands of volts at the location where the fault occurs. Due to the earth's electrical resistance to current flow, the earth's potential decays outward from the GPR event location where the energy is dissipated by the soil. Therefore, the potential at the CO's ground can be much lower than that at the substation ground (where the power fault occurs), causing an HV potential between the two grounded objects. The "remote" location (CO) becomes the reference point in a GPR situation. The degree at which the earth's ground potential rises, with respect to the remote location, follows an exponential curve as shown in Figure 1.2. Thus the earth's potential drops exponentially as the distance from the faulted location increases.

Figure 1.2 shows how the earth's potential rises nonlinearly with respect to remote ground during a power fault occurrence in a

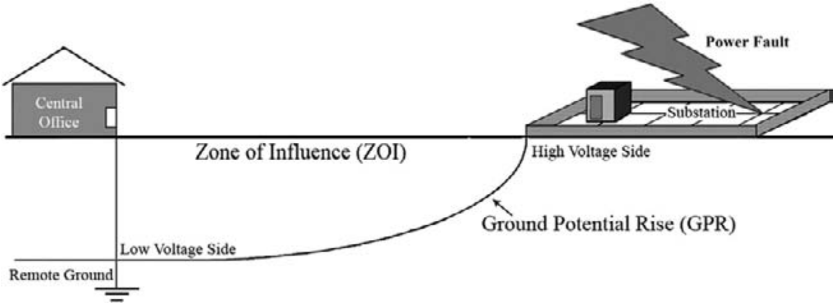

Figure 1.2 Substation ground potential rise.

substation. The same is true with all ESLs. The HV GPR occurs at the substation in this case, and the low voltage (LV) side of the GPR is located at the "remote ground" location (the CO side in this case). Since the fault is located at the substation, the CO side is also referred to as the remote ground location. In other words, when a copper telecommunications cable is connected between the CO and a substation and both ends of the cable are grounded, the CO side is referred to as remote ground location, and the station side of the cable is referred to as the ESL.

> *The paramount issue is when the ESL (substation) side of the telecommunications cable shield (or sheath) is connected to the substation's ground conductors (i.e., ground grid) when a power fault occurs and GPR is created, the telecommunications equipment is likely to be damaged due to the large potential difference across the cable shield, and personnel injures are possible when equipment fails catastrophically. Further, personal injury can also occur if the person comes in contact with both potentials at the same time*. (These situations are discussed in more detail throughout this book.)

The distance between the HV fault location (substation) and the remote LV area is called the "zone of influence" (ZOI). Note that the LV location of the ZOI does not have to be the CO location. The ZOI is usually measured or calculated as the distance from the HV side (substation) to a point in the ZOI that measures or is calculated to be 300 V. This is referred to as the "300-V point." Thus, the 300-V point is the location where the HV GPR decays exponentially to the 300-V level regardless of the magnitude of the GPR at the substation. For example, the substation GPR could be 30,000 V or 5000 V, and the ZOI is the distance to the 300-V point. The length or area of the ZOI depends on GPR magnitude and the soil type (details of GPR and ZOI are discussed later in this book).

Note that the "300-V point" is recommended in the United States, and other countries may use other values in a similar manner.

Combining the conditions of cable grounding at both ends, as in Figure 1.1, with the effects of earth's GPR shown in Figure 1.2 when a power fault or lightning strike occurs, as in Figure 1.2, results in the possible cable damage and personal injury scenario shown in Figure 1.3. GPR is directly imposed on the copper cable and the copper cable

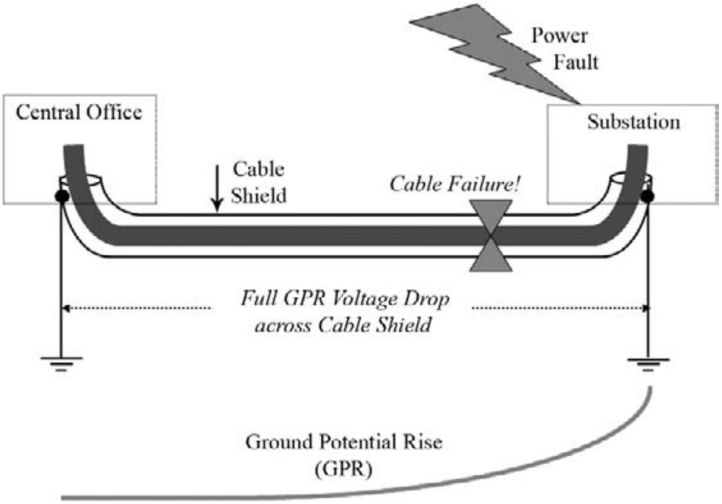

Figure 1.3 Unprotected cable in failure mode both ends grounded.

is not designed to withstand that much voltage. Although the copper shield of the telecommunications cable is typically jacketed with insulation, the conductive shield will most likely fail the cable and create safety concerns.

The essence of this book is to explain how this undesirable situation can be prevented and how to design reliable telecommunications circuits in the event of a high GPR condition. Locations where these HV events can occur are referred to as HV environments.

Aside from wireless and other telecommunications systems that provide GPR isolation by nature, there are two IEEE recommended practices of protecting telecommunications cables from the adverse effects of GPR. The two IEEE standards are

1. IEEE Std. 487-2007™; "IEEE Recommended Practice for the Protection of Wire-Line Communications Facilities Serving Electric Power Stations." This standard applies to copper cables traversing the ZOI as shown in Figure 1.4.
2. IEEE Std. 1590-2006; "IEEE Recommended Practice for the Electrical Protection of Optical Fiber Communication Facilities Service, or connected to, Electrical Supply Locations." This standard applies to all dielectric optical fiber cables traversing the ZOI as shown in Figure 1.5.

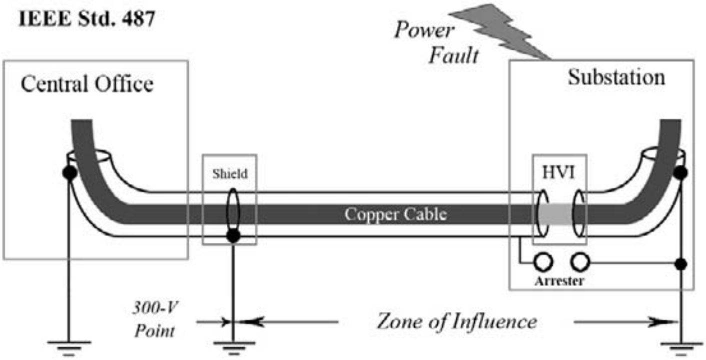

Figure 1.4 Isolated copper cable in failure mode.

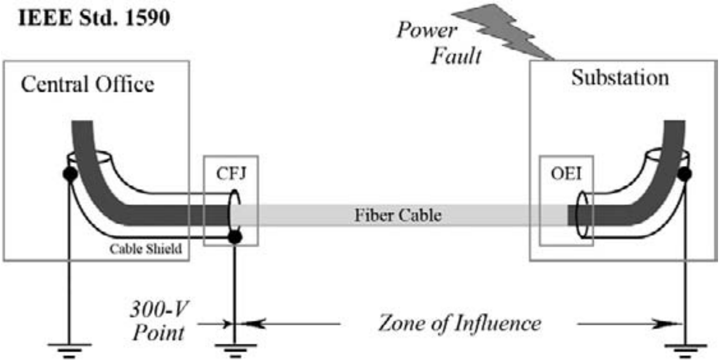

Figure 1.5 Isolated optical fiber cable in failure mode.

HV ISOLATION STANDARDS

There are two standard practices to protect telecommunications circuits in HV environments: those associated with copper cables crossing the ZOI and those associated with optical fiber cables crossing the ZOI. There are acceptable variations of the recommended practices, usually resulting in additional protection; however, minimum conditions must be met to assure equipment protection, personnel safety, and reliable circuit operations.

Copper Cables Crossing the ZOI (IEEE Std. 487-2007)

The most significant point to recognize when using copper telecommunications cables across the ZOI is that the cable shield is *not* grounded at both ends. The cable shield is grounded only at the remote ground location (300-V point, CO side) and isolated from all grounded conductors at the ESL and everywhere in the middle (see Fig. 1.4). Note that the cable shield is not connected directly to the substation ground grid.

The high voltage interface (HVI) is the telecommunications equipment that provides isolation from the voltage across the cable when the GPR occurs. Lightning arresters can be part of the HVI equipment. The lightning arrester protects the HVI when the GPR exceeds the insulation strength of the HVI by limiting the voltage across the HVI to the clamping voltage of the lightning arrested. When the GPR exceeds the breakdown voltage level of the arrester, the arrester conducts and limits or clamps the voltage across the HVI. The arrester is connected to the copper telecommunications cable between the cable shield and the station ground grid.

Lightning arresters are often installed at the substation end. The arrester connects the copper cable's shield to the substation ground grid. The purposes of the lightning arrester are to limit the voltage potential across the HVI and to utilize the remote ground to help dissipate some lightning energy during extreme lightning strike conditions. During extreme lightning strike conditions, the lightning arrester conducts (fires) and helps dissipate lightning energy directly to the earth ground electrodes (the station ground grid in this example). Normally, the magnitude of the GPR is less than the firing voltage of the arrestor, and therefore the arrestor does nothing. Its purpose is to provide a secondary path for extreme lightning energy should the substation side experience an unusually high lightning event. Additionally, the arrester limits the voltage across the HVI, thus protecting the HVI from voltages exceeding its insulation capability.

The copper cable-type HVI accomplishes circuit isolation two ways; either through high dielectric strength transformer action (coupling through electromagnetics) or short-reach fiber optics (coupling through an optical interface).

Transformer HVI

The HVI equipment can be composed of transformer isolation, where the LV CO side is isolated from the HV station side through specially designed HV isolation transformers. These special transformers provide circuit isolation up to about 90 kV (asymmetrical peak voltage, which is defined later in this book).

Fiber HVI

When a short 6-inch section of fiber optics telecommunications equipment is used to bridge an air gap between the CO side of the HVI and the station side of the HVI, about the same 90 kV level of isolation is provided. The insulation properties of a short section of glass are used to isolate the HV potentials.

Optical Fiber Cables Crossing the ZOI (IEEE 1590-2009)

Optical fiber cables provide inherent isolation because of the fact that glass and plastic are nonconductors of electricity. In this application, the all-dielectric optical fiber cable itself serves as the HVI isolator, provided the conversion from copper cable to optical fiber cable is located outside the ZOI, and the conversion of optical fiber cable back to copper cable is located at the ESL (substation). The all dielectric optical fiber cable must traverse the entire ZOI (between the 300-V point and station ground grid) to conform to IEEE Std. 1590-2009.

Figure 1.5 shows the optical fiber cable isolation method. When optical fiber cables are used across the ZOI as the isolation method, the copper-to-fiber and the fiber-to-copper transition points are referred to as the following:

- copper fiber junction (CFJ): implying the CO side of the installation
- optical electrical interface (OEI): implying the station side.

Note that the figure shows that the optical fiber cable is not of the metallic shielded type. Only all dielectric optical fiber cable is recommended, where there is *no* copper or conductive shield present in the optical fiber cable (as recommended by IEEE 1590-2009). Should a metallic shield-type optical fiber cable be desired, then the HVI design and installation procedures must follow the standards recommended for copper cables crossing the ZOI (IEEE Std. 487-2007).

CHAPTER 2

Electric Power System Fundamentals

LEARNING OBJECTIVES

- Discuss basic power system terminology that is used throughout this book
- Describe what is meant by asymmetrical peak voltage and how it impacts insulation levels
- Explain how generation, transmission, and distribution systems are used to produce and consume electrical energy
- Explain how three-phase alternating current (AC) electrical power is generated
- Discuss the differences between wye and delta connection configurations
- Discuss the differences between grounding and bonding
- Describe substation major equipment and how reliable telecommunications affect their operation
- Explain how lightning arresters work and how they protect high voltage (HV) power system equipment
- Discuss substation ground grids and the importance of equipotential grounding

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- Explain the basic components of transmission lines and tower structures and how they are used for wireless telecommunications sites
- Discuss distribution lines and how joint use telecommunications cables are attached electrically
- Explain how reliable telecommunications circuits are essential in power system protective relaying
- Describe automatic reclosing and how it affects ground potential rise and telecommunications circuit protection
- Explain how direct current (DC) control circuits help restore power to customers after power faults and why telecommunications circuits must be powered with a DC backup

POWER TERMINOLOGY FOR TELECOMMUNICATIONS

Industry professionals should be completely familiar with the following electrical power industry terms and concepts in order to properly apply high voltage interface (HVI) principles to the isolation of telecommunications circuits.

Voltage

Voltage is the potential energy source in an electrical circuit that causes current to flow, work to be performed, and energy to be produced and consumed. Voltage is sometimes called electromotive force or EMF. The basic unit of voltage is the volt. Electrical voltage is identified by the symbol "*e*" or "E" (some references use the symbols "*v*" or "V" to represent voltage).

Voltage does nothing by itself, but it has the potential to do work. Voltage is a push or pull force that appears between two points. Voltage is either constant (direct), alternating, or in a transient state.

Electric power systems are based on alternating voltage from levels as low as 120 VAC in residential systems to extra high voltages (EHVs) up to 765,000 VAC used as backbone interconnected transmission

Table 2.1
System Operating Voltages

System voltage class	Voltage category
Under 600	Secondary
601–7200	Distribution
15,000	Distribution
25,000	Distribution
34,500	Distribution or sub-transmission
69,000	Sub-transmission
115,000	Sub-transmission
138,000	Sub-transmission
161,000	Transmission
230,000	Extra high voltage (EHV)
345,000	EHV
500,000	EHV
765,000	EHV
Above 1,000,000	Ultra high voltage (UHV)

systems in the power grid. The common voltage classes used in the electric power industry are summarized in Table 2.1:

Current

Current is the flow of electrons in a conductor (wire). Electrons are pushed and pulled by voltage through an electrical circuit that is sometimes called a closed-loop path. The electrons flowing in a conductor always return to their voltage source. Current is measured in amperes, usually called amps (one amp is equal to 6.28×10^{18} electrons flowing in the conductor per second). The number of electrons is constant in a loop or circuit. The flow of electrons in a conductor produces heat from the conductor's resistance (friction). Electrical current is identified by the symbol "*i*" or "I."

Voltage always tries to push or pull current. Therefore, when a complete circuit path or closed loop is provided, voltage will cause current to flow. The resistance in the circuit will reduce the amount of

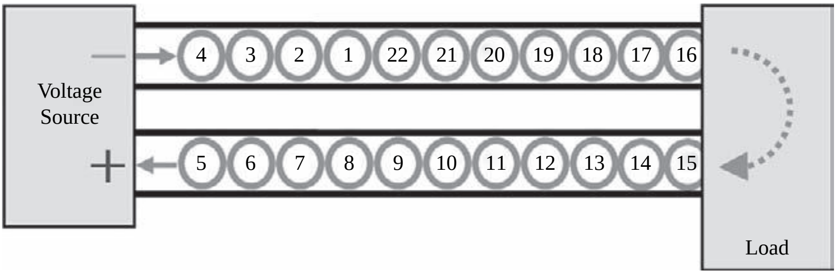


Figure 2.1 Current flow.

current flow and will cause heat to occur in the process. As the electrons flow in a circuit, the potential energy (voltage) is converted into kinetic energy. Kinetic energy is then used by the load (consumption device) where it is converted into useful work.

Current flow in a conductor is similar to ping-pong balls lined up in a tube. Referring to Figure 2.1, a pressure on one end of the tube (i.e., voltage) pushes the balls through the tube. The pressure source (battery) collects the balls exiting the tube and reenters them into the tube in a circulating manner (i.e., closed-loop path). The number of balls traveling through the tube per second is analogous to current flow as measured in amps (electrons per second).

In interconnected power systems, currents can range from a few amps (a residential electrical appliance) to several thousand amps during a power fault short circuit event. Short circuit implies a sudden abnormal very low resistance path that allows very high levels of current to flow. The high current flows that are returning to their source or sources can travel in several paths simultaneously: earth soil, power company transmission and distribution lines, metal facilities (water pipes, rails for transit systems, etc.), and other conductive paths if available. Note that current flows in all closed-loop conductive paths when a voltage is applied. Note also that most of the current flows in the path of least resistance but a proportion of the current flows in all available paths.

The engineer and technician are always concerned about the amount of current that flows in the earth during a power system fault or lightning strike. Currents flowing in the earth cause stray voltages to occur on the surface of the earth. Large stray voltages from large power faults or lightning strikes can be great enough to cause equipment damage and personal injuries.

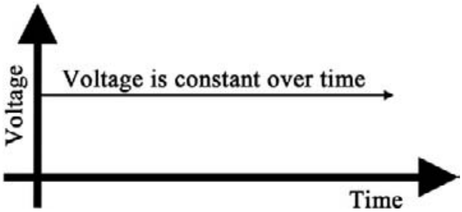


Figure 2.2 Constant voltage (i.e., direct current).

Direct Current (DC) Voltage and Current

DC is the flow of electrons in a circuit path that is always in the same direction. DC occurs when the voltage is kept constant, as shown in Figure 2.2. A battery, for example, produces a direct current when connected to a circuit. The electrons that leave the negative terminal of the battery move through the circuit, returning to the positive terminal of the battery.

Telecommunications engineers/technicians should be aware that HV DC events occur during the early stages of power faults when the current ramps up quickly and decays more slowly. This characteristic shape of a sudden DC rise and slower decay can negatively affect telecommunications circuits (the effect of transient voltage conditions on telecommunications circuits is discussed later in this book).

Alternating Current (AC) Voltage and Current

When the terminals of the potential energy source (voltage) alternate between positive and negative, the current flowing in the electrical circuit likewise alternates positive and negative.

Figure 2.3 shows voltage or current increasing over time from zero to a positive peak value, then decreasing through zero to a negative peak value and back through zero again, completing one cycle. The mathematical term for this shape is the "sine wave."

Frequency

The sine wave in an electric utility power system repeats itself many times in a second, minute, hour, or day. The length of time it takes to complete one cycle is called the "period" of the cycle. The number of

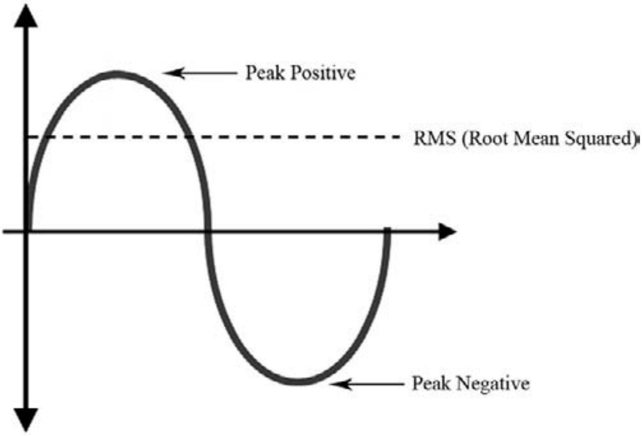


Figure 2.3 One cycle of a sine wave.

cycles in a second is called frequency, measured in Hertz (or cycles per second). Note DC has no frequency; therefore, frequency is a term used only for AC circuits.

For electric power systems in the United States, the standard frequency is 60 cycles/s or 60 Hz. The standard frequency in most European countries is 50 Hz. Countries other than the United States and Europe may use 50 and/or 60 Hz.

Asymmetrical Peak and Insulation Level

When voltage transients occur on a power system, the sine wave is distorted. When the distortion results in a peak voltage that is momentarily greater than the positive peak portion of the sine wave, the condition is called "asymmetrical peak" as shown in Figure 2.4. The asymmetrical peak voltage (APV) is considered the highest voltage that occurs on the power system during a transient condition.

The insulation level of a device, conductor, air gap, and so on must be sufficient to withstand the peak asymmetrical voltage transient, or an insulation failure could result. The coordination between the basic insulation level (BIL), sometimes referred to as "basic impulse level," and the APV is the essence of insulation design. There must exist a safety margin of protection between the APV and the BIL or flashover or cable insulation puncture is possible.

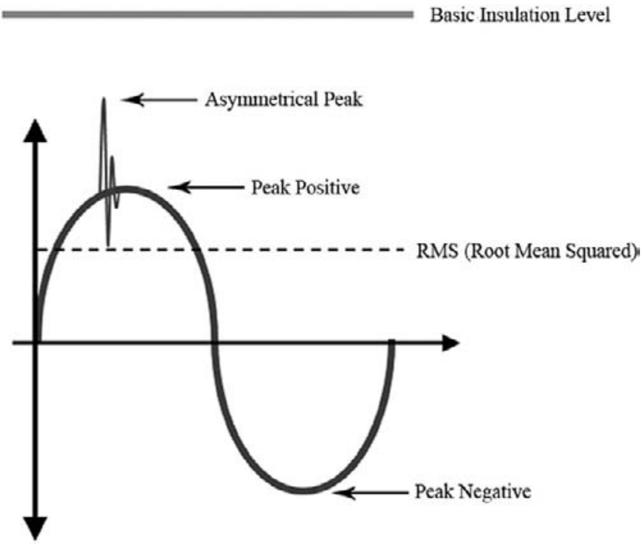


Figure 2.4 Asymmetrical peak voltage.

A very important note for the engineer/technician is that this APV of a ground potential rise (GPR) condition dictates the insulation level required of the HV isolation device (plus a protection safety margin). This APV is also used to determine the distance to the nonaffected area such as the 300-V point in the zone of influence (ZOI).

Switching Surges

HV electric power systems can produce switching surges that can cause voltage and current transients on telecommunications equipment through a concept called induction. For example, closing a 120-kV circuit breaker in a substation energizing a transmission line will put a voltage and current transient on the electric power system. The sudden increase in current can induce a voltage onto the telecommunications cable. Switching transients can be as high as 1.5–2.5 times the source voltage (and higher). Typical switching transients are caused by:

- Energizing long power lines, especially when picking up load,
- Switching on/off power system capacitors,
- Starting large motors,

- Lightning strikes causing arresters to fire,
- Opening/closing large HV circuit breakers,
- Faults on distribution cables,
- And many other conditions.

Transients on power systems are identified as high frequency and short-duration voltage fluctuations having a decaying amplitude characteristic. For example, switching transients can have characteristics of frequencies from 200 kHz to 2.9 MHz, with amplitudes of 12 kV and lasting from 10 to 100 ms. In some cases, repeating pulses can occur.

Longitudinal-induced voltages on telecommunications cables, caused by continuous AC current flowing on the power lines, can be elevated by switching transients, power faults, and lightning strikes. Usually the induced voltage on telecommunications cables can be kept below 1000 V if the telecommunications cable is shielded or a large diameter copper conductor parallels the cable to bypass the induced voltage (the assumption is that these cables are outside the ZOI or one side would have to be isolated from ground potential). Telecommunications cables should be oriented perpendicular to HV power conductors whenever possible to minimize induction (telecommunications cable induction is discussed in more detail later in this book).

Comparing AC and DC Voltage and Current

Resistive electrical load such as light bulbs, toasters, and hot water heaters can be served by either AC or DC voltage and current. DC voltage sources cause continuous heating of the load, while AC voltage sources cause heating to increase and decrease during the positive and the negative parts of the cycle. In AC circuits, there are moments when the voltage and/or current are zero and no additional heating occurs. The heat is averaged in an AC circuit from the continual cycling effect.

It is important to note that there is an equivalent AC voltage and current that will produce the same heating effect in electrical load as if it were a continuous DC voltage and current. The equivalent AC voltages and currents are referred to as the “root mean squared” values, or "rms" values. The reason this concept is important to the subject of high voltage protection for telecommunications (HVPT) is that all electric power systems rate transmission and distribution voltages and current in rms quantities and HVI protection is applicable to APVs. It is very important for the engineer/technician to know the difference between the asymmetrical peak, peak, and rms values of voltage in a power system. For example, electrical insulation is usually rated in BIL (a peak voltage), and power system voltage is usually rated in rms. However, the voltage that breaks down the BIL insulation is APV. The engineer/technician has to make sure the references match or conversion factors must be used. Note that conversion factors are used when calculating GPR because fault currents that are typically provided by the power company are in rms values, but the engineer must calculate GPR in peak asymmetrical in order to determine the 300-V point in the ZOI. The 300-V point is also referenced in peak asymmetrical (this is explained in more detail later in this book).

As an example of rms voltage, consider the ordinary 120 VAC wall outlet. All electrical outlets are rated in rms. Therefore, one could plug a 120 VAC toaster into a 120 VDC battery source and cook the toast in the same amount of time since DC and rms AC have the same heating value. (Note that the 120 VAC rms value in the common wall outlet has a peak voltage value of 165 V and a peak-to-peak voltage value of 330 V.)

This concept of rms versus DC is important to the engineer/technician in that GPR calculations involve converting the power company's standard rms values into peak values and then into asymmetrical peak values to properly determine the communication circuit's isolation requirements.

Power

Voltage by itself does not do any real work. Current by itself does not do any real work. However, voltage and current together can produce real work. The product of voltage × current is power. Power is used to produce real work. The basic unit (measurement) of power is the watt. Electrical power can be used to create heat, spin motors, light lamps, and so on. Power is the product of voltage × current; therefore, power equals zero if either voltage or current is zero.

Energy

Electrical energy is the product of electrical power × time. The amount of time a load is on (i.e., current is flowing) × the amount of power used by the load (watts) is energy. The common measurement for electrical energy is watt-hours. The more common units of electrical energy in power systems are kilowatt-hours (kWh, meaning 1000 watt-hours) for residential applications and megawatt-hours (MWh, meaning 1,000,000 watt-hours) for large industrial or power company applications.

Impedance

The concept of circuit impedance is a little challenging to comprehend. Impedance is the term used to describe the total opposition to current flowing in AC circuits. It is composed of resistors, capacitors, and inductors. Electrical impedance extends the concept of resistance to AC circuits. When the circuit is DC only, there is no distinction between impedance and resistance. When the circuit is AC, capacitors and inductors have different resistances for different frequencies. Therefore, the AC impedance of a circuit varies depending on frequency.

Impedance of a circuit is represented by the symbol “Z.” Impedance is the total opposition to current flow in a circuit that is made up of resistance, inductance, and capacitance. The impedance of an AC circuit is measured in ohms. The impedance of a DC circuit (i.e., resistance circuit) is also measured in ohms.

Resistance

The electrical resistance of an element measures its opposition to current flow. It is similar to friction in mechanical movement. The resistance of a body stays the same whether the current flowing is AC or DC. In other words, a resistor maintains its value of resistance over all frequencies. It is measured in ohms.

Inductance

There are two common forms of inductance: self-inductance and mutual inductance. Self-inductance is the property of an electrical circuit that causes voltage to be generated proportional to the rate of change of current in a circuit. Mutual inductance describes the voltage induced in an electrical circuit by the rate of change of the electrical current flowing in another circuit. This term becomes prevalent when copper communications cables parallel HV power cables.

Capacitance

Capacitance describes the ability of an object to store an electric charge. A capacitor is a device that provides capacitance in an electric circuit by storing energy in the dielectric material between two conducting bodies. The energy is placed in the dielectric material by an electric field.

This book refers to impedance and resistance from time to time as they pertain to grounding electrodes, station ground grids, and their contribution to GPR. When analyzing AC situations having relatively large values of inductance and small values of resistance, the term impedance (Z) is used. When analyzing situations having small values of inductance and large values of resistance, the term resistance (R) is used. However, if only DC is considered, then only resistance applies.

ELECTRIC POWER SYSTEM OVERVIEW

People responsible for HV protection of telecommunications circuits should have a working knowledge of how electric power systems work, especially under fault conditions, in order to be effective in providing reliable telecommunications circuits in HV environments. This knowledge will help ensure the safety of personnel working on telecommunications HV isolation equipment. Engineers and technicians that understand the behavior of power systems during normal and abnormal conditions are able to apply proper design clearances, construction procedure details, personnel protective equipment requirements, and so on while installing and maintaining these systems safely. Further, this knowledge enables one to quickly identify improper installations that could produce undesirable situations (equipment failures and personnel injuries) if not corrected.

This chapter discusses power systems fundamentals and system behavior to the level necessary for telecommunications and electric power protection engineers and technicians to grasp the essential

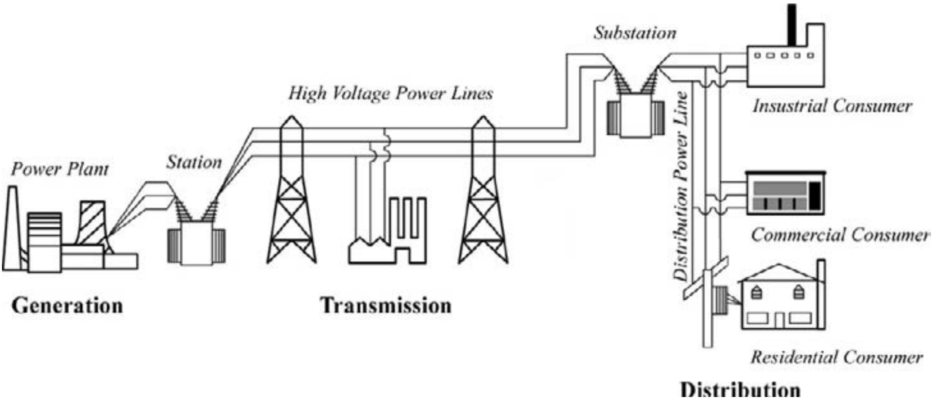


Figure 2.5 System overview.

concepts discussed in the IEEE and other industry standards regarding power fault or lightning strike conditions on critical telecommunications circuits.

Figure 2.5 shows the basic building blocks of an electric power system. A full-scale actual interconnected utility electric power system (the grid) is much more complex than that shown; however, the basic principles, concepts, theories, equipment, operations, and terminologies that affect telecommunications and power system reliability are the same.

Starting with generation (power plants, wind turbines, etc.), the means to transform various natural resources into electrical energy is transported long distances using EHV transmission power lines and then distributed to large and small consumers. HV (EHV) transmission lines are more efficient for transporting power long distances compared with medium voltage (MV) distribution power lines. MV distribution lines are an efficient means for distributing electrical energy to several localized consumers such as industrial, commercial, and residential consumers. Distribution substations transform transmission-level EHV energy into lower level MV energy. Service transformers are then used on distribution lines to convert MV distribution electrical energy to service voltages that are suitable for residential, commercial, and industrial loads.

Electrical equipment called step-up transformers at large power plants convert the low voltage (LV) and high current electrical energy output of generators to HV low current electrical energy for the transmission lines. The use of low current minimizes system losses, making EHV the cost-effective means for energy transportation over long distances. The electrical energy at the far end of the transmission line is then converted back to MV and current electrical energy for distribution. The distribution voltages are suitable for service transformers to be used to further reduce the electrical energy to usable service voltages for residential, commercial, and industrial consumption. Note that it is impractical (not cost-effective) to provide transformers capable of connecting service voltage consumers directly to EHV transmission lines.

The next section discusses electrical terminology and concepts used in the electric power industry. Later chapters apply these terms frequently when explaining the reasons behind the special design, construction and maintenance methods and procedures of HVPT.

AC VOLTAGE GENERATION

AC voltage generation is the main source for current flow in power systems and power faults. Faulted power lines or substation equipment cause fault currents to flow back to their sources through paths such as earth returns, distribution lines' multigrounded neutrals (MGNs), or transmission lines' shield wires. The fact that fault current flows back to voltage sources through earth is the main reason for engineers to provide HV isolation equipment.

To best understand power system power faults and how to properly joint-use telecommunications and power on common poles/structures is to know the fundamentals of three-phase power. This section discusses how three-phase AC voltage is generated and connected to transmission and distribution lines and eventually consumed. The engineer/technician should recognize that whether the source for fault current is the output of a three-phase rotating machine called a generator or the output of a three-phase power transformer, earth return current will flow back to its sources and create a GPR.

AC voltage is generated in electric power systems by a fundamental physical law called "Faraday's law." Faraday's law represents the phenomena behind how electric motors turn, how electric generators produce electricity, and how power lines can induce voltage and current into telecommunications cables. Faraday's law is a foundation principle for electric power systems.

Faraday's law states, "A voltage is produced on any conductor in a changing magnetic field." It may be difficult to grasp the full meaning of that statement at first. It is easier to understand the meaning and significance of this statement through graphs, pictures, and animations. In essence, it is saying that if one takes a coil of wire and puts it next to a moving or rotating magnet (changing magnetic field), a voltage will be produced in that coil that can be measured across its leads. Generators, for example, use a spinning magnet (rotor) next to a coil of wire (stator) to produce voltage on the stator windings' output leads. This voltage is then distributed throughout the electric power system as an electrical energy source.

Power plant generators in service today have coils of wire mounted on stationary housings, called "stators," where voltage is produced due to the changing (or moving) magnetic field provided by the spinning rotor. The rotor is sometimes called the "field" because it is responsible for the magnetic field portion of the generator. The rotor is spinning by a steam, wind, or hydro turbine. The rotor's strong magnetic field passes by the stator windings (coils) to produce the alternating voltage (AC) described by Faraday's law.

The amplitude of the generator's output voltage can be changed by changing the strength of the rotor's magnetic field. Thus, the generator's output voltage can be lowered by reducing the rotor's magnetic field strength and vice versa. The means by which the magnetic field in the rotor is actually changed will be discussed later in this chapter when the second physical law for power systems is addressed.

Single-Phase AC Voltage Generation

Placing a coil of wire in the presence of a changing magnetic field produces a voltage, as discovered by Faraday. This principle is graphically presented in Figure 2.6. While reviewing the figure, note that changing the rotor's speed changes the frequency of the sine wave. Also realize that increasing the number of turns (loops) of conductor in the coil increases the resulting output voltage.

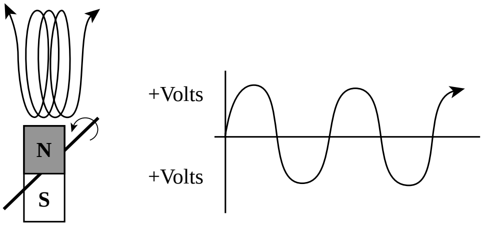


Figure 2.6 Single-phase generator.

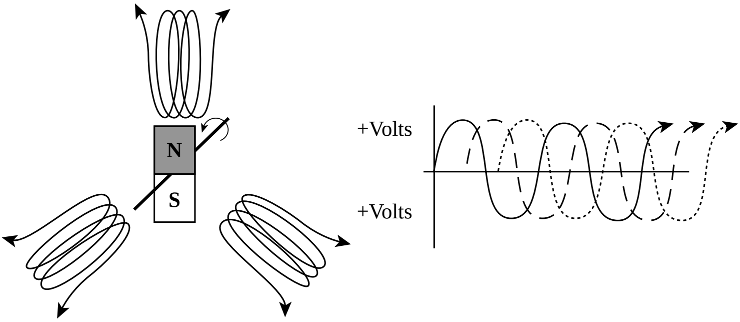


Figure 2.7 Three-phase voltage production.

Three-Phase AC Voltage Generation

When *three* coils are placed in the presence of a changing magnetic field, three voltages are produced. When the coils are spaced 120 degrees apart in a 360-degree circle, three-phase AC voltage is produced. Three-phase voltage generation was selected due to its several advantages over single-phase sources. For example, system losses are less, current does not flow in the neutral when the currents are balanced in the phases, and other benefits. More than three phases do not add significantly to the benefits, and they would require more wires, right of way, and so on. Figure 2.7 shows three-phase generation viewed as three separate single-phase generators, each of which is displaced 120 degrees.

Generator Connections

Three-phase generators and power transformers have three coils and six wires (leads) for connections. There are two ways to connect these three windings that have a total of six leads symmetrically. The two

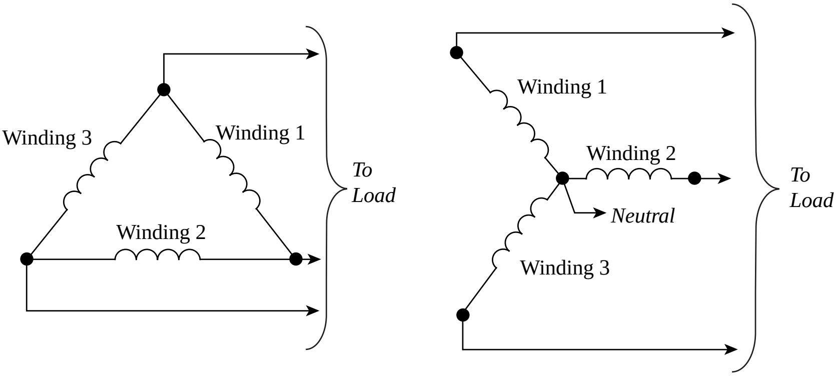


Figure 2.8 Delta and wye configurations.

symmetrical connection configurations of a three-phase generator (or motor) are called "delta" and "wye." Figure 2.8 shows these two connection types. Generator stator windings can be connected in either a delta or wye configuration. The generator nameplate specifies which winding configuration type is used on the stator.

Delta

Delta configurations have all three windings connected in a series as shown in Figure 2.8. The phase leads are connected to the three common points where windings are joined. Therefore, three wires are available for connections in three-phase delta configurations.

Wye

The wye configuration in Figure 2.8 connects one lead from each winding together to form a common point called the "neutral." The other three-phase leads are brought out separately for system connections. Therefore, four wires are available in three-phase wye configurations. The neutral is often grounded to the station ground grid for voltage reference and stability. Grounding the neutral is discussed later in this book.

Delta and Wye Generator Connections

Electric power plant generators use either wye or delta connections. The phase leads from the generator are connected to the plant's step-up

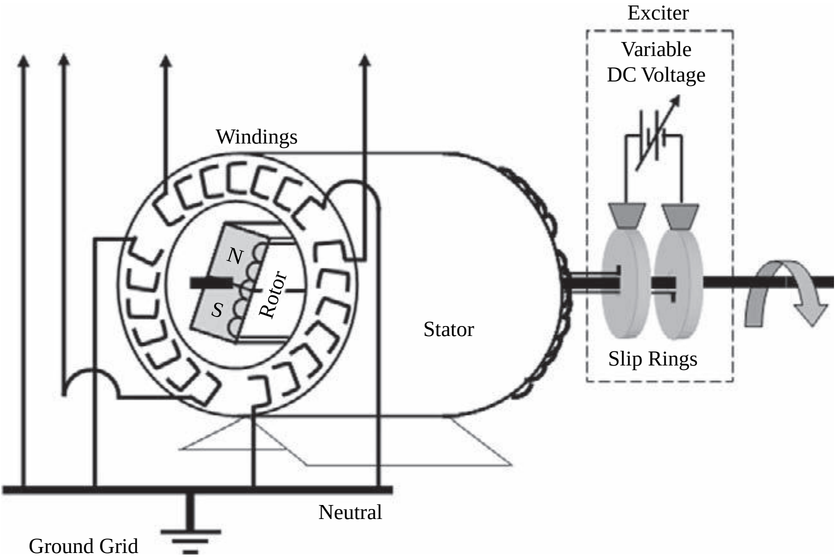


Figure 2.9 Wye-connected generator.

transformer (not shown) where the generator output voltage is increased significantly to transmission voltage levels for the efficient transportation of electrical energy. Figures 2.9 and 2.10 show both the wye and the delta generator connections.

The rotor uses an electromagnet as opposed to a permanent magnet. As shown in Figure 2.11, current flowing in a wire produces a magnetic field around the wire (physical law similar to Faraday's voltage law). Applying voltage to the field winding on the rotor creates a magnetic field in the rotor winding. Increasing/decreasing the applied voltage on the rotor's field winding increases/decreases the rotor's magnetic field, thus increasing/decreasing the generator's output voltage. Permanent magnet rotors do not have the benefit of changing the strength of the rotor's magnetic field. Permanent magnet rotors are often found on small wind turbines where varying voltage output is regulated through the AC/DC converter/inverter system.

Power Transformer Connections

Power transformers and generator stator windings provide voltage sources to transmission and distribution lines. The transmission engineer/technician should not care if the source on a transmission or

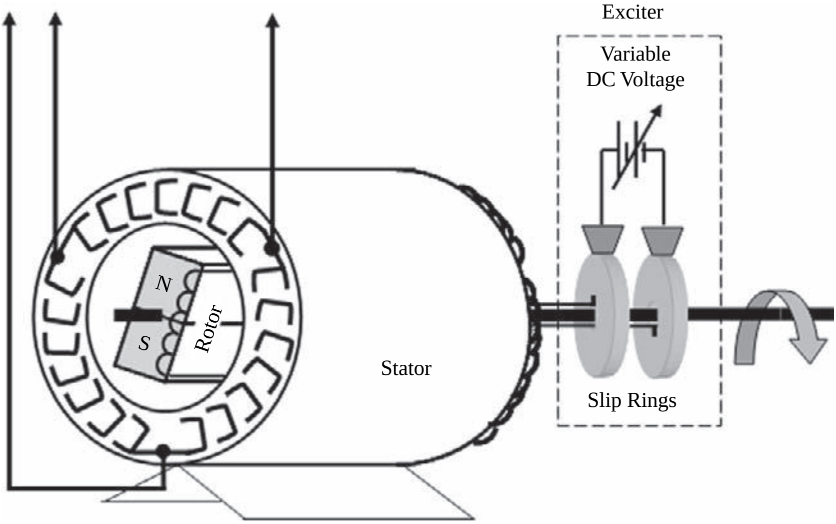
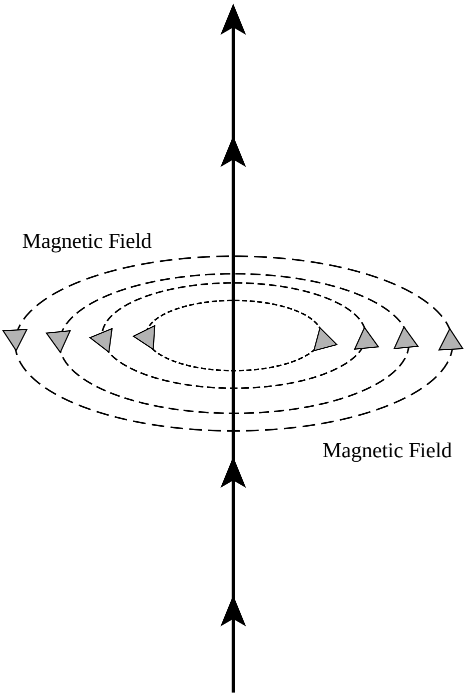


Figure 2.10 Delta-connected generator.



Current Flowing in a Wire

Figure 2.11 Current and magnetic field.

distribution line is a generator or transformer. What is important to the telecommunications protection engineer is whether the source is wye or delta, meaning is there an earth return grounded neutral configuration. A fault on a transmission line, for example, will have earth return current flow through the generator's grounded neutral, the step-up transformer neutral, or the substation power transformer neutral, whereas faults on a delta system may not result in earth return current. A fault on a delta power line to a grounded telecommunications cable shield could result in a telecommunications cable failure by providing a current path for high electrical energy discharge to ground (this is discussed in more detail later in this book).

With regard to HVPT and HVI equipment, what is important to determine is the maximum amount of current entering the earth creating the GPR and not necessarily whether the source is wye or delta, transformer or generator, single or three phases, and so on. The maximum earth return current data is usually provided by the power company's protection engineer.

As discussed in the next section, wye or delta transmission and distribution lines can have an impact as to how the telecommunications engineer grounds or isolates the aerial cable on joint poles.

Delta and Wye Characteristics

The wye and delta configurations have advantages and disadvantages in three-phase power systems. Electric power companies prefer the wye configured distribution system because the neutral can be grounded in multiple locations to provide a very effective ground resulting in better voltage control, fault protection/isolation, and safety. This type of wye configuration on distribution lines is called the MGN-wye and is used in most distribution systems. Delta distribution systems are also used but not as often.

Most aerial telecommunications cables are installed on MGN-wye electric distribution lines. Note that aerial telecommunications cables are installed differently depending on whether the power line is configured delta or wye. In the case of the MGN-wye configuration, all carrier wires, guy wires, shields, and so on are commonly bonded to the electric power line grounds. However, aerial telecommunications cables installed on delta configuration power lines should use separate ground rods, use insulators in the telecommunications guy wires, and not share electric power system grounds (except at the service entrance ground, per National Electric Code [NEC] [NFPA 70-2008®—NEC®]). The reason for not grounding the telecommunications cable to the power system grounds in a delta configuration is to avoid power faults from using the telecommunications conductors as current paths to earth return sources. This can damage telecommunications cables and other equipment.

Line-to-Line (L-L) versus Line-to-Neutral (L-N) Voltages

For the benefit of clarification, grounded wye systems have two voltages available for use. These two voltages are "L-L" and "L-N." They are related mathematically by $\sqrt{3}$. Equipment can be connected either L-L or L-N. The L-N voltage is less than the L-L voltage. The neutral side of the L-N voltage is normally connected to earth by means of the MGN grounding wires and rods.

For example, 12.5 kV L-L distribution systems have a 7.2 kV L-N voltage available for transformer connections (12.5 kV divided by $\sqrt{3}$ equals 7.2 kV).

The term "line" is interchangeable with the term "phase." It is correct to say either "line to line" or "phase to phase." It is also correct to say L-N or "phase-to-neutral" voltage.

Neutral versus Ground versus Bond

The center connection of the three-phase wye electrical circuit is called the neutral. When the neutral is connected to the earth via ground rods, ground grid, or ground conductors, the neutral is said to be "grounded." Neutral current then flows through the earth via the ground connections. Unbalanced neutral currents also flow through the earth connection and can cause annoying stray voltages and currents, leading to other problems. Power companies try to balance the currents on three-phase systems to minimize neutral current unbalanced for improved power quality performance, among other things. Telephone companies also prefer balanced neutrals to minimize induction and cable pair noise.

As shown in Figure 2.12, grounding provides a path for high current to flow back to the voltage sources during a fault. Bonding, on

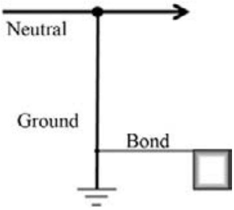


Figure 2.12 Ground versus bond.

the other hand, provides an electrical connection between equipment and grounded conductors and is used to equalize voltage during a power fault or lightning strike. Bonding minimizes potential differences in equipment grounds and is not intended to be the direct path of fault or lightning current to enter earth soil. Bonding helps provide an equipotential situation to minimize electrical problems during power fault and lightning events.

SUBSTATION EQUIPMENT

Telecommunications protection engineers/technicians should have a basic understanding of certain substation major equipment items since power system operations, reliability, and safety depend on reliable critical telecommunications circuits, especially those circuits that are controlled by the telephone company. Operations control of this major equipment is often accomplished using telecommunications circuits and therefore should be protected by HVI equipment if GPR is an issue.

The purpose, function, design characteristics, and key operating properties of the major equipment that can be affected by telecommunications reliability are discussed in this section. The telecommunications engineer/technician should know the effects of protected or unprotected telecommunications circuits during power fault and lightning strike scenarios involving substation major equipment. The proper operation of this substation equipment affects how power faults are cleared, how lightning arresters minimize disturbances, and how properly protecting telecommunication circuits from faults can improve power system operations, reliability, and safety.

Figures 2.13 and 2.14 are pictures of typical distribution and transmission substations. These substations include the same types

Figure 2.13 Typical distribution substation.

Figure 2.14 Typical transmission substation.

of major equipment. The main electrical differences between transmission and distribution substations are voltage levels, power flow capabilities, and whether they serve load (customers/consumers) directly. The main physical differences are the size, spacing between conductors, and dimensional clearances. For example, transmission substations have higher system voltages and require greater dimensional clearances.

The available power fault currents that affect telecommunication circuits can be greater in either transmission or distribution facilities. For example, a distribution substation could have a higher available fault current (hence higher earth return current), higher GPR, and a greater distance to the 300-V point than a transmission substation.

The substation equipment discussed in this section includes

- Transformers
- Circuit breakers and reclosers
- Lightning arresters
- Control building equipment
- Ground grids

Transformers

Power transformers, such as the one shown in Figure 2.15, are used to step up or step down voltage and, inversely, current. Power (consisting of voltage and current) can flow either direction through a transformer. Generator step-up transformers, for example, increase the power voltage (at the same time, reduce power current), enabling power to flow more efficiently over long distances. For the same amount of power and conductor resistance, high current power has higher losses than low current power. Power transformers in substations convert the EHV and low current power in transmission lines to lower HV and higher current power distribution lines to then serve as electrical energy feeders to consumers. Service transformers are then used on distribution lines to further reduce voltage in order to provide the consumer with usable service voltages. Customer service voltage is provided as single-phase, three-phase, wye, and, sometimes, delta configurations, depending on the need.

Figure 2.15 Power transformer 345 kV/120 kV.

Transformers can be single-phase, three-phase, or configured as a bank of single-phase transformers that operate as a single three-phase unit.

Another important note regarding power transformers with respect to telecommunications circuits is that the LV side of a transformer can have the higher available fault current than the HV side. Meaning, faults on the LV side of a power transformer inside a substation can cause higher GPR situations than faults on the transmission side! Similarly, faults on distribution lines can have higher GPRs than faults on transmission lines! The protection engineer determining the effects of GPR on the telecommunications equipment should know the maximum available fault current possible flowing through the earth return in a substation, regardless of whether it is from transmission or distribution, when designing telecommunications protection isolation systems.

Figure 2.16 Gas circuit breaker 345 kV.

Circuit-Opening Devices

Circuit-opening devices such as fuses, circuit breakers, reclosers, and protective relays are used to clear power faults and lightning strikes. Circuit breakers are normally filled with sulfur hexafluoride (SF_6) gas, oil, or vacuum, or use air blast assist to minimize arcing during current interruption as the breaker opens its contacts. Circuit breakers, such as those shown in Figures 2.16 and 2.17, are operated by protective relay devices. Via the substation battery bank, these protective relays provide 125 VDC control signals to trip (open) the power circuit breakers in a substation during fault conditions. If the protective relay or the 125 VDC electrical control circuit fails to send a trip signal to the breaker, the breaker will not trip (open), and fault current will continue damaging facilities and producing GPR situations until backup relaying protection schemes operate. Fuses, on the other hand, do not rely on protective relays, battery banks, control signals, and so on; instead, they melt open with sufficient current and melting time.

Most distribution lines and some transmission lines are equipped with automatic reclosing. Automatic reclosing means that circuit breakers are actually automatically closed after a predetermined time

Figure 2.17 A 138 kV oil circuit breaker.

delay. The automatic reclose operation re-energizes the line. When the fault is still present, the line trips again. Automatic reclosing can occur several times before the line is finally locked out and deemed de-energized. Note that the GPRs recur each time the circuit breaker is reclosed and the fault is still present. Some distribution lines extend great distances where end-of-line faults do not draw enough current from its sources to trip the circuit breaker or melt a fuse. In those rare cases, GPRs can exist for extended periods of time without tripping circuit breakers.

Reliable telecommunication circuit operation depends on faults being cleared quickly. Faults that do not clear quickly will have sustained GPRs. Properly designed telecommunications protection systems should not be affected by prolonged or repeated power fault situations.

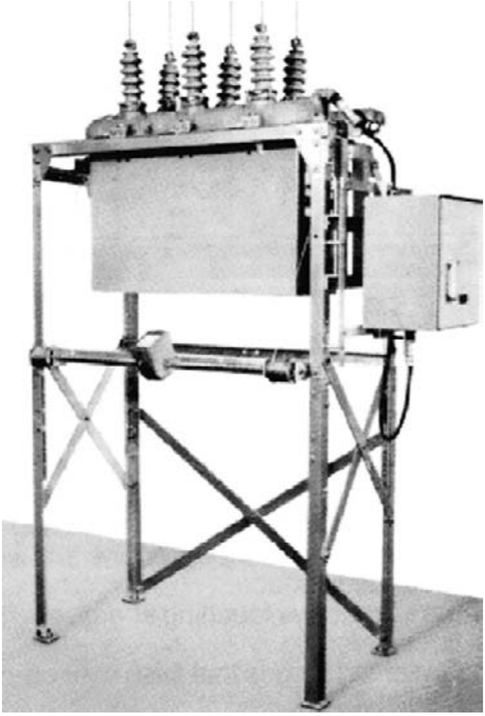


Figure 2.18 Distribution recloser.

Reclosers

A recloser is a prepackaged combination of a circuit breaker and fault detection/control devices. Reclosers such as the one shown in Figure 2.18 de-energize distribution lines when a fault occurs. In contrast to breakers that rely on protective relays, battery banks and control schemes reclosers incorporate their own protective relaying functionality and normally have automatic reclosing equipment enabled. Reclosers can be programmed to automatically reclose the circuit once, twice, or three times after trips and have different dead time intervals.

The ability for a power fault to be automatically reclosed multiple times can affect telecommunications circuits' operation and reliability if not properly protected. Although not recommended in most substations applications, protector devices such as carbon, gas, and solid-state shunting can operate (fire) repeatedly, thus interrupting telecommunications service multiple times during reclose operations. Repeated operation of certain protector devices (e.g., carbon protectors) can cause them to fail or change operating characteristics without warning.

Power System Lightning Arresters

Lightning arresters are designed to limit the line-to-ground voltage exposure in the event lightning or other excessive transient voltage condition occurs. Lightning arresters limit the voltage to a safe margin below the equipment's overall BIL. Some older gap-type lightning arresters actually short-circuited the power line or equipment, forcing the circuit breaker to trip. In these cases, GPRs are produced as a normal means of opening circuit breakers after a lightning strike.

The newer lightning arresters use gapless metal oxide semiconductor materials to clamp or limit the high voltage transient. These newer designs offer better voltage control and have higher energy dissipation characteristics.

For example, suppose an 11-kV lightning arrester was installed on a 7.2-kV L-N distribution system. The lightning arrester will conduct when the L-N voltage exceeds 11 kV. Equipment connected to this distribution system might have an insulation or flashover rating of 90 kV. The arrester limits or clamps the HV transient and prevents the equipment from experiencing an insulation failure.

Aside from the continuous voltage rating of an arrester, arresters fall into energy dissipation classes depending on how much energy the arrester is able to dissipate. Station class arresters (see Fig. 2.19) are the largest types and can dissipate the greatest amount of energy. They are usually located adjacent to large substation power transformers. Distribution class arresters (see Fig. 2.20) are generously distributed throughout the distribution system. They can be found near distribution transformers, overhead to underground transition structures, and along long distribution lines. Intermediate class arresters are normally used in substations that do not have excessive fault current. Residential and small commercial customers may use lower voltage secondary class arresters to protect large motors, sensitive electronic equipment, and other voltage transient sensitive devices connected to their electrical service panel.

Figure 2.19 Station class lightning arrester.

Figure 2.20 Distribution class arrester.

Regarding HVI telecommunications circuit protection in substations, distribution class metal oxide lightning arresters are most often used for their nonfragmenting benefit over the older porcelain glass gap arresters. They normally have 10 kV or 15 kV continuous rating. This continuous rating identifies their voltage class. Under lightning strike conditions, they might have a voltage limiting value in the order of 50–60 kV. These arresters are used to protect the telecommunications HVI unit itself by limiting the voltage across the HVI, protecting its BIL rating.

The older gap-type lightning arresters were also used to protect the HVI equipment and several are still in service today. These older gap-type arresters were constructed out of porcelain glass, and special compartments/cabinets were provided outside the control building in case the arrester failed and exploded. The newer metal oxide gapless arresters handle significantly more energy, are nonfragmenting, and are therefore installed inside the control building or cabinet, or next to or included as part of the HVI equipment.

Substation Ground Grids

The ground grid as shown in Figure 2.21 is a network of buried bare copper conductors (sometimes copper-clad to reduce incentive for copper theft) and ground rods, usually installed early in the substation construction process. The grid is laid out as squares or rectangles,

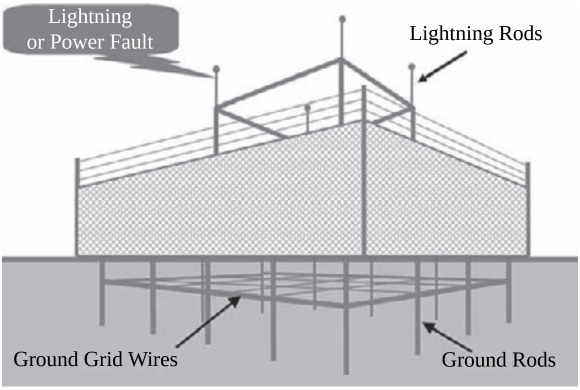


Figure 2.21 Substation ground grid.

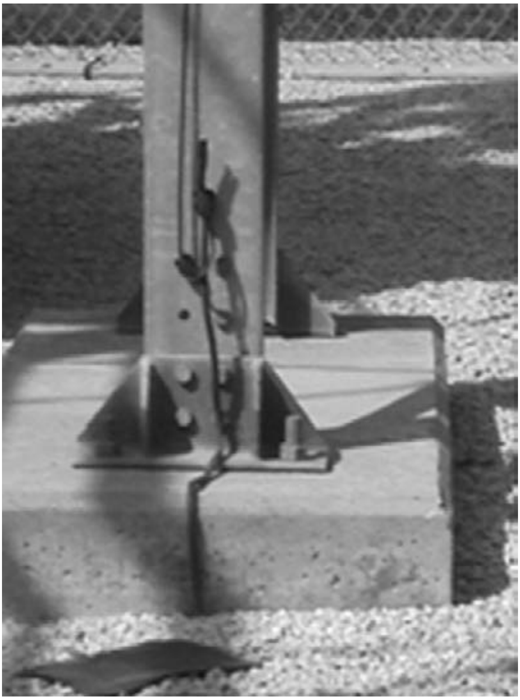


Figure 2.22 Grounded structure.

12–18 in. below the surface. All underground copper ground grid connections are exothermically connected together. The fence is connected to the grid, as well as all structures (see Fig. 2.22), equipment housings, metal control buildings, and all other metal objects. Having all metal components of a substation connected together forming a ground grid, an equipotential situation results when a power fault occurs in the substation. Transmission substations typically use 4/0 copper conductors, whereas distribution substation ground grids are typically composed of 7#7, 7#5, or 4/0 copper conductors. Ground rods are typically installed at the base of each footing, slab, fence, and large area.

When power faults occur, these ground grids help provide a connection to earth soil where fault current can return back to its sources. Once a fault occurs, it is up to the protective relays to sense the fault and trip the corresponding circuit breakers.

There are basically three reasons for substation ground grids:

1. Grounding all metal equipment protects personnel by providing an area of equipotential. Theoretically, everything connected together experiences approximately the same voltage potential during a lightning strike or power fault. Anything the person or animal touches, when in the area of equipotential, does not experience excessive potential differences. Theoretically, everything within a person's reach is approximately at the same potential, and therefore, minimal current is able to flow through the person.
2. Ground grids help dissipate power fault and lightning energy better than simply using ground rods.
3. The lower the ground grid resistance, the higher the earth return fault current, thus causing the protective relays and circuit breakers to operate faster. Note that protective relays are normally designed to trip faster as fault current increases.

Control Building Equipment

Control buildings are commonly found in the larger substations. They are used to house the equipment associated with the monitoring, control, and protection of the substation equipment. The control buildings such as the one shown in Figure 2.23 contain protective relaying, breaker controls, metering, batteries and battery chargers, AC and DC load centers, air conditioning/heating, and telecommunications equipment.

The types of equipment found in control buildings that use critical telecommunications circuits having a high reliability requirement include the following:

1. Protective relaying equipment
    - Transfer trip
    - Phase comparison
    - Pilot wire
    - Others
2. Supervisory control and data acquisition (SCADA)
    - Data telecommunications circuits
    - Event recorders
    - Smart grid sensors and intelligent electronic devices (IEDs)

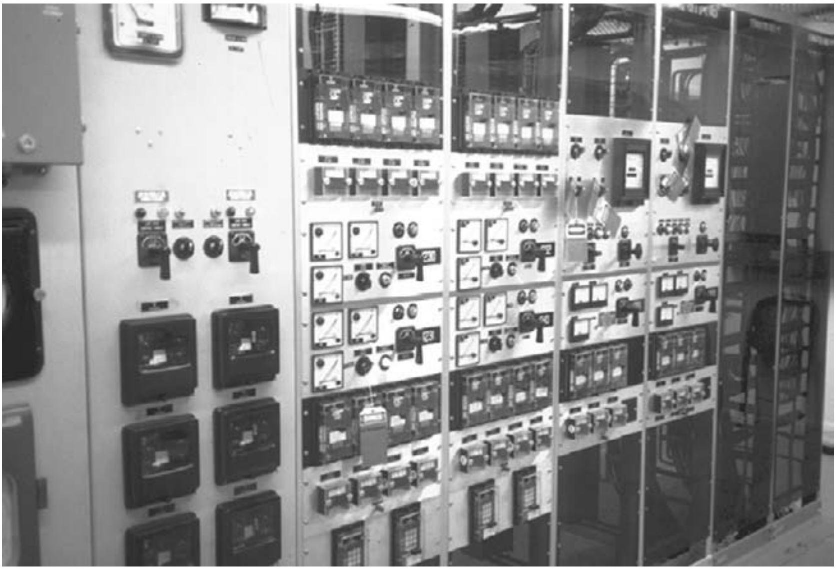


Figure 2.23 Control building.

3. Metering equipment
    - Advanced metering infrastructure (AMI)
    - Automatic meter reading (AMR)
    - Dial-in data download
4. Phones
5. Ethernet/intranet services

Take special note that telecommunications circuits need to be reliable to make the power system reliable. Telecommunications equipment should operate on batteries and chargers so that loss of AC power does not interrupt telecommunications service and the remote control of equipment. Electric power control centers restore power to customers via telecommunications circuits. Therefore, telecommunications circuits must operate even when there is a loss of AC power.

TRANSMISSION LINES

Figure 2.24 shows a three-phase 500-kV transmission line with two conductors per phase. The two conductors per phase option is called bundling. Power companies bundle conductors in order to double, triple, and so on the power transport capability of the power line and to improve the electrical performance of the line. The type of insulation used in this line is referred to as “V-string” insulation. V-string insulation, compared with “I-string” insulation, provides stability in wind conditions. This line also has two static wires on the very top to shield the conductors from lightning. Most of the time, static wires are directly connected to the grounded metal towers so that lightning strike energy is immediately directed to earth. These shield wires help prevent the main power conductors from experiencing direct hits from lightning.

Transmission towers play a very important role in HVPT. Wireless communications radio equipment sites are often located on HV power towers as shown at the top in Figure 2.25. Wireless equipment sites face the same electrical GPR issues as do substations or other electric supply locations. Insulation flashovers on power structures from power faults or lightning strikes cause great GPR situations that require HV isolation of telecommunications equipment.

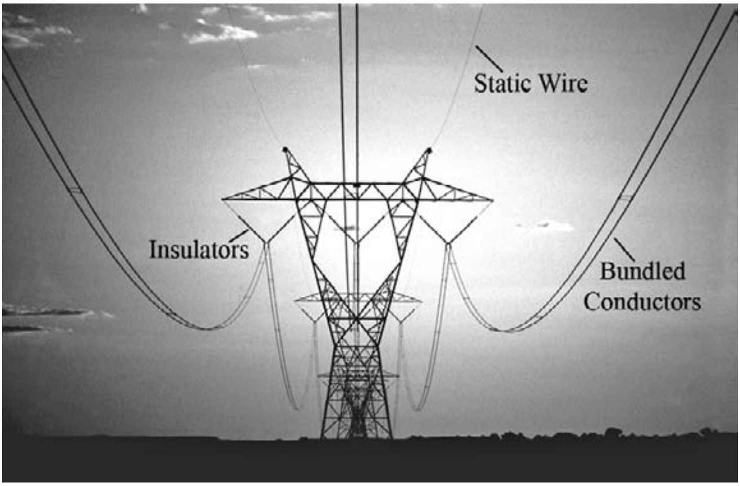


Figure 2.24 Transmission lines.

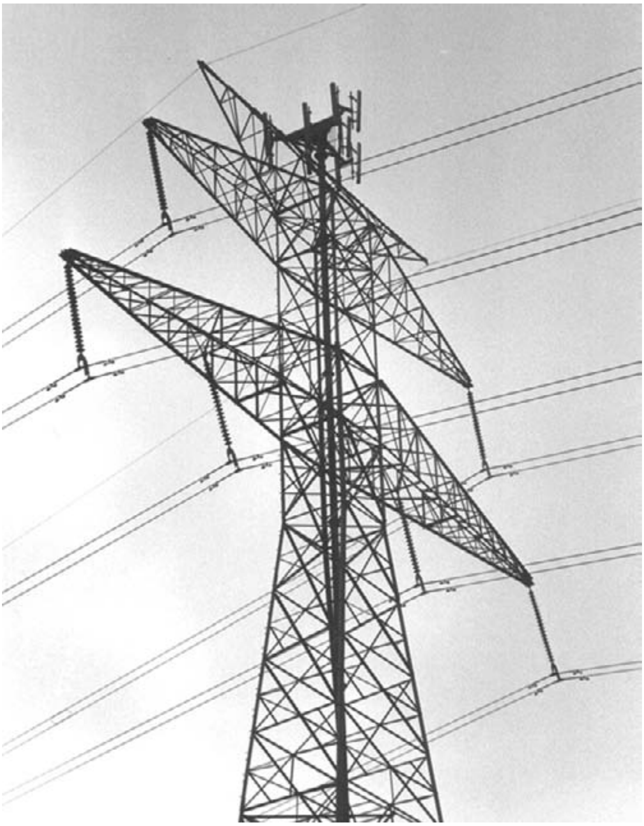


Figure 2.25 Cell site on power tower.

DISTRIBUTION LINES

Distribution systems are responsible for delivering electrical energy from the substation to the service entrance equipment located at residential, commercial, and industrial consumer facilities. Most distribution systems in the United States operate at three-phase grounded-wye primary voltages between 12.5 kV and 24.9 kV L-L. Some operate at 34.5 kV. The lower voltage distribution systems such as 4 kV are being phased out.

Aerial telecommunications cables (both fiber and copper) are often mounted on distribution power lines, referred to as a “joint-pole” use. The methods used to attach grounds and maintain joint-use aerial

Figure 2.26 Wye distribution configuration.

telecommunications cables are different for wye and delta configurations. The following provides brief discussions of these two construction methods and the considerations telecommunications engineers/ technicians must recognize when designing HVI systems.

Wye Configuration

Wye-connected three-phase primary distribution lines consist of three phases and a neutral, as shown in Figure 2.26. The common practice is to ground the neutral at every pole (most systems). When the neutral is continually grounded, the line is said to have an MGN. The National Electrical Safety Code Rule 092C1 requires MGN systems to be grounded at least four times per mile.

One can identify a wye primary configuration by the way a single-phase transformer is connected to the power line. One of the transformer bushing connections will be grounded, and the other bushing is connected to a phase conductor. Examining the transformer bushing wire connections closely helps determine if the transformer is connected line to ground or L-L. Some wye-connected transformers only have one HV bushing, and the other connection is internally connected to ground via the transformer tank ground lug.

Regarding wye power line configurations, telecommunications equipment grounds are normally connected together with power company grounds.

Delta Configuration

Delta three-phase primary distribution lines use three conductors (one for each phase) and no neutral. Single-phase transformers must have two HV bushings, and each bushing is connected to different phases. Since delta primaries do not have primary neutrals, the transformer tank and lightning arrester grounds must be connected to ground rods at the base of the pole. Figure 2.27 shows a delta primary distribution line with a single-phase transformer connected phase to phase. Notice that there is no neutral.

Regarding delta power line configuration, telecommunications equipment grounds are normally kept separate from the power company grounds. This configuration usually involves small isolators in the guy wires. The main reason for separating the grounds is to minimize or eliminate power fault current flow through the telecommunications cable shield conductors. Should telecommunications cable shields share the same ground rods as the power company grounds without MGN, fault current will seek all available grounds, and telecommunications cable and electronic equipment damage is possible.

SYSTEM PROTECTION EQUIPMENT AND CONCEPTS

System protection (sometimes called “protective relaying”) is very important to the reliable operation of large-scale electric power systems. Advanced protective relay schemes incorporate system critical

Figure 2.27 Delta distribution configuration.

telecommunications circuits, such as transfer trip, phase comparison, pilot wire, and others that enable remote tripping of circuit breakers and other important remote actions, especially during power fault conditions. The importance of telecommunications circuits in electric power systems is crucial, and reliability is essential. The purpose of this section is to provide basic information about protective relaying to give the reader insight as to the importance of communication circuit reliability. Keep in mind that the goals for protective relaying are to clear power faults, trip only the line or equipment in despair, and stop any violent energy discharge as quickly as possible.

The most important telecommunications circuits employed by power companies are those used for system protection. One of the many important examples for the use of critical telecommunications is transfer trip. Proper relay coordination calls for power faults on transmission lines to have the near-end circuit breaker trip open instantaneously while at the same moment have the near-end protective relay send a transfer trip signal over a secured reliable telecommunications circuit to the remote-end circuit breaker for a fast trip that would otherwise be time delayed. “Transfer trip” is the term used to identify a protective relay scheme that uses remote tripping of breakers or control of other critical equipment that involves a secure and reliable telecommunications signal between substations.

Power system protective relays monitor voltages and currents for real-time conditions that are over or under preset programmed quantities. Protective relays react to overcurrent situations, for example, by sending a DC station battery trip signal to the corresponding HV AC circuit breaker. The protective relay gets its analog sensing information from instrument transformers. Instrument transformers are composed of current transformers (CTs) and potential transformers (PTs).

The telecommunications circuits described earlier are considered critical telecommunications circuits to power company personnel. They are so critical that backup systems are provided just in case the primary communication system fails.

Instrument Transformers

Instrument transformers “CTs” and “PTs” are used to scale down the actual high power quantities (amps and volts) for use with low power protective relaying, metering, and remote terminal unit (RTU), which are part of the system control center’s computer system.

SCADA (discussed in more detail later) are computer systems involving two-way telecommunications circuits used by system control operators to monitor and control the HV equipment located in remote locations such as substations, power plants, and other power grid facilities. The analog SCADA information from the instrument transformers is then upscaled at the system control center computer where the information is displayed to the operators in actual values and in effect real time.

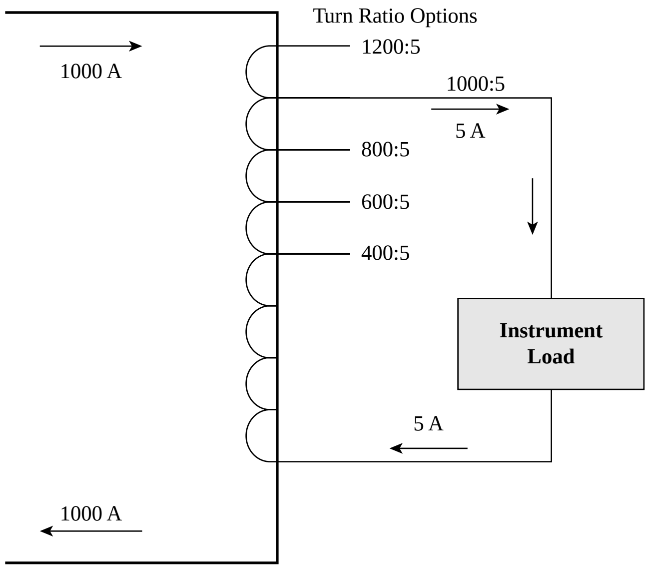


Figure 2.28 CT connections.

CTs

CTs are used to scale down the high magnitude of current flowing in the HV conductors to a level much safer and practical for use by protective relaying, metering, and SCADA. For example, it is much easier and safer to work with 5 A of current in the CT's secondary circuit than it is to work with 1000 A of current in the CT's primary circuit (this represents a 200:1 transformer turns ratio or scale factor).

Figure 2.28 shows a typical CT connection diagram. The current flowing in the main HV power conductor is scaled down by the CT for the instrument load. The CT's turns ratio becomes the scale factor when upscaling for real values. The power company protection engineer determines the proper CT ratio required for the instrument load. Taps (or connection points on the coil) are used to select the turns ratio option suitable for the main conductor current flows and instrument requirements.

The secondary of a CT can also be grounded to provide safe working conditions. Note: never open-circuit an energized CT secondary, for it can produce extreme HVs.

Figure 2.29 Bushing CT.

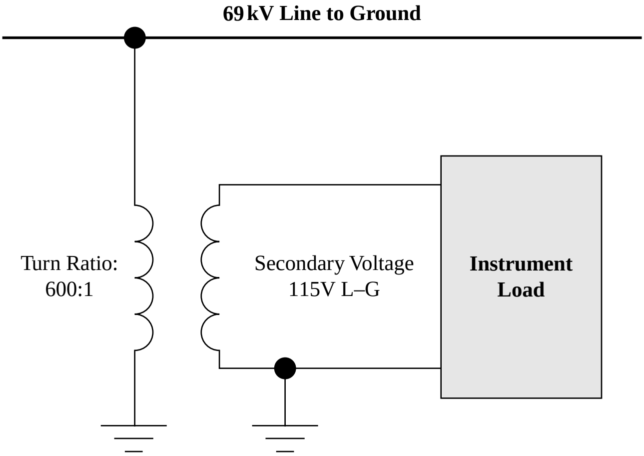


Figure 2.30 PT connections.

Most CTs are located on transformer and circuit breaker bushings as shown in Figure 2.29.

PTs

Similarly, PTs are used to scale down very high levels of voltages to levels that are safer and more practical. For example, it is much easier to work with 115 VAC than 69 kVAC. Figure 2.30 shows how a PT is connected. The protective relays or metering equipment might use these scaled-down voltage quantities. This 600:1 turns ratio (hence scale factor) is taken into account in the calculations of actual voltage displayed to a system operator in the control center's SCADA system.

Similar to most transformers, taps are used to allow turns ratio or scale factor selection to best match system operating voltage and instrument transformer load. An example of an HV PT is shown in Figure 2.31.

Note: never short-circuit the secondary side of a PT, for it can produce extremely high currents.

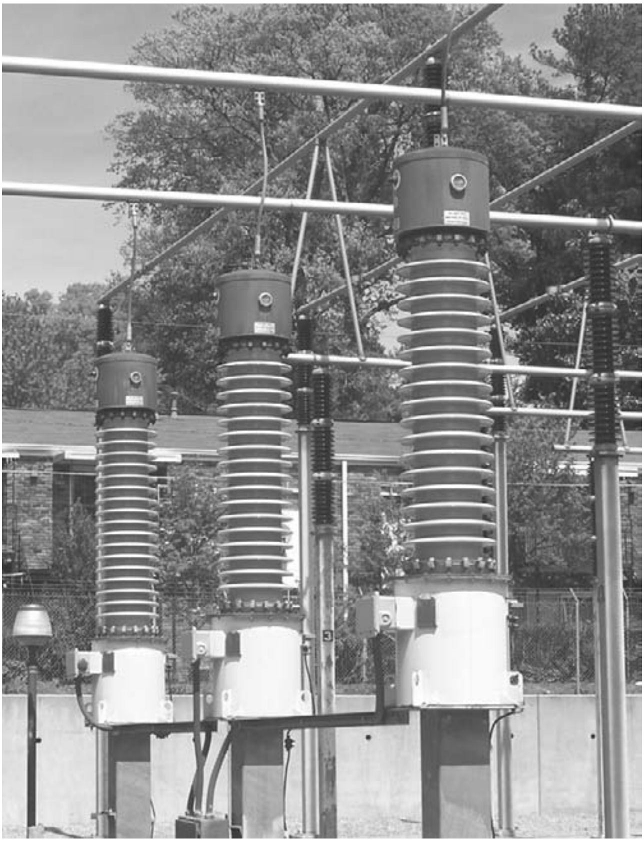


Figure 2.31 High voltage PTs.

Protective Relays

A protective relay is a device used to monitor system conditions (amps, volts, etc. using CTs and PTs) and reacts or initiates a DC control signal to a circuit breaker upon detection of abnormal conditions. The protective relay compares the real-time actual quantities against preset programmable threshold values and sends 125 VDC control signals to the appropriate circuit breaker or other devices to clear the abnormal condition such as a power fault on the equipment it is protecting. When system problems are detected and breakers are tripped, alarm indications are sent to the system control center via SCADA. As a result, power equipment is de-energized and taken out of service or de-energized immediately and the system control operator is informed. De-energized equipment may result in consumers being out of power; however, there is minimal power equipment damage if the circuitry is fast and reliable. The operation of protective relays is the stabilizing force against the unwanted destabilizing forces that occur when unanticipated power faults and lightning strikes impede the power grid system.

Protective relays are manufactured as electromechanical, solid state, and/or microprocessor. Electromechanical relays are of the older style and are composed of coils of wire, magnets, spinning disks, and moving electrical switch contacts and are often considered one-function devices. They are very mechanical in nature. The newer solid-state electronic or microprocessor type relays have no moving parts, are more reliable, offer enhanced telecommunications options, and are sometimes considered multifunctional. Most utilities are replacing the older electromechanical relays with solid-state or microprocessor relays.

The solid-state relays have several advantages over the traditional electromechanical relays. The basic differences between electromechanical and solid-state relays are the following:

Solid state (see Fig. 2.32):

- Advantages: multiple functionality, small space requirements, easy to set up and test, self-testing, remote access capability, provides fault location information, and detects abnormal conditions under one cycle, sometimes called “sub-cycle” relays for this reason.
- Disadvantages: external power required, software can be complex, and many eggs in one basket.

Figure 2.32 Solid-state relays.

Electromechanical relays (see Fig. 2.33):

- Advantages: usually self-powered, simple, and single function design.
- Disadvantages: normally one relay per phase, difficult to set up and adjust, and require more frequent testing.

Inverse Current–Time Concept

A very important concept for all protection engineers and technicians is to understand the "inverse current–time" relationship. Most overcurrent relays are designed to follow the inverse current–time curve as shown in Figure 2.34. In other words, *the time to trip a circuit breaker shortens as the amount of fault current increases.* This has many implications; lower station ground grid resistances trip breakers faster, power faults that are closer to power sources trip faster, and high resistive faults trip slower. These implications will be referenced later in this book.

Once the breaker receives a trip signal from the protective relay, a fixed amount of time is required to actually open the breaker's contacts. The breaker can receive a trip signal from the local protective relay or from a transfer trip telecommunications circuit. Some circuit breakers

Figure 2.33 Electromechanical relays.

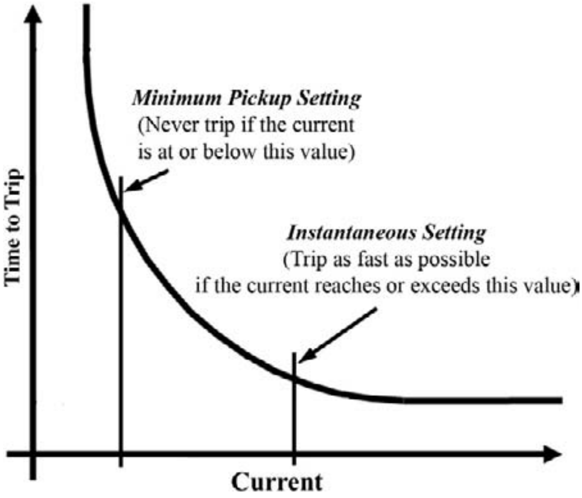


Figure 2.34 Time versus current curve.

trip open the power line in less than two sine wave cycles after receiving a trip signal from the protective relay. Some older style breakers take nine cycles or more to trip. Note the GPR remains until the line is de-energized by the open circuit breaker.

The telecommunications protection engineers and technicians should understand the importance of protective relays, transfer trip telecommunications, SCADA concepts, and applications to best serve the needs of the power utility.

The curve in Figure 2.34 shows the time to trip along the vertical axis, and the amount of current flowing in the power line is shown along the horizontal axis. When the actual current magnitude is below the "minimum pickup setting" of the protective relay, the relay does not operate and the breaker does not trip (normal power flow conditions). When the fault current exceeds the "instantaneous setting" of the relay, the trip signal is sent to the breaker immediately and the breaker trips. When the current exceeds the minimum pickup setting, the relay sends a trip signal to the breaker after a programmed time delay that follows the inverse current–time curve.

Relay coordination is the term used to create a situation where the most downstream clearing device (from the source) trips the line. In other words, the clearing device closest to the power fault actually stops the fault current. Upstream clearing devices are used for backup with additional time delay settings.

Note that failure of a critical telecommunications circuit to bypass time delays can cause excess electrical energy discharge and possible equipment damage, GPRs that are prolonged, customers who are out of service longer, and other undesirable effects.

Typical Fault Clearing Times

GPR is present during the time power fault initiates and clears by the breaker. Table 2.2 summarizes the typical fault clearing and reclosing times on transmission and distribution lines. Distribution lines typically use "automatic reclosing," whereas transmission lines normally have manual reclosing (system operator closes the breaker using SCADA). The telecommunications circuit can be exposed to multiple GPR conditions during a permanent fault event when automatic reclosing is used. Temporary power faults and lightning strikes normally have one GPR

Table 2.2
Typical Fault Clearing Times

Voltage (kV)	Clearing time (no. of cycles)	Clearing time	Typical reclosing
500	2–4	34–68 ms	1 trip to lock out
345	2–4	34–68 ms	1 trip to lock out
230	3–5	51–85 ms	1 trip to lock out
115	3–8	51–136 ms	1 trip to lock out
69	4–40	68 ms–0.68 s	1 trip to lock out
4/12/25/34	5–120	85 ms–2.04 s	1–3 recloses

NOTE: One cycle equals 17 ms.

event. GPRs are present during the fault and disappear after the breaker clears the fault and the breaker is successfully reclosed. The GPR is not present during the intervals between reclosing operations.

Normally, transmission lines are cleared well under a second unless there is an abnormal operation. Distribution circuit breakers (controlled by protective relays) or fuses (melting open) typically clear faults in 0.03–3.0 s. Backup protection is rarely over 3.0 s.

Reclosing (automatic or manual) recreates the GPR situation. GPR duration is considered longer when automatic reclosing is used due to the repetitiveness of the fault condition. Having fuses clear faults instead of breakers helps to sectionalize the outage and minimize the number of customers experiencing a prolonged outage.

Breaker Control Circuits

Power system breakers open and close via DC control circuits. The common DC voltage used for protective relay systems is 125–130 VDC. A 125-VDC battery bank and charger system (separate from a telecommunications battery system) is usually found in the control building and is the same DC source used for the protective relays and SCADA. The relays also use this DC source to operate the trip and close coils in circuit breakers. DC power is used so that breaker control and other activities can be operated remotely (using SCADA) when AC power is out of service.

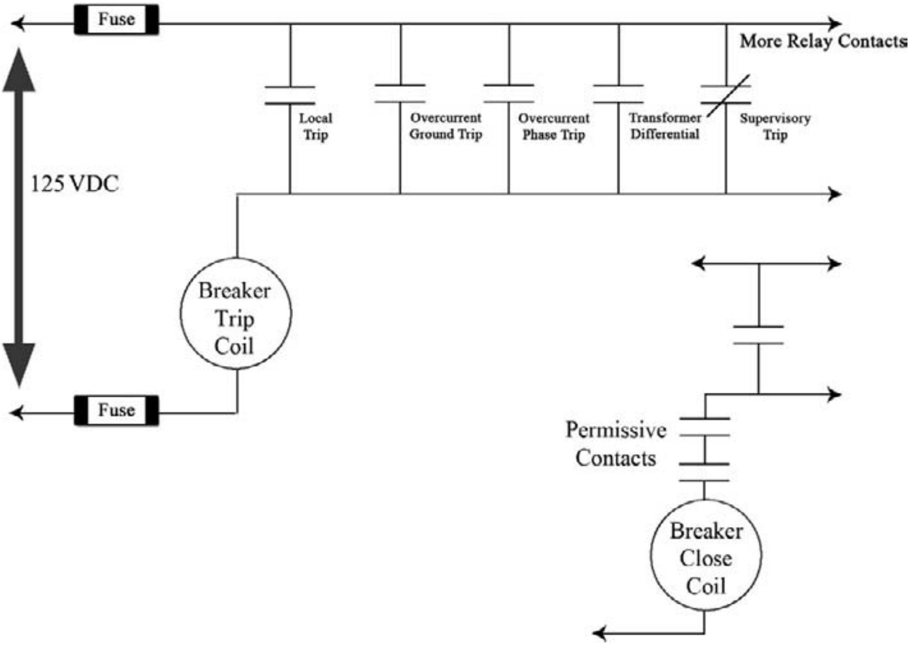


Figure 2.35 Trip and close control circuits.

Figure 2.35 shows typical breaker tripping and closing control circuits. The breaker-tripping circuit uses a “trip coil” (similar to a solenoid used to lock/unlock car doors) to activate the breaker’s mechanical linkage to the arc chamber of the circuit breaker. The breaker-closing circuit uses the “close coil” (solenoid) to activate the mechanical linkage that ultimately closes the electrical contacts inside the breaker’s arching chamber. When any contact in the trip circuit closes, the breaker opens. Note in the figure that the supervisory trip contact is closed. This implies that the SCADA control command has completed the circuit and is tripping the circuit breaker. Note that without the SCADA telecommunications circuit being operational, the system operator would not be able to trip the circuit breaker remotely, nor would the operator be alarmed that the breaker was open or closed.

There is often one extra provision in closing circuits called “permissive contacts.” Permissive contacts are used to prevent the wrongful closing of breakers for certain known damage-causing conditions. For example, the permissive contacts of a generator’s frequency relay must be closed (indicating the generator is rotating at 60 Hz) before the generator breaker can be closed by the closing circuit.

Another example of permissive contacts is to have one's car transmission in park before the key is able to start the engine. Permissive contacts help assure proper operating conditions exist before a high power breaker can be closed.

Transmission versus Distribution Protection

Transmission protection is much different from distribution protection simply because distribution systems are radially fed (meaning single source to consumer loads), and transmission systems normally have multiple lines or power sources to substations. Distribution systems normally use overcurrent relays only to trip local breakers. Transmission protection requires more sophisticated relay schemes due to the need to identify the actual faulted transmission line when there are multiple lines feeding the fault. To complicate matters, some transmission lines have generation sources at both ends that combine for the total fault. There are radial transmission lines too where protective relay schemes are similar to overcurrent distribution protection.

The up-and-coming smart grid and distributed automation technology utilizes high reliability telecommunications circuits to accomplish its energy efficiency and reliability objectives. This fast-developing power system enhancement (smart grid) is an expansion of SCADA and therefore requires reliable telecommunications circuits at all times.

Zones of Protection

The purpose of this section is to provide the reader with a better understanding of how highly reliable telecommunications service plays a vital role in protection coordination in large-scale power systems. The concept of transfer trip, sometimes called "carrier trip," using telecommunications circuits is explained in this section.

Transmission protection schemes incorporate overlapping zones of protection to achieve fast fault detection, clearing, and backup. These overlapping protection zones are shown in Figure 2.36. These overlapping zones protect against faults on the transmission lines, substation bus, generators, and transformers. Overlap is accomplished using CTs located on opposite sides of circuit breakers, transformers, or standalone CTs.

Figure 2.37 shows how transfer trip telecommunications is used to reduce the fault clearing time. Note the location of the fault on the transmission line (closer to one substation than the other). Note the

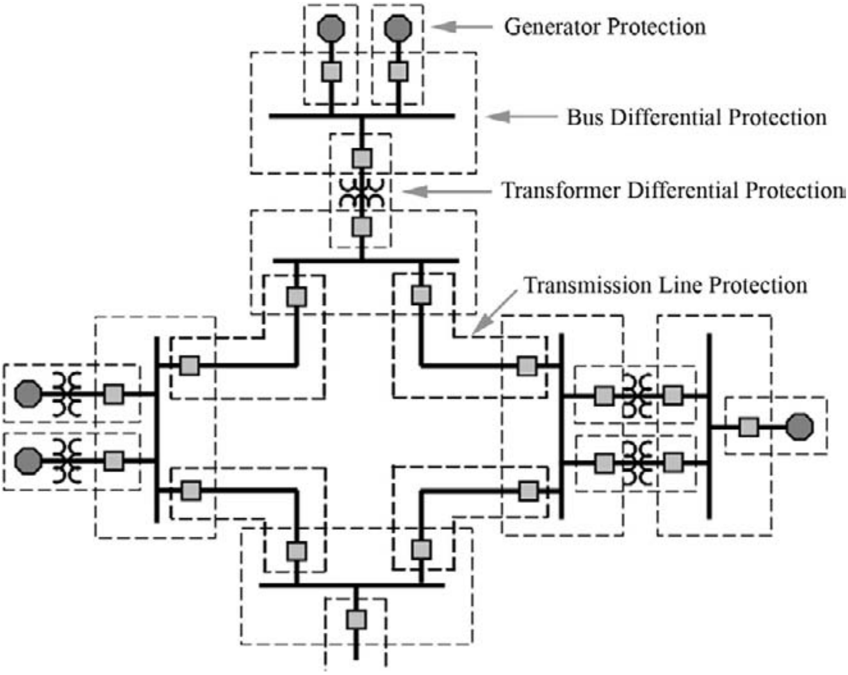


Figure 2.36 Transmission protection.

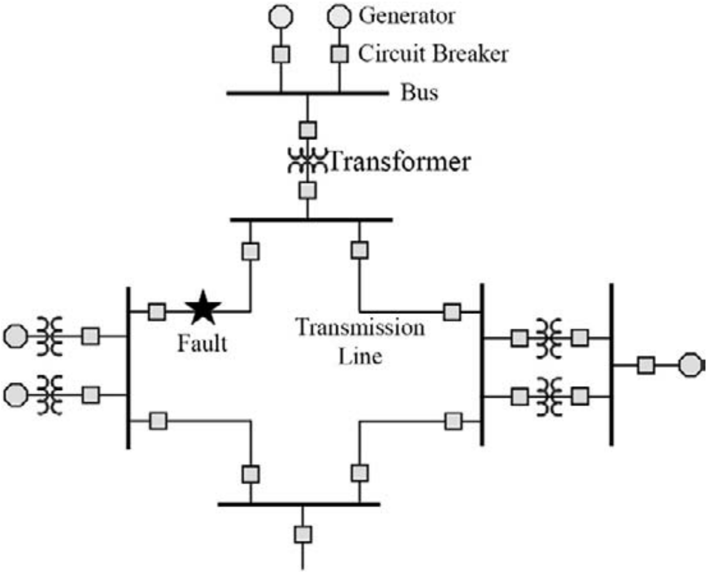


Figure 2.37 Transmission fault.

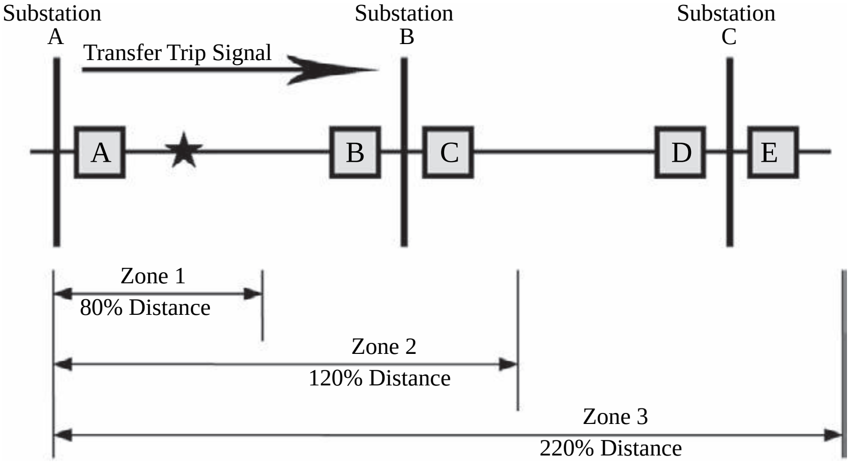


Figure 2.38 Transfer trip signal.

multiple transmission lines, generators, transformers, and buses of the power system. A fault on one of the transmission lines requires just the breakers on both ends of that one line to trip even though there are multiple AC power sources to the fault. The method used to clear the right transmission line breakers, as opposed to inadvertent trips, is referred to as "zone or distance relaying." Zone relaying identifies the faulted line and trips the appropriate breakers at both ends at high speed, utilizing telecommunications circuits. Also, zone relaying provides backup tripping protection should a primary protection scheme fail to operate properly.

Figure 2.38 shows the concept of zone or distance relaying. In this example, each breaker has three protection zones. Breaker "A" has three zones looking toward the right (as shown), breaker "B" has three zones looking toward the left (not shown), breaker "C" would have three zones looking toward the right, breaker "D" would have three zones looking toward the left, and so on. The following zone relay settings are typically used:

Zone 1 Relays. The Zone 1 relay is programmed to recognize faults that are located from 80% to 90% of the line section and trip instantaneously (i.e., two to three cycles).

In this example, the fault is in Zone 1 of breaker "A," and therefore, breaker "A" is tripped at high speed. High speed implies that the relay is set for instantaneous clearing and fault clearing depends only on the time it takes for the breaker contacts to interrupt the fault current.

Zone 2 Relays. The Zone 2 relay is programmed to recognize faults that are located about one and a half lines (approximately 120–150%). The trip is time-delayed (typically 20–30 cycles or 0.5 s) to coordinate with Zone 1 relays. The program settings depend on line length (i.e., line resistance) and the amount of maximum fault current available.

In this example, the fault is in Zone 2 of breaker “B” and would trip after a short time delay. However, in zone protection schemes using a transfer trip telecommunications signal that is sent via fiber optic, microwave, power line carrier, or copper circuits tells the remote end distance relay to bypass its programmed time delay and trip the breaker at high speed similar to the local breaker. In this case, the Zone 1 relay of breaker “A” would send a transfer trip signal to substation “B” breaker, telling the Zone 2 relay of breaker “B” to bypass its time delay setting and trip breaker “B” immediately, thus reducing fault clearing time.

Zone protection schemes provide high speed transmission line clearing even though there are built-in time delays in the Zone 2 relays. Note that if the fault were in the middle of the line, both ends would trip Zone 1 at high speed.

Zone 3 Relays. Zone 3 relays are set to reach the protected line section plus the next line section plus an additional half line section (approximately 250%) to serve as backup protection. The trip is time-delayed more than Zone 2 to coordinate with Zone 2 and Zone 1 protection.

In the example earlier, Zone 3 backup protection would not be involved. Should a Zone 2 breaker fail to trip the line, then Zone 3 trips as the backup.

There are several more uses of telecommunications circuits in power system protection schemes. Most of the time, highly reliable telecommunications systems are needed to properly protect high energy power systems, to limit damage during power faults, and to remotely operate the system (SCADA). Several of the critical telecommunications circuits that are commonly used in power systems are discussed later in Chapter 5.

CHAPTER 3

Ground Potential Rise (GPR) and Zone of Influence

LEARNING OBJECTIVES

- Describe the different types of power faults, causes of faults, and which ones are most common to overhead and underground power systems
- Explain how power faults and lightning strikes cause ground potential rise (GPR)
- Explain how GPR results in a zone of influence (ZOI)
- Describe the contributing factors that make up GPRs and ZOI
- Explain the meaning of 300-V point and why it is important
- Describe how fault current is divided and creates ancillary GPRs
- Describe the electrical characteristics of faults, fault types, current ratings, and fault clearing time
- Describe ground grid resistance and how it is measured and calculated

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High Voltage Protection for Telecommunications, First Edition. Steven W. Blume.

- Discuss the meaning of DC-offset and what is peaking factor
- Explain how GPR magnitude is determined, mathematically calculated, graphically analyzed, and measured utilizing computer programs
- Describe how earth resistivity plays important roles in GPR and ZOI and how it is measured
- Describe how changing various components of GPR and ZOI can have critical, significant, and/or minor impact
- Discuss how lightning faults compare with power faults with regard to GPR and ZOI
- Explain how electromagnetic induction adds stress to telecommunications cables near power lines
- Explain how to calculate cable induction from nearby power lines
- Discuss how shield factors affect cable induction
- Describe how GPR and induced voltages are summed together to determine total cable stress

INTRODUCTION TO GROUND POTENTIAL RISE (GPR)

GPR is an issue both telecommunications and electric power companies must face, respect, and manage. Power faults and lightning strikes can create high voltage (HV) earth surface potentials, called GPR, which can cause telecommunications equipment damage and possible personal injury if not properly managed. This chapter explains the components creating GPR situations and industry best practices for their management. One should realize that a GPR event is a highly unlikely probability occurrence; however, they do happen and equipment and personnel must be prepared for their random, unexpected, and invisible occurrence.

The main factors involving GPR are power fault current levels, electrical grounding schemes, earth resistivity, and adjusting for the proper/consistent units of measurement. Proper units of measurement include such definitions as asymmetrical versus root mean squared (rms) voltages, maximum fault current versus earth return current, and theoretical versus practical applications. This book attempts to present the real and practical treatment and applications that are based on experience and industry standards.

GPR

When a fault occurs on a power system and high levels of electrical current flow in the earth's soil, a GPR condition occurs, creating a voltage profile on the earth's surface. This voltage profile decays exponentially outward from the fault location as shown in Figures 3.1 and 3.2.

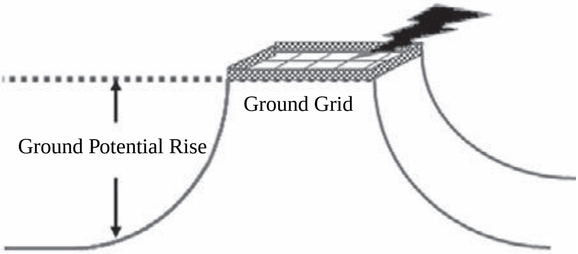


Figure 3.1 Substation ground potential rise.

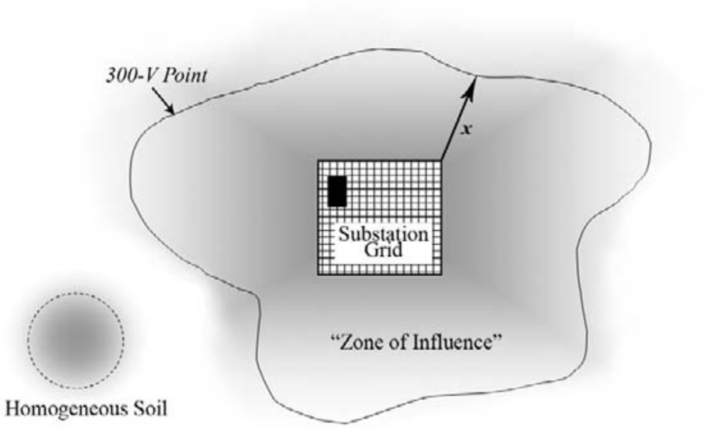


Figure 3.2 Ground potential rise and zone of influence.

The GPR looks similar to Figure 3.2 from an aerial perspective. When the earth soil is homogeneous, the GPR contour is a circle. When the soil is nonhomogeneous, the GPR contour is nonsymmetrical. Figure 3.2 shows both possibilities. Reality is the nonhomogeneous condition. Many industry standards refer to the GPR shape as a circle, the homogeneous state. The telecommunications engineer/technician should be aware that the two conditions are entirely possible, and consideration for either type to occur is important when applying proper protection design boundaries.

GPR LOCATIONS

The definition of GPR, according to IEEE Std. 367-2002™ and IEEE Std. 487-2007™, is ". . . the product of a ground electrode impedance, referenced to remote earth, and the current that flows through that electrode impedance."

GPR is a condition where high electrical currents from a power fault or lightning strike are dissipated in the earth, and the earth creates an HV gradient along its surface. This voltage gradient decays exponentially outward from the fault location (i.e., current penetration point into the earth's soil) and can be very dangerous. This voltage gradient on the earth's surface provides a voltage potential between two points. For example, two different voltages can exist on the earth's surface between a location 10 m out from the substation fence and one 20 m out from the substation fence. This difference in voltage levels is also referred to as a potential difference. Assuming a circular homogeneous soil condition, the voltage potential between two points that are equally distant from the substation fence is theoretically zero (same voltage level). The mere fact that a difference in potential can exist radially outward from a grounded object injecting current into the earth causes concern for equipment damage, personnel injury, or both.

Substations minimize the effects of GPR inside the fence by providing an equal-potential zone about the station ground grid. The station ground grid connects all metal parts together (bonding) to form an equipotential zone. Essentially, everything in a person's reach within the station is said to be at the same potential. A person should not experience a harmful current flow in the body when the difference in potential is approximately zero due to the equipotential characteristics of a well-designed station ground grid.

A power system fault event on a transmission or distribution line outside the substation, such as a power transmission tower, will have a large current flow through the earth back to the substation and other contributing power sources. The fault event occurring on a transmission line structure (hence possible wireless cell site) will create a GPR situation at the structure footing with exponential voltage decay similar to a substation under fault conditions.

GPR Distribution

Fault current divides among all circuit paths to return to its sources. Fault current divides among metallic paths, earth paths, and even high resistance paths. However, most of the fault current will flow through the path of least resistance. The return paths can include transmission line overhead ground wires and grounded structures, multi-grounded distribution line neutrals, station ground grids, equipment bonds, grounded telecommunications cable shield wires (if not properly protected), and incidental grounds such as grounded railroad tracks and metallic pipes. Most of the fault current is usually the station ground grid. Determining all the possible earth return currents under a fault condition can be exhausting and tedious. This book's treatment of GPR return path is that of IEEE Std. 367-2002, that being to assign a percentage of total available fault current to be that value of fault current flowing through the earth soil at the location where the fault occurs. The IEEE Std. 367-2002 recommends 60% of the total fault current value that is flowing through the earth. The design engineer must choose a percentage based on whether no other ground paths exist (such as a remote isolated substation) versus a location where several grounding paths exist (metropolitan city location).

Note that if no overhead ground wires or multi-grounded neutrals (MGNs) are assumed, then the worst-case GPR can be the full fault current (100%). If the fault location is a substation in a metropolitan city location, then the GPR could approach 0%.

Normal Power Flow Conditions

Under normal power flow conditions (nonfaulted), the electrical energy flows from the generation sources through the three-phase power transmission and distribution systems very efficiently and with negligible earth return current as shown in Figure 3.3.

When a fault occurs in a substation, earth return fault current flows as shown in Figure 3.4. Note that two GPR conditions exist while the earth return current flows (one around the faulted substation and one around the generation station). These earth return currents and GPRs will continue to exist until the protection relays trip the circuit breakers contributing to the fault.

Fault with MGNs and Shield Wires

When there are MGN distribution lines and shielded transmission lines connected to the substation ground grid under fault conditions, the

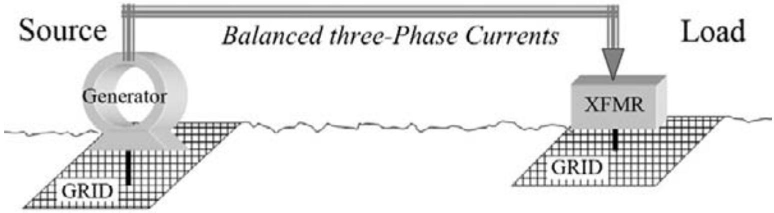


Figure 3.3 Normal power flow conditions.

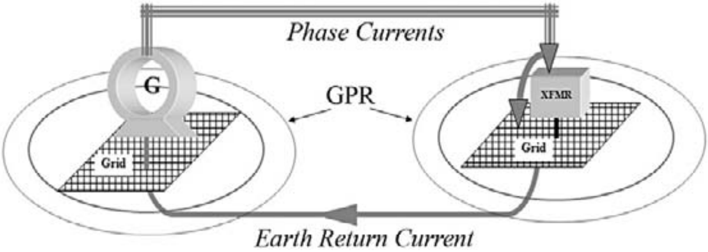


Figure 3.4 Fault at substation.

available fault current distributes as shown in Figure 3.5. Notice the multiple GPRs that occur.

Fault with Surrounding Ground System

When the distribution load center is composed of many power system neutrals, grounded telecommunications shield wires, metal structures, subways, piping systems, rail systems, conductive soils, and other conductive path conditions, the GPR surrounds the entire grounding system. Figure 3.6 illustrates how the GPR can include a large grounding system. This is the typical situation when a substation is

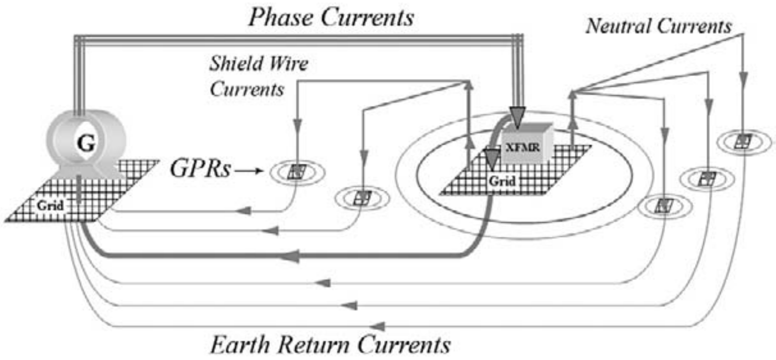


Figure 3.5 Fault with MGNs and shield wires.

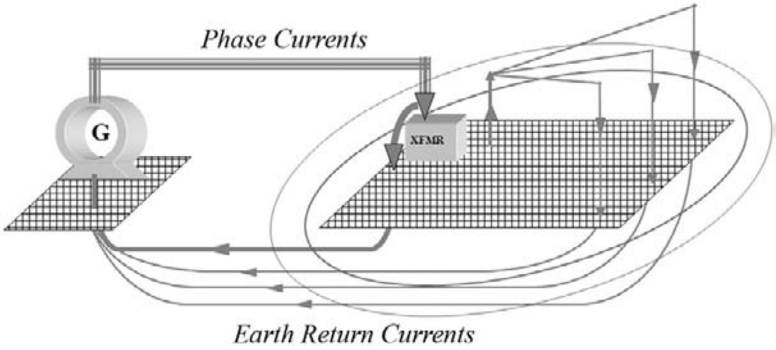


Figure 3.6 Fault with surrounding ground system.

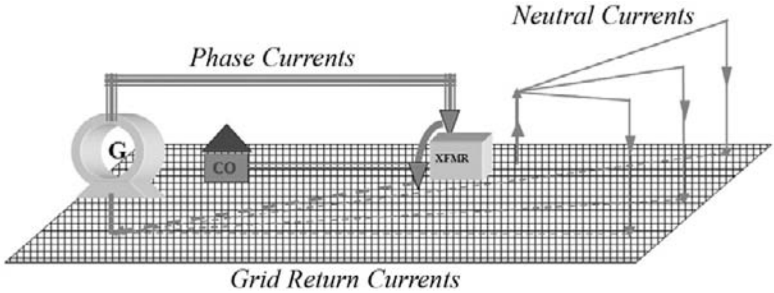


Figure 3.7 Fault with all-inclusive ground system.

located within an industrial or residential area where the power company's grounded neutral and other grounding objects are abundant.

Fault with All-Inclusive Ground System

Lastly, when the generation source, distribution substation, MGNs, shield wires, and surrounding metal grounding system are all on the same plane (i.e., the all-inclusive ground grid) as in a metropolitan area, the GPR is the voltage drop across the ground system. All metal objects on the ground system have approximately the same voltage potential as shown in the example in Figure 3.7. This situation is very similar to a station ground grid equipotential scenario.

The worst-case scenario for a GPR to cause telecommunications cable/equipment failure is the faulted remote substation that is surrounded by natural earth with few, if any, MGNs and shield wires. The best-case scenario for little to no GPR is the dense metropolitan area.

Faults on Joint Pole Usage

Regarding joint pole usage, telecommunications providers typically bond their telecommunications cables to the power line's primary neutral, generally at a minimum of four times per mile. On underground installations, telecommunications cables are typically bonded to the power company's primary neutral, not to exceed a longitudinal separation distance of 1000 ft. This approach helps to minimize the amount of fault current returning to its sources via the telecommunications plant.

Fault current distribution in the aforementioned situation results in a distribution of fault current through the main power company grounds and the telecommunications cable shield and its grounds help maintain equipotential. This situation applies to power company four-wire wye distribution power line configurations. Power company three-wire delta distribution lines could pose problems sharing grounds.

Caution must be taken when connecting telecommunications cable shields to power company grounds where the distribution power line is of the delta configuration. In this case, an MGN is not available, and fault current could travel through the telecommunications cable shield seeking return paths to the generation sources. Joint use on delta power lines should be avoided. Otherwise, telecommunications grounds should be kept separate from delta power line grounds.

FACTORS AFFECTING GPR

The GPR's asymmetrical peak voltage (APV) magnitude, the distance to a specified voltage location, and the voltage profile across the earth's surface at different points can be calculated and/or measured. GPR calculations can provide varying results depending on the formulas used, variables assumed, and accuracy of the input data. Measured values can vary depending on the soil conditions at the time of measurement. No matter which approach is used to determine GPR, the factors that affect the results are discussed in this section.

Fault Current

The magnitude of fault current is a direct factor in the GPR calculation. The higher the fault current, the greater the GPR and the longer the distance is to the 300-V point. The value of fault current used in GPR calculations has many factors associated with its derivation. Understanding the factors that contribute to the fault current magnitude may help determine whether a reasonable GPR value has been obtained and helps assure that conclusions are accurate and not misleading.

When it comes to telecommunications equipment protection, the question becomes what level of fault magnitude is acceptable? Or, what reasonable value of fault current should be assumed in the GPR calculations? A sensitivity analysis or probability study of the factors discussed later could help answer these questions and reduce protection cost and concern issues.

Fault Types

Power faults are generally classified as types. Examples of fault types are temporary or permanent, phase-to-ground, phase-to-phase, two phases to ground, three phases to ground, and three-phase bolted. The type of fault can affect GPR calculations. For example, three-phase faults that do not go to ground normally do not create GPR situations. Phase-to-ground faults are often used in GPR calculations since most faults are of this type.

Overhead versus Underground Faults

Generally speaking, there are far fewer transmission line faults than distribution faults. Transmission faults are fewer due to their higher levels of insulation, greater distances between conductive components, and shielding that is commonly provided for lightning protection. Transmission lines are typically designed for one outage per year per hundred miles of line. Distribution lines can have much higher fault rates because of their exposure to several more fault-causing factors and whether they are constructed overhead or underground where weather, animals, and other environmental conditions affect fault rates.

Table 3.1 shows the common causes of overhead distribution faults and their typical percentage to fault causes.

Generally speaking, 80% of the faults that occur on overhead distribution systems are phase-to-ground faults, and 80% of those faults are temporary. Therefore, approximately 64% of line-to-ground overhead distribution faults can be successfully reclosed while 36% are considered persistent or permanent.

Underground faults (whether transmission or distribution) are generally permanent. There are no wind, bird, or lightning issues in underground faults causing the percentage for permanent underground faults to be much higher than overhead construction. Most underground faults are due to cable, elbow, and splice failures. There are occasional

Table 3.1
Common Distribution Overhead Faults

Cause of fault	Percentage of total
Wind and trees	38.0
Lightning	16.0
Birds	13.0
Equipment and wiring failures	9.0
Human error	9.0
Ice	6.0
Snow unloading	1.5
Foreign objects	1.5
Other	6.0

backhoe incidents that fault underground power lines. Because of the high percentage of permanent faults in underground systems versus temporary faults, the power system protection equipment is normally set to provide one trip to lockout with no automatic reclosing. Overhead construction, with its high probability of temporary faults, has multiple reclosing operations as an effort to increase the likelihood of service restoration (*warning: since overhead lines may trip and reclose several times after a fault, always wait for complete clearing of the line before proceeding with any work activities*).

Substation faults are typically caused by equipment failure or animals. Equipment failure such as bushings, transformer windings, and sometimes rifle gun fire (remote stations) are the most common causes of substation equipment faults. Birds, squirrels, and rodents are common animals to cause faults in substations.

Fault Path Impedance

Regardless of the cause of fault, the amount of current flowing through the total fault path controls the magnitude of the GPR and ZOI. The total fault path impedance is composed of resistive and inductive components. The resistive component is composed of the arc initiator, equipment ground conductors, station ground grid, and earth's soil back to the power sources. It also includes the fault path resistance of the source's grid and equipment. If the fault path resistance can be increased, then the fault current magnitude is reduced, and consequently the GPR and ZOI are reduced. For example, the added electrical resistance from a tree limb reduces fault current, GPR, and ZOI, especially dry limbs. On the flip side, if the fault path resistance is decreased, then the fault current increases, and consequently, GPR and ZOI are increased.

Fault circuit path inductance also plays an important role in controlling fault current magnitudes and is partly responsible for the fault current rise time and decline slope characteristics. Inductance is associated with transformer coils, the close proximity to other circuit conductors, conduit characteristics, and the creation of magnetic fields associated with current flow. Inductance has the natural tendency to lengthen the time it takes for fault current to rise to maximum value and decline.

In summary, the more resistance and inductance in the fault path, the less available fault current, and the more inductance in the fault path, the longer it takes to build up to maximum fault current and decline. One of the key factors in determining the peak asymmetrical voltage characteristics in calculating GPR is the ratio between circuit resistance and inductance (discussed later as "peaking factor").

Power fault magnitude also depends on whether there is maximum generation (summer peak), minimum generation (early morning when load is low), facility conditions (maintenance), and protective relay settings. GPR calculations should take into consideration these variables to help determine a more realistic GPR and, consequently, ZOI. For example, most power companies, when asked for fault current, provide worst-case maximum fault current information with no fault resistance. It is up to the telecommunications or power protection engineer who is responsible for determining HVI equipment placement if substation ground grid resistance, generation levels, multiple ground paths, and so on should be considered in the calculations in order to provide the most realistic, practical, and acceptable GPR, and, likewise, ZOI.

Fault Current Rating

It is important for telecommunications engineers/technicians to understand how available fault currents are determined and how to properly use them in GPR studies. The power protection engineer uses maximum and minimum fault current values to program protective relays and to coordinate the tripping of circuit breakers.

Most of the computer programs used in the power industry are capable of determining fault magnitudes for all fault types (i.e., three-phase bolted and line-to-ground). The determination of fault current magnitudes for faults down a transmission or distribution line requires the insertion of line resistance and inductance. Line resistance and inductance lowers the fault current down the line where the faults on wireless cell sites might happen. The available fault current in loop-fed lines (lines having sources from both ends) is the sum of the individual fault current from either end. Fault current-calculating computer programs can determine fault currents down the power line where a wireless site is located and most of them have capability for inserting fault/arc resistance, substation ground resistance, and inductance factors. The application of these fault current reducing factors helps lower fault current contribution to determine a more realistic GPR and ZOI. (Note that a reduced ZOI can result in cost savings simply due to less dedicated cable crossing the ZOI.)

Unless specifically requested, the telecommunications engineer/technician is usually provided with the maximum fault current at a substation or line location. That information is then used to determine the GPR and the distance to the 300-V point, providing results in worst case scenarios. In questionable situations (situations where equipment is located right on the edge of the ZOI), one may take into consideration fault current reduction factors to see if any apply. Good judgment and common sense can deem a borderline situation acceptable.

Other Factors that Affect Fault Current Magnitude

The available fault current at a substation is the summation of fault currents from all the sources (lines, local generation, etc.). Therefore, local generation, motors, and capacitor banks can increase available fault current. Large motors and/or capacitor banks connected to the electrical system can add fault current. Large motors become fault current sources when their connection terminals are suddenly short-circuited. Spinning inertia provides fault current flow from the motor's collapsing magnetic fields (i.e., motor acting as a generator). Large capacitor banks produce high amounts of discharge current when their terminals are shorted via the fault.

Distribution fault currents decrease if the substation power transformer has phase and/or neutral reactors as part of the power delivery system. Power companies use single winding transformers (called “reactors”) to reduce available fault current, especially where large power plants are located near residential services.

Summary of Fault Current Magnitude Factors

The higher fault currents occur when the following conditions exist:

- Maximum generation
- Low ground grid resistance
- Short distance to faulted structure
- Larger wire sizes
- Low earth soil resistivity
- Slow-tripping circuit breakers
- Reclosing with time-delayed tripping
- Inoperative transfer trip protection
- Low fault resistance

The lower fault currents occur when the following conditions exist:

- High earth soil resistivity
- Minimum generation
- Long distances to faults
- High ground resistances
- High fault resistance

Ground Grid Resistance

Grounding schemes are typically designed using IEEE Std. 80-2000™, commonly referred to as IEEE Std. 80, the Guide for Safety in AC Substation Grounding. The purposes of IEEE Std. 80 are

1. Establish the safe limits of touch and step potentials that can exist in a substation under fault conditions
2. Review substation grounding practices and develop criteria for a safe grounding design

3. Provide a procedure for the design of practical grounding systems
4. Develop analytical methods to understand and solve earth gradient problems
5. Provide a bibliography of literature on grounding

This standard is very detailed and takes into account copper conductors in various configurations, earth soil characteristics, and other factors resulting in calculated ground grid resistances and voltage profiles. The information contained in this book frequently references this important and highly utilized standard.

Similar to fault current, ground grid resistance is another quantity directly entered in the formula for GPR calculation. The higher the ground grid resistance, the higher the GPR is for the same magnitude of fault current. The trade-off being higher fault currents occur when there is lower fault resistance, and lower fault currents occur when the grid resistance is higher. Therefore, if the fault current were to be constant regardless of ground grid resistance, then the higher the grid resistance, the higher the GPR, and the lower the grid resistance, the lower the GPR. When the fault current is assumed to be worst case (maximum available), then increasing the ground grid resistance increases the GPR (and ZOI) when, in fact, increasing ground resistance should decrease fault current and ZOI from a protective relay perspective. Most power utilities want to assume worst-case fault current and not include fault or grid resistance. A more accurate GPR may be determined if the electric supply station fault current value included ground grid resistance and the other fault lowering factors mentioned earlier.

The next section discusses terminology and variables involved in ground grid resistance contributions to GPR and ZOI.

Concept of "Remote Earth"

Remote earth, sometimes called "True Ground" or "True Earth" (see Fig. 3.8), is a theoretical concept in which an area located deep below the earth's surface is assumed to have zero resistance and is a perfect conductor. Ground resistance measurements from ground grids, ground rods, and so on are referenced to "remote earth," the perfect conductor below the surface of the earth. This way, calculations can be made of the fault current distribution throughout the network of connected resistances.

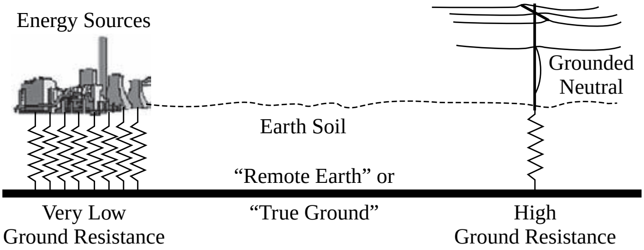


Figure 3.8 Remote earth or true ground.

Structure/Footing Ground Resistance Approximations

Station ground grids and structure footing resistances can vary significantly depending on the soil resistivity (loam, sand, clay, etc.) and type of grounding scheme (rod, counterpoise, grid, etc.). Some grounding schemes in high resistivity soils can have very high footing resistances (above 100 Ω). Regarding transmission tower footing resistances, often, a more complex counterpoise-type grounding scheme is used to meet a maximum footing resistance requirement. Low resistivity soils can provide low footing resistances even with simple ground rod schemes. Table 3.2 provides reasonable values for footing resistance for use in basic GPR calculations.

Determination of Ground Grid Impedance

The value of the substation or power line structure's ground grid impedance is required in the GPR calculation. The total station grid (Z_{SGT}) impedance is the total impedance consisting of the station/structure ground, the transmission line's overhead static wire (OSW) grounds, and the distribution line's MGN grounds. All of these grounds working together distribute the available fault current, and each earth ground has its associated GPR.

The basic formula for calculating the total station ground grid impedance having multiple ground paths is shown in the next section:

$$Z_{SGT} = \frac{1}{\dfrac{1}{Z_{SG}} + \dfrac{1}{Z_{Line1}} + \dfrac{1}{Z_{Line2}} + \dfrac{1}{Z_{Line....}}}$$

Table 3.2
Footing Resistance Values

	Footing resistance (Ω)	
Structure	Low soil resistivity	High soil resistivity
Distribution poles With MGN	10	20
Distribution poles Without MGN	25	50
Transmission structures With overhead shield wires	5	25
Transmission structures Without overhead shield wires	15	50
Distribution substations	0.1–0.5	0.5–2
Transmission substations	0.01–0.2	0.3–1

A small factor worth mentioning is the incidental current paths created by metal rail lines, utility pipes, and so on. GPR calculations normally ignore these incidental current paths and they could change without notice. Omitting them in calculations provides more conservative results (per IEEE Std. 367-2009™).

Direct Station Impedance Measurement

The generally accepted best method to determine station ground grid impedance (Z_g) is through actual measurement techniques. There are two methods for determining station grid impedance and both require measurements. The accuracy of each method depends on the completeness and care with which such measurements are made.

Method A (Calculations Based on Measurements of Earth Resistivity). As outlined in great detail in IEEE Std. 80-2000, Method A is a good way to predict the GPR of electric power stations that has not yet been built. Calculations are first based on measurements of earth resistivity using the four-probe method, and then the designed amount and size of buried conductor are included in calculations to determine the expected ground grid resistance. The designed ground grid resistance using Method A is then verified by actual ground grid resistance measurements after the station is built, using Method B.

Method B (Measurement of Existing Ground Grid). Method B measures the impedance of the grounding electrode, station ground grid, or other grounding system once it has been built using the three-probe method, also called "fall of potential," which is described in IEEE Std. 81.2-1991™ (revised from 1983) and further addressed in IEEE Std. 367-2002. The steps to determine the station ground resistance based on the "fall of potential" method are discussed in these standards. This method measures the grid impedance while the substation is energized. This approach takes into account the connected transmission line shield wires, distribution grounds (MGN), and any incidental grounds such as metallic water, gas, and sewer lines. Although this is a direct measurement method, results can vary depending on soil and seasonal conditions.

Fall of Potential Gradient Measurements

The most accurate method for determining the potential gradient is to actually measure the voltage gradient using a current injection probe and voltage measurement probe. The industry standard and industry acceptable method for actually measuring the potential gradient is the fall of potential method as discussed in great detail in IEEE Std. 81.2-1991. This method is primarily used for measuring the ground impedance of large grounding systems (substations) having multiple ground paths. In addition, it is possible to measure the current distribution in the grounding system, the mutual impedance to the paralleling utility facilities, and step, touch, and profile voltages.

Refer to Figure 3.9 for the measurement diagram. This method calls for placing a faraway remote current probe into the soil and inserting a known current, usually between 1 A and 100 A and usually between 55 Hz and 70 Hz (not 60 Hz). (Note that a current greater than 50 A is preferred, particularly where the ground impedance is less than 1 Ω.) The current through the remotely located probe back to the ground grid should be held constant during the test. The remotely located current probe must be sufficiently distant from the grounded object (station grid) under test in order to not be influenced by currents spreading out from the grounded object (sufficiently distant is approximately eight times the diameter of the station, if possible, or a minimum of three

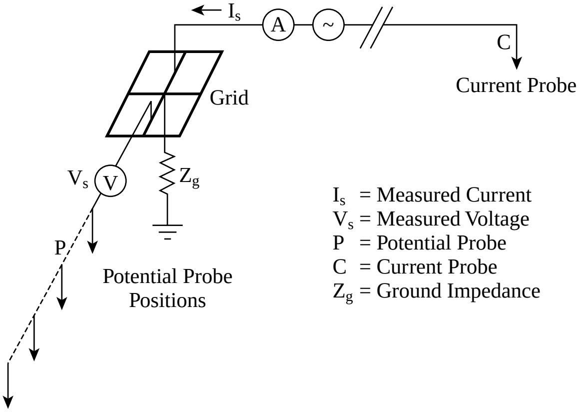


Figure 3.9 Fall of potential.

times the station diameter). Note that insulated conductors are needed for traversing the earth's surface.

The voltage probe is then moved outward from the station ground grid incrementally, and the resulting voltage measurements are recorded. For improved accuracy, the current probe should traverse 90° from the potential probe. Since the goal is to measure the GPR created by the current probe, measuring the voltage away from the flow of current to the current probe will give a more accurate representation of the fall of potential (provided the soil is homogeneous). Most soils are not homogeneous in nature, and one has to decide the best direction for both probes or use multiple directions for a better analysis.

Warning: proper personnel protection equipment (PPE) and equipment safety practices must be observed when working with remote ground probes in the event a power fault occurs (PPE is discussed in Chapter 7).

The ideal situation is to run the remote current probe down an open field and measure the voltage gradient at 90° as shown in Figure 3.9. However, working with very long probe distance parameters can be cumbersome. Large stations in populated areas, for example, might require one to select a best direction with several infringements. The common types of measurement infringements are listed in the next section:

- Rough mountain terrain
- Across rivers

- Across parking lots
- Across houses

Note that if the intent for measuring the fall of potential (hence GPR profile) is to determine the 300-V point for locating telecommunications equipment, then it is best to measure the profile along the telecommunications cable path.

The actual ZOI potential contours can be plotted using the measured potentials (V_s) radially outward from the station grid. (Note that the potential measurements should be made with very high internal impedance volt meters as to not impact measurement results.)

The station grid impedance (Z_g) can be calculated for various potential probe distances using the following formula:

$$Z_g = \frac{V_s}{I_s}$$

The grid impedance (Z_g) will tend to level out between the measurements' end points (station and remote current probe). When the current probe is adequately remote from the station ground grid (i.e., three to eight times the station grid diameter), there should be a flattening or leveling of the impedance curve. A sample graph of station grid impedance calculations and leveling of the impedance is shown in Figure 3.10. The actual impedance Z_g is then determined using the aforementioned formula with the voltage and current measurements at the leveling part of the curve.

Legend

C_1 = current probe (connection to station ground grid)

C_2 = current probe (remote location three to eight times diameter)

P_1 = voltage probe (connection to station ground grid)

P_2 = voltage probe (used for incremental voltage measurement)

Figure 3.11 shows a simple calculation worksheet that can be used to identify the leveling of the graph to determine Z_{SGT}.

Note that extreme care in electrical safety procedures, as explained in Chapter 7, must be used to protect against dangerous touch potentials should a fault occur in the substation at the time measurements are being taken. In essence, a dangerous touch potential can exist between

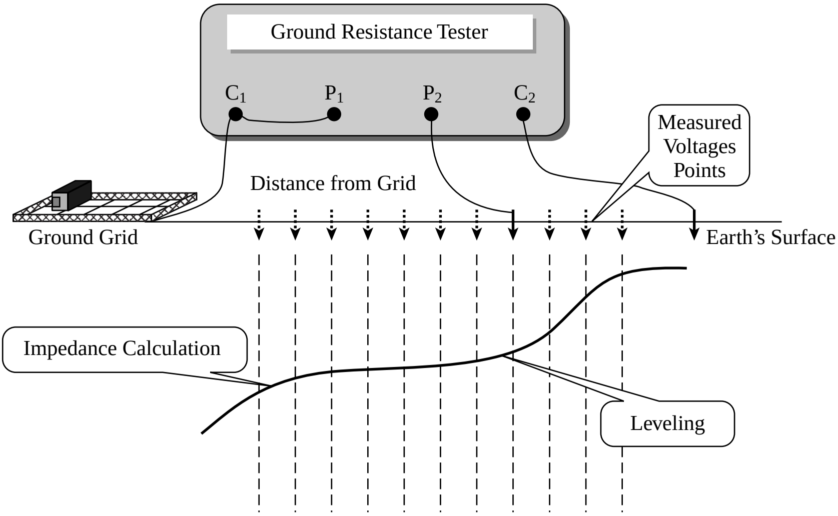


Figure 3.10 Ground grid impedance measurement.

Measurement Increments	**Distance**	**Volts (P_2)**	$Z_g = \frac{V_g}{I_s}$		**Notes**
At Edge of Sub					Max GPR
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					Minimum GPR

Figure 3.11 Determining Z_g using the "fall of potential" method.

the station ground grid and the insulated wire connected to the remote probe.

Peaking Factor (Direct Current [DC] Offset)

Another factor used in calculating GPR (in addition to fault current and ground grid resistance) is "peaking factor." Peaking factor has to do with the electrical characteristics of circuit resistance and inductance during the fault. The peaking factor helps determine the fault current's rate of rise and decay time. Fault current consists of both a steady-state symmetrical component and a rapidly increasing component caused by the short circuit condition. This rapidly increasing component of current peaks then decays over a short period of time. This rapidly increasing current component is viewed as a DC transient component (sometimes called "DC offset") and levels off after a short period of time. The magnitude of this DC offset current component and its resulting effect on the GPR is a function of the inductive reactance (*X*) to resistance (*R*) ratio (*X*/*R*) of the power system's electrical characteristics at the fault location. Some of the other factors affecting the DC offset factor include fault current duration and the phase angle between the system voltage and current at the initiation of the fault. The rate of decay of this DC offset component is also a function of the *X*/*R* ratio.

Figure 3.12 shows a typical DC offset waveform.

The *X*/*R* ratio of the system is proportional to the discharge time constant of the system's net inductance and resistance. A large *X*/*R* ratio

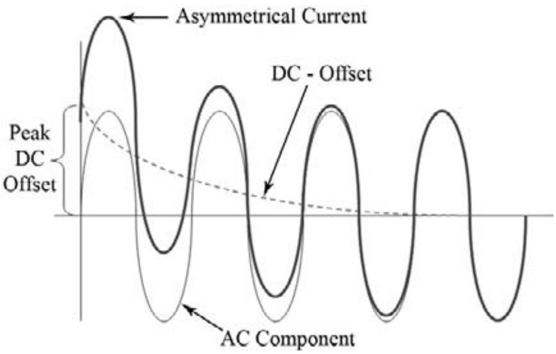


Figure 3.12 Total fault current waveform with DC offset.

corresponds to a large time constant and therefore, a slow rate of decay. A small X/R ratio indicates a small time constant and a fast rate of decay of the DC offset component.

The highest DC offset occurs when the change in current, from just before fault initiation to just after fault initiation, is maximum. Since the alternating current cannot change state instantaneously due to the inductance of the circuit, initially, the DC offset counter balances the change in alternating current. With a highly inductive circuit, the maximum DC offset will occur when the fault is initiated close to a voltage zero crossing, a condition that is most unlikely for faults resulting from insulation breakdown. Also, a highly inductive circuit will have a prolonged DC offset.

In HV power systems where the fault impedance is often negligible, the rate of decay of the DC component is usually within 5–40 ms and is determined by the effective power system X/R ratio. Typical values of X/R ratios are shown in Table 3.3.

Table 3.3
Typical X/R Ratios

X/R ratio	Peaking factor
1	1.04
2	1.21
3	1.35
4	1.46
5	1.53
6	1.59
7	1.64
8	1.68
9	1.71
10	1.73
15	1.81
20	1.85
30	1.90
40	1.92
50	1.94

Table 3.4
Typical DC Offset Ratios

System voltage (kV)	Approximate X/R ratio
4–25	2–4
34–115	3–10
161–500	Above 30

Typical values of DC offset are summarized in Table 3.4.

Note that the value of the X/R ratio is typically derived from the same computer program the power company protection engineer uses to determine maximum fault current.

CALCULATION OF GPR

There are several ways to calculate the GPR of a power fault in a substation, structure, or grounded object. Some methods provide reasonable ballpark solutions while others involve complex mathematical equations involving boundary conditions (such as near the substation fence and amount of buried conductors) and measured values. IEEE Std. 367-2002 provides the essential information to determine basic solutions and the factors leading to advanced solutions. Simple and complex computer programs are also available for calculating GPR. This chapter provides the basic GPR calculation methods including mathematical, graphical, and measured. A simple computer program that is based on IEEE Std. 367-2002 is also discussed.

Ohm's law (a fundamental mathematical formula used in electrical circuits) can be used to provide the basic perspective of calculating GPR. The simple Ohm's law equation is shown below.

$$\text{Voltage} = \text{Current} \times \text{Resistance}$$

An electric supply location's (ESL) GPR follows Ohm's law and is equal to the product of the station ground grid impedance (Z_{SG}) and that portion of the total fault current that flows from the substation ground grid back through the earth to its power sources, after then adjusting for peak versus rms values and the DC offset peaking factor.

GPRs are also produced at locations where the fault current distributes and enters the earth at the alternative ground paths. These alternative path GPRs are equal to the product of their ground impedance and their respective portion of the earth return current.

The GPR is calculated using the following adjusted Ohm's law formula:

$$GPR = (\sqrt{2})\, I_{Fault\text{-}rms}\, Z_{SG}\, (Peaking\ Factor)$$

where

$\sqrt{2}$ converts the rms fault current into peak current

I_{Fault} is the maximum earth return fault current to the sources

Z_{SG} is the station ground grid impedance and is usually a field measurement in ohms.

Peaking factor converts the peak voltage to APV. Peaking factor is derived from the DC offset (Table 3.3) resulting from the X/R ratio provided by the power protection engineer.

GPR Calculation Example

Referring back to Figure 3.2, suppose one is trying to calculate the asymmetrical peak GPR of a substation in a remote location that has the following characteristics:

- Maximum earth return fault current: 5000 A rms
- Substation ground grid impedance: 0.25 Ω
- X/R ratio: 10

From the equation earlier,

$$GPR = \sqrt{2}\, I_{Fault\text{-}rms}\, Z_{SG}\, (Peaking\ Factor).$$

Substituting and solving,

$$\text{GPR} = \sqrt{2} \times (5000) \times (0.25) \times (1.73) = 3058\ \text{V}.$$

Therefore, the GPR for this situation is 3058 V peak asymmetrical (VPA). Once the GPR and soil resistivity are known, the voltage gradient or profile outside the substation fence can be determined. The voltage gradient will determine the distance to the 300-V point or the ZOI.

ZOI

A very important concept to understand for the proper design and application of HV protection is the ZOI. The ZOI is an area around a ground electrode (structure or station grid) bounded by points of specified equal potential resulting from the voltage drop through the earth between the ground electrode and a distant location in the earth's soil. During a power fault condition and when a GPR occurs, zones of equipotential contours surround the grounded object. These contours, similar to equal-elevation contours on a topographical map, display lines of equal potential. The higher potential curves are located close to the grounded object under fault, and the lower potential curves are located farther out from the grounded object.

The distance to the outermost equipotential lines is a function of GPR, earth resistivity, and the size of the grounded object. In general, the greater the GPR magnitude, the higher the earth resistivity, and the larger the size of the grounded object, the greater the distance to the edge of the ZOI. The edge of the ZOI is normally referred to as the 300-V point. Most GPR/ZOI standards refer to the 300-V point equipotential curves as the boundary of the ZOI, primarily for recognizing a safe telecommunications equipment location.

The voltage profile or gradient radially outward from the ESL, defining the ZOI, follows an exponential decay pattern. Basically, one can view the situation as the voltage dropping in half for a specified equidistant increment away from the grounded object under fault conditions.

Telecommunications cables that traverse the ZOI that are not properly protected can experience the full GPR potential (voltage), resulting in serious cable and equipment damage and possibly injury of personnel. For example, if an insulated telecommunications cable's shield is grounded outside the ZOI and the same shield is connected to a substation ground grid, full GPR voltage can appear across the cable shield, causing it to explode, become severely damaged, and so on. Another example: if a telecommunications grounding electrode is located in the vicinity of an HV power substation or transmission line tower under fault conditions, part of the GPR is transferred to the telecommunications electrode and can still damage telecommunications equipment. Furthermore, standard telecommunications circuit overvoltage protectors (i.e., carbon, gas, solid-state protector blocks) can operate (fire) resulting in the telecommunications cable pairs being shorted to the GPR potential, causing damage to telecommunications equipment. An HV appearance on an insufficiently insulated telecommunications cable can cause cable jacket failure when exposed to the conditions of GPR.

Proper HV isolation of telecommunications cables is required to mitigate the GPR problem. The job of the telecommunications protection engineer is to properly coordinate expected GPR with the proper HV protection/isolation equipment.

The 300-V Point

The generally accepted edge of the ZOI is the 300-V point. The distance out from the GPR location to the 300-V point is of particular interest for multiple reasons:

1. Most overvoltage protectors used in telecommunications circuits operate (fire) in the 280- to 300-V range. Keeping the GPR potential at or near 300 V helps prevent the annoyance or miss operation of these overvoltage protectors.
2. Telecommunications equipment is continually grounded as a general practice. Grounded telecommunications equipment will help lower the GPR provided the GPR is in the 300-V range.
3. The human body can tolerate short-duration contact voltages better than long-duration contact voltages. In other words, the human body can tolerate slightly higher voltages if the contact duration is shorter rather than longer. The 300-V point is a

> measurement of the APV where the rms voltage (referring to heating effect on body resistance) is much lower. These points imply that the 300-V APV location has borderline safety implications/factors on human touch potential tolerance should the GPR disappear quickly as in proper operation of protective relays.

Therefore, in the United States, the industry accepted design objective and permissible maximum GPR ZOI voltage is 300 VPA.

Potential Contour Lines

ZOI consists of equipotential voltages surrounding the grounded object under fault conditions. Drawings of these lines look similar to elevation lines on a topographical map. These lines of equipotential are sometimes called "contour" lines or "gradient" lines. Depending on the homogeneity of the soil, these equipotential lines take on different shapes. For example, equipotential lines take on the shape of circles if the faulted grounded object is buried in homogeneous soil. Figure 3.13 shows the concept of fall-off potential in homogeneous soil and Figure 3.14 shows contour lines in nonhomogeneous soil.

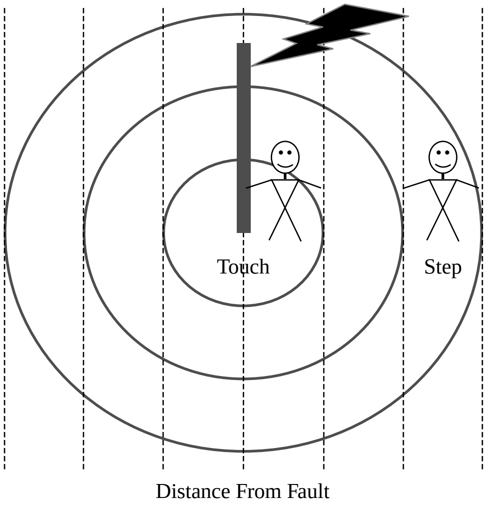


Figure 3.13 Equipotential lines in homogeneous soil.

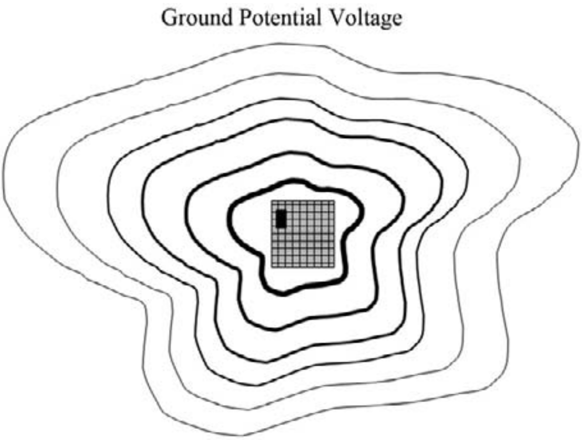


Figure 3.14 Equipotential lines in nonhomogeneous soil.

EARTH RESISTIVITY

So far, this chapter has dealt with the key factors that make up the GPR calculation. In order to determine the ZOI and the distance to the 300-V point, knowledge of the earth's soil resistivity is needed. Details on measuring earth soil resistivity can be found in IEEE Std. 80-2000. The commonly used earth resistivity values to determine GPR and ZOI (i.e., homogeneous, one layer, and two layers) are discussed in IEEE Std. 367-2002.

The spread of the ZOI and the distance to the 300-V point depends on the GPR and soil resistivity. Earth's soil resistivity is a measured characteristic of the conductive nature of the earth's soil when electric current flows through it. The standard units for soil resistivity are ohm-meters (ohm-m). As defined, 1 m^3 of soil will have a resistance characteristic measured in ohm-meters. Sometimes, earth resistivity is stated in ohm-centimeters (ohm-cm).

Earth resistivity changes with rain, soil chemistry, temperature, moisture, and several other factors. Generally, moist black loam-type soil has very low resistivity (good conductive soil), while dry, sandy, and rocky soil has very high resistivity (poor conductive soil). Soil resistivity tends to decrease (become more conductive) with moisture and alkalinity (salts). Low earth resistivities provide low resistance station grounds, and high resistivities provide high resistance station grounds.

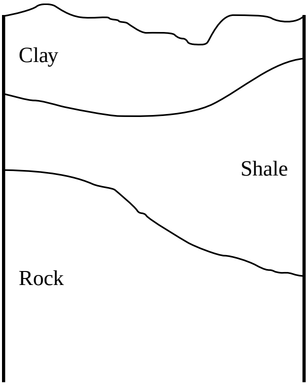


Figure 3.15 Layers of soil resistivity.

Earth's soil is typically not homogeneous when drilling downward and is commonly represented as layers. Each layer can have significantly different electrical characteristics. Fault current will flow through the different layers as though it is flowing through different resistances. Most of the current will flow through the layer having the lowest resistivity provided it is reasonably close to the surface, making contact with the grounding electrodes. Figure 3.15 shows different soil layers, each having different soil resistivities.

Note that for more information on soil resistivity, refer to IEEE Std. 81.2-1991 Guide for Measuring Earth Resistivity, Ground Impedance and Earth Surface Potentials for a Ground System.

There are basically three ways to determine earth's resistivity.

1. Utilizing resistivity tables of common soil types
2. Measuring resistivity using the four-probe method
3. Calculations using Dr. Frank Wenner's four-probe method (IEEE Std. 80-2000)

Determining Earth's Resistivity Using Table of Common Values

There are several published tables on soil resistivity. Table 3.5 shows most of the common types of soils and their respective resistivities.

Table 3.5
Table of Common Soil Resistivities

Type of soil	Resistivity Ohm-meters
Sea water* (reference)	1
Loam–clay–chalk	3–30
Trap–diabase–shale	20–100
Limestone–sandstone	100–1000
Sand–gravel–slate	1000–4000
Dolomite–granite	3000–8000
Rock–gneisses	8000–10,000

*Note distilled water is close to an insulator, while adding salt makes water very conductive. Salt water can have a resistivity equaling 1 ohm-meter.

Measuring Earth's Resistivity: The Four-Probe Method

The same earth ground resistance tester used to measure substation ground grid impedance (Fig. 3.10) can also be used to measure earth's resistivity. The process involves using two current and two voltage probes (C_1, C_2, P_1, and P_2).

Earth resistivity is measured with all four probes spaced an equal distance apart in a straight line. The separation distance is also indicative of the depth of the soil being measured. The current probes are placed on the outside of the area being tested and the potential probes inside. By placing a voltage across the outside current probes, current is injected into the earth (hence the reason for calling them current probes). The two potential probes are used to measure the voltage present in the earth's surface as a result of the injected current. The ground megger instrument determines (calculates) the earth resistivity by dividing the measured surface voltage by the measured injected earth current (Ohm's law).

Probe spacing is indicative of the depth of the soil being measured. In other words, greater probe spacing (maintaining equal distance between probes) results in deeper soil being measured and vice versa.

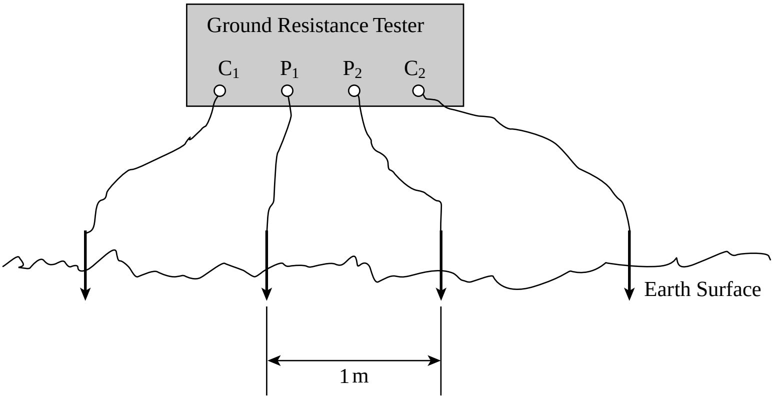


Figure 3.16 Four-probe earth resistivity method.

The setup method for measuring earth resistivity is shown in Figure 3.16. Repeating this procedure for various probe separation distances will produce an average value of earth resistivity. Linear measurements in different directions and with at least two different spacing (depths) give a better picture of the earth resistivity for that location than just one test procedure. Varying results indicate nonhomogeneous soil conditions; both surface and depth variations in soil resistivity are possible.

Determining Earth's Resistivity Using Wenner's Formulas

Dr. Frank Wenner of the U.S. Bureau of Standards (referenced in IEEE Std. 81.2-1991) is responsible for the theory that if the electrode depth is small with respect to electrode spacing, then the depth measured resistivity (ρ) is representative of length between the electrode probes.

Then the following formula applies:

$$\rho = 2\pi AR$$

where:

A = probe spacing in meters

R = resistance reading on the megger instrument

π = 3.14

Keep the units of measurement consistent: (1 m = 3.28 ft)

Example: If $A = 20$ ft and $R = 6\ \Omega$, then

$$\rho = 2(3.14)(20)(0.3048)(6) = 229.7\Omega\text{-m}$$

GPR AND ZOI CALCULATION METHODS

GPR and ZOI are closely interrelated, especially when it comes to designing safe and reliable HV protection systems for telecommunications circuits. This section discusses the GPR concepts in IEEE Std. 367-2002 and computer program tools that are available that involve the concepts learned thus far.

Graphically Determine Potential Gradient (IEEE Std. 367-2002)

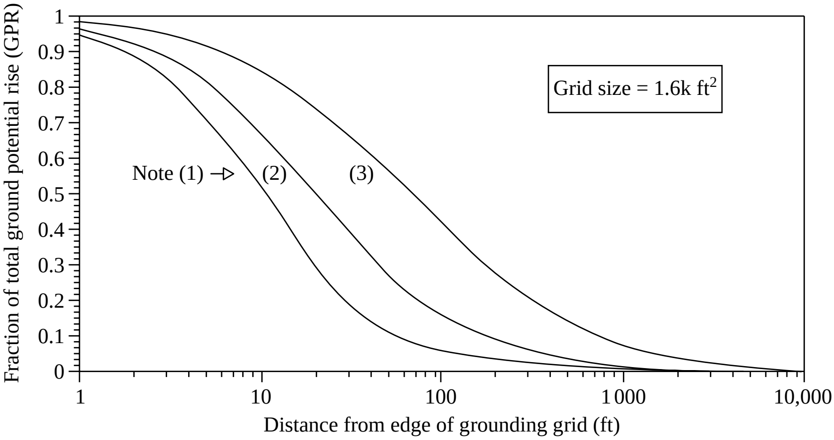
IEEE Std. 367-2002 includes a discussion on how to determine the distance to the 300-V point using graphs that are based on computer results and measured values. This approach for determining the potential gradient requires selecting specified ground grid sizes and earth resistivity options. The graphs are normalized to apply for various GPR situations.

IEEE Std. 367-2002 offers four separate grid sizes and three earth resistivity options and are provided herein as Figures 3.17–3.20. These curves were developed using the Electric Power Research Institute (EPRI) computer program Substation Grounding Analysis (SGA). These curves are normalized for a power station GPR of 1000 V (V_{SG}). They do not take into account the effects of buried metallic objects that may act as an electrical extension of the station grounding grid.

The figures are based on a normalization calculation. The term "normalized" means that the graphs are based on the 100% value being maximum GPR, and values less than maximum are simply percentages of the maximum value. For example, if the maximum GPR is 3058 V, then 300 V is 9.81% (300 ÷ 3058 = 0.0981 or 9.81%).

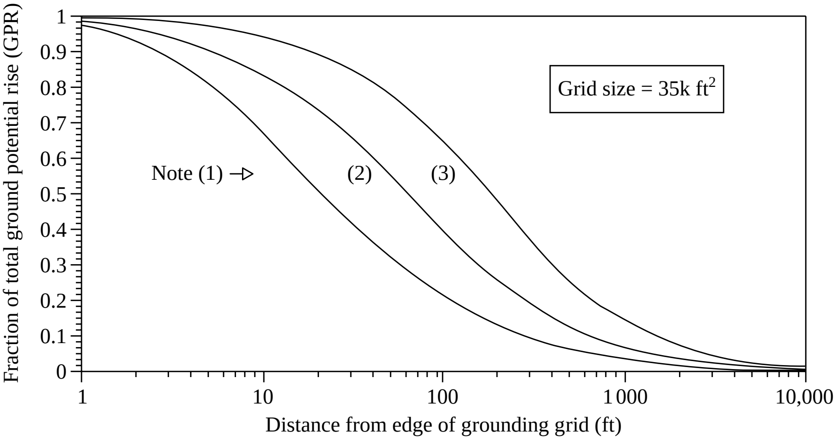
Graph Application Example

Suppose one wants to estimate the distance from a station grid to where the GPR has decreased to 300 V using the IEEE graphs when



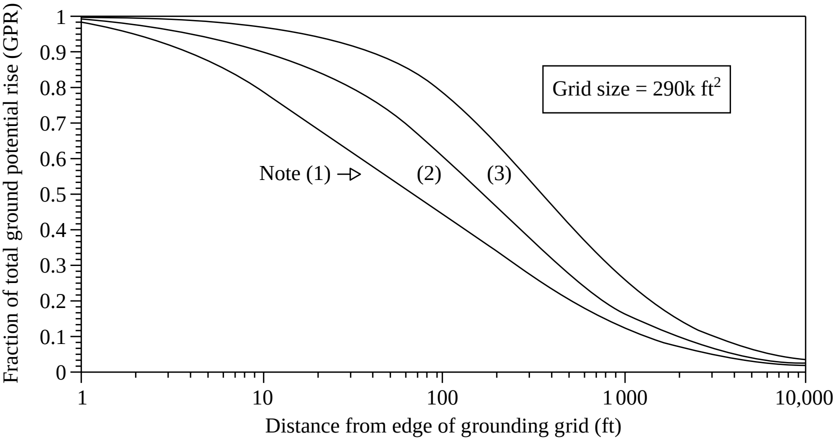
Note 1 — Two-layer soil, 100/20 Ω·m (top layer is 20 ft in depth).
Note 2 — Single-layer soil, 100 Ω·m.
Note 3 — Two-layer soil, 100/1000 Ω·m (top layer is 20 ft in depth).

Figure 3.17 Fall-off potential for grid size = 1.6 kft^2.



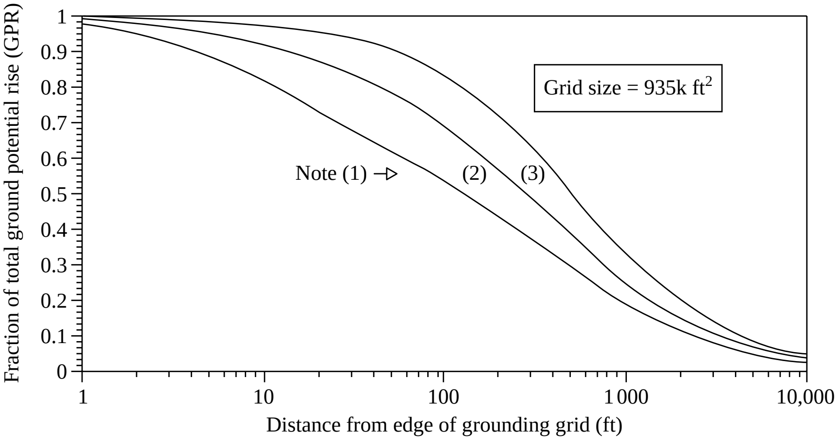
Note 1 — Two-layer soil, 100-20 Ω·m (top layer is 20 ft in depth).
Note 2 — Single-layer soil, 100 Ω·m.
Note 3 — Two-layer soil, 100/1000 Ω·m (top layer is 20 ft in depth).

Figure 3.18 Fall-off potential for grid size = 35 kft^2.



Note 1 — Two-layer soil, 100/20 Ω·m (top layer is 20 ft in depth).
Note 2 — Single-layer soil, 100 Ω·m.
Note 3 — Two-layer soil, 100/1000 Ω·m (top layer is 20 ft in depth).

Figure 3.19 Fall-off potential for grid size = 290 kft^2.



Note 1 — Two-layer soil, 100/20 Ω·m (top layer is 20 ft in depth).
Note 2 — Single-layer soil, 100 Ω·m.
Note 3 — Two-layer soil, 100/1000 Ω·m (top layer is 20 ft in depth).

Figure 3.20 Fall-off potential for grid size = 935 kft^2.

Table 3.6
Fall-off Potential Contours per IEEE Std. 367-2002

Figure	Size of grid (m^2/ft^2)	Soil resistivity (Ω-m)	GPR	Distance to 300-V point (m/ft)
Figure 3.18 (1)	3250/35,000	100/20	1000	17/55
Figure 3.18 (3)	3250/35,000	100/1000	1000	122/400
Figure 3.19 (2)	27,000/290,000	100	1000	137/450
Figure 3.20 (3)	87,000/935,000	100/1000	1000	396/1300

NOTE: Table assume GPR = 1000 V and graph interpolation.

the GPR is 5 kV, the soil resistivity is 100 Ω-m and the station grid size is 35 kft^2.

The following steps will produce the results:

- Step 1: Calculate the fraction of the total GPR (i.e., 300 V/5000 V = 0.06). This represents 6% of the GPR.
- Step 2: Find the best curve that matches the grid parameters (i.e., 35,000 ft^2 and resistivity = 100 Ω-m; Fig. 3.18).
- Step 3: Note that the distance to the calculated fraction (i.e., 0.06) is approximately 1000 ft.

Table 3.6 is a summary of the distance to the 300-V point from a 1000-V GPR utilizing the aforementioned IEEE curves for different substation grid sizes and soil resistivities. As one can see, the distance to the 300-V point varies considerably based on grid size and soil resistivity. The variation increases significantly for higher GPRs.

Transfer Potential

The term “transfer potential” is commonly used in the electrical industry and by safety organizations when referring to metal objects, especially insulated metal objects that make contact with voltage potential. A telecommunications cable can provide a transfer voltage in its jacketed shield to distant locations where someone or something can come in contact with it. An example of transfer potential is when a car–pole accident occurs and an energized power conductor falls onto the car. Having the rubber tires acting as insulators, a person touching the car while standing on the earth's surface can experience electrical shock. Transfer potential of a GPR is likewise possible, especially through jacketed cables including very long ones. If there is no load at the end of a long telecommunications cable, the transfer potential at the distant end can be the same voltage as its GPR source end. A GPR transfer voltage can result in arcs, equipment damage, or possibly injury to personnel not expecting a sudden voltage to appear a great distance away from the source.

Care and caution must be taken to identify possible transfer potential locations and safety preparedness or practices must be in place prior to incident. Other sources of transfer potential include pipes, rails, metal buildings, fences, and so on.

Advanced Calculations Using IEEE Std. 367-2002

IEEE Std. 367-2002 offers formulas for calculating voltages and distances when the boundary conditions may influence results. For example, when calculating the fall-off potential near a substation fence (distance less than three times substation grid radius), the formulas assume a spherical model representation. Whereas, when calculating the fall-off potential that is far from a substation (distance is greater than three times substation grid radius), the formulas assume a disc model representation. The values may be different depending on the model selected. Keep in mind that these graphs and calculations are based on data that are inherently variable (weather, seasonal, other metal in the soil, generalized resistivities, etc.) and therefore do not represent the exact situation at all times.

Voltage at Any Boundary ($x \geq 3r$)

The following formula can be used to determine the GPR fall-off voltage that is a distance "*x*" from the center of the substation ground grid. This equation assumes the distance is greater than three times the substation ground grid radius. The radius referred to in these equations refers to a circle having the same area of the rectangular substation ground grid.

$$V(x) = \frac{\rho I_g}{2\pi x}\sqrt{2}\,(\text{Peaking Factor}),$$

where

$V(x)$ => earth's peak asymmetrical potential with respect to a remote location

I_g => the rms station ground grid earth return fault current (amps)

ρ => the resistivity for uniform soil (Ω-m)

x => the distance from the center of the ground grid (m)

r => the radius of a circle equal in area to the grid (m)

Voltage at Any Boundary ($x \leq 3r$)

The purpose of this formula is to determine the voltage at a specified distance from the center of the substation when the point is less than three times the radius of the substation ground grid.

$$V_{peak-asym}(x) = \frac{\sqrt{2}\rho I_g}{2\pi r}\sin^{-1}\left(\frac{r}{x}\right)(\text{Peaking Factor}).$$

Note: refer to the actual IEEE Std. 367-2002 for details on this formula, applications, and assumed values.

Distance to Any Voltage ($x \geq 3r$)

Protection engineers/technicians might need to know the expected GPR fall-off potential at a specified distance from the center of the substation. This value may be needed for any of the following reasons:

- Where to place protection equipment, for example, the 300-V point
- Where safe touch and/or step potentials exist
- To determine where special HV dielectric strength cable is required

The following equation can be used to determine the distance (x) from the center of the station ground grid to the boundary that has a specified voltage $V(x)$.

$$x = \frac{\sqrt{2}\rho I_g}{2\pi V(x)}(\text{Peaking Factor})$$

Note: refer to the actual IEEE Std. 367-2002 for details on this formula, applications, and assumed values.

Distance to Any Voltage ($x \leq 3r$)

The aforementioned equations were rearranged to solve for distance (x) instead of voltage $V(x)$ for distances that are less than three times the power station grid radius: the following equation is then available:

$$x = \frac{\sqrt{2}r}{\sin\left(\frac{2\pi r V(x)}{\rho I_{Grid}}\right)}(\text{Peaking Factor})$$

Note that to avoid confusion as to which equation to use, IEEE Std. 367-2002 strongly recommends that the aforementioned equation be used at all times. This formula is based on a disc model, and actual values can be different.

Example

Calculate the 300-V distance (x) from the substation under the following conditions. Refer to Figure 3.21.

- The desired boundary voltage is 300 V ($V[x]$)
- The station GPR is 4500 V (GPR)
- The fault current through the grid is 5000 A (I_g)
- The power station grid impedance is 0.8 Ω (Z_{SG})
- The equivalent radius of the station grid is 50 m (r)
- The soil resistivity is 100 Ω-m (ρ)
- The X/R ratio is 12 (for peaking factor).

Using the simpler equation where $x \geq 3r$ yields:

$$x = \frac{\sqrt{2}\rho I_{grid}}{2\pi V(x)}(\text{PF}) = \frac{(1.414)(100)(5000)}{(2)(3.14)(300)}(1.8) = 675.5\,\text{m (or 2215.6 ft)}$$

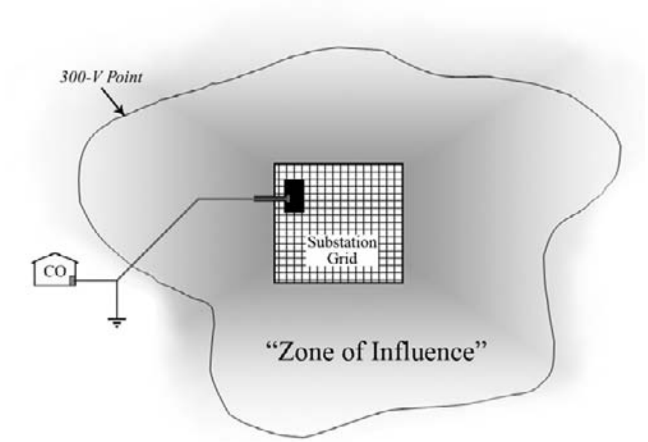


Figure 3.21 Example of distance to 300-V point.

Using the IEEE Std. 367-2002 preferred equation, where it is not known if x is greater or less than $3r$, yields:

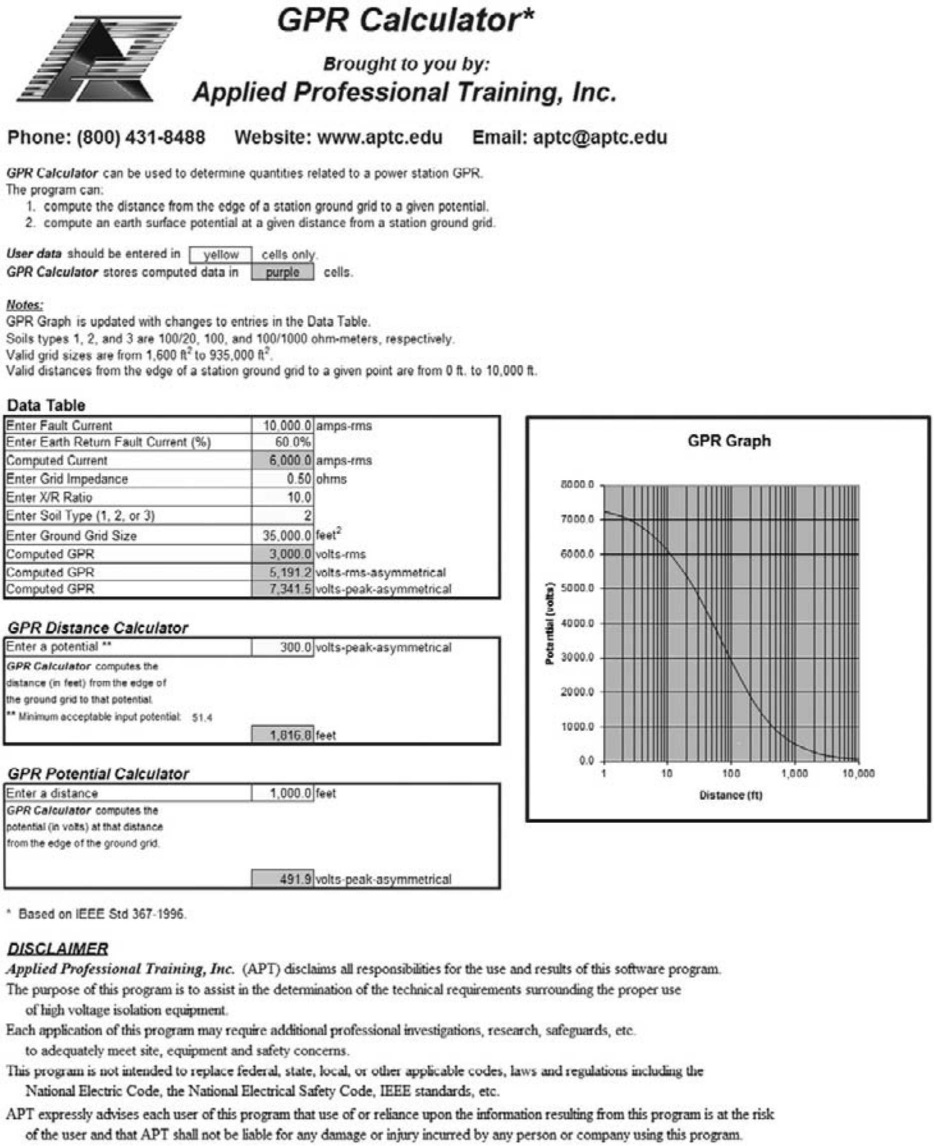
$$x = \frac{\sqrt{2}r}{\sin\left(\dfrac{2\pi r V(x)}{\rho I_{Grid}}\right)}(\mathrm{PF}) = \frac{(1.414)(50)}{\sin\left(\dfrac{(2)(3.14)(50)(300)}{(100)(5000)}\right)}(1.8)$$

$$= \frac{127.3}{\sin(0.1884)} = \frac{127.3}{0.1873} = 697.7\mathrm{m}\ (\text{or } 2229.4\mathrm{ft})$$

Note that the results are similar.

Calculations Using Computer Programs

There are several computer programs on the market that help protection engineers calculate the GPR and the distance to the 300-V point. The Applied Professional Training's (APT's) GPR Calculator is shown in Figure 3.22. This tool is self-explanatory. All one has to do is enter the site-specific data and the APT GPR Calculator performs all the necessary calculations based on IEEE Std. 367-2002.



GPR Calculator*

Brought to you by:
Applied Professional Training, Inc.

Phone: (800) 431-8488 Website: www.aptc.edu Email: aptc@aptc.edu

GPR Calculator can be used to determine quantities related to a power station GPR.
The program can:

1. compute the distance from the edge of a station ground grid to a given potential.
2. compute an earth surface potential at a given distance from a station ground grid.

User data should be entered in yellow cells only.
GPR Calculator stores computed data in purple cells.

Notes:
GPR Graph is updated with changes to entries in the Data Table.
Soils types 1, 2, and 3 are 100/20, 100, and 100/1000 ohm-meters, respectively.
Valid grid sizes are from 1,600 ft^2 to 935,000 ft^2.
Valid distances from the edge of a station ground grid to a given point are from 0 ft. to 10,000 ft.

Data Table

Enter Fault Current	10,000.0	amps-rms
Enter Earth Return Fault Current (%)	60.0%	
Computed Current	6,000.0	amps-rms
Enter Grid Impedance	0.50	ohms
Enter X/R Ratio	10.0	
Enter Soil Type (1, 2, or 3)	2	
Enter Ground Grid Size	35,000.0	$feet^2$
Computed GPR	3,000.0	volts-rms
Computed GPR	5,191.2	volts-rms-asymmetrical
Computed GPR	7,341.5	volts-peak-asymmetrical

GPR Distance Calculator

Enter a potential **	300.0	volts-peak-asymmetrical
GPR Calculator computes the distance (in feet) from the edge of the ground grid to that potential. ** Minimum acceptable input potential: 51.4	1,816.8	feet

GPR Potential Calculator

Enter a distance	1,000.0	feet
GPR Calculator computes the potential (in volts) at that distance from the edge of the ground grid.	491.9	volts-peak-asymmetrical

* Based on IEEE Std 367-1996.

DISCLAIMER

Applied Professional Training, Inc. (APT) disclaims all responsibilities for the use and results of this software program.
The purpose of this program is to assist in the determination of the technical requirements surrounding the proper use of high voltage isolation equipment.
Each application of this program may require additional professional investigations, research, safeguards, etc. to adequately meet site, equipment and safety concerns.
This program is not intended to replace federal, state, local, or other applicable codes, laws and regulations including the National Electric Code, the National Electrical Safety Code, IEEE standards, etc.
APT expressly advises each user of this program that use of or reliance upon the information resulting from this program is at the risk of the user and that APT shall not be liable for any damage or injury incurred by any person or company using this program.

Figure 3.22 APT GPR calculator. Courtesy of Applied Professional Training, Inc.

This tool provides the following features to help make GPR calculations simple:

- A GPR graph is provided for visual presentation.
- A *Distance* calculator allows one to simply enter a specific *V(x)* and immediately determine the distance to that specified voltage (the 300-V point is located at 1816.8 ft).
- A *Potential* calculator allows one to simply enter a specific distance and immediately determine the voltage at that specified distance (the GPR voltage at 1000 ft is 491.9 V).
- The size of the substation is not limited to the four used in the IEEE standard. The APT GPR calculator is limited to the smallest to largest graph in the IEEE standard; however, all sizes between the four IEEE graphs are available for use by the engineer.
- The APT GPR calculator is free of charge. For more information, contact *Applied Professional Training* (800.431.8488, www.aptc.edu, or aptc@aptc.edu).

General Considerations/Assumptions

The following tidbits of information may prove to be helpful when trying to determine what measures to take should the high volatage protection for telecommunications (HVPT) situation require field changes in GPR and ZOI:

Critical Contributions to GPR and ZOI

The following factors can have a critical effect on GPR, ZOI, and distance to the 300-V point.

1. ***Area or Size of the Grid.*** Larger grids tend to have lower grid impedance. Larger grids push out the distance to the 300-V point.
2. ***Ground Grid Impedance.*** Lowering grid impedance generally lowers the GPR. This only applies if the fault current does not change with varying grid impedances or the fault current is perceived to be at maximum for all grid impedance conditions.

Otherwise, lowering grid impedance could increase the fault current, thus causing a higher GPR.

3. ***Amount of Fault Current Actually Flowing through Earth.*** One should check with the electric utility to determine actual available fault current at a given location and during a given time frame (the time frame can be seasonal, maximum generation, low generation, etc.). One should also spend time determining precisely the amount of total fault current that actually flows through the earth compared to ancillary grounds. The distance to the 300-V point is very dependent on the actual amount of fault current flowing through the earth and not the other paths such as MGN, static wires, and so on.

Major Contributions to GPR and ZOI

The following factors can affect GPR, ZOI, and distance to 300-V point and might be worth pursuing if a GPR/ZOI situation is untenable:

1. ***Grid Density.*** Fewer large-grid meshes versus several small-grid meshes making up the ground grid results in lower station ground impedance.
2. ***Seasonal Variations in Soil Resistivity.*** This can have significant effects on GPR, ZOI, and distance to the 300-V point. One should study the best- and worst-case scenarios regarding dry or moist seasonal soil conditions.
3. ***Changes in Soil Resistivity.*** Thin layers of high resistivity soil can increase station impedance, resulting in a higher GPR. Deep penetration grounds or chemical additives can lower the grid resistance. Correctly modeling soil resistivity is out of the scope of this book; however, one can study this subject in more detail in IEEE Std. 80-2000 and IEEE Std. 81.2-1991.

Minor Contributions to GPR and ZOI

The following factors have a minor effect on either GPR, ZOI, or distance to 300-V point:

- *Lateral changes in soil resistivity:* Averaged values are generally used and produce the same calculated results.

- *Buried pipes* usually have little effect on overall GPR results.
- *MGNs on distribution systems* tend to localize disturbances.
- *Urban areas with mesh-like layouts of buried pipes and other civic facilities* tend to reduce surface potentials.
- *Irregularly shaped grids* usually have little charge effect on GPR and ZOI.

Mitigating and Reduction Factors Applicable to GPR Calculations

The following mitigation factors may help improve a tenuous situation:

1. ***Factors Affecting Fault Current Magnitude.*** One should consider total fault impedance when determining maximum fault current. Most power company computer programs used to calculate maximum fault current assume zero ground and arc impedance. Subtle changes in these impedances tend to reduce GPR and distance to 300-V point.
2. ***Factors Affecting Fault Current Duration.*** Faster relay settings and faster breaker clearing times will reduce the amount of energy in the fault and therefore reduce potential damage.
3. ***Factors Applicable to GPR Calculations.*** One should do a sensitivity analysis on each factor contributing to GPR, ZOI, and distance to 300-V point if there are issues or concerns stemming from the calculations. Evaluate the effects of changes in soil conditions, magnitudes of assumed fault current, distribution of fault current, and the peaking factor. Peaking factor alone can almost double the calculated GPR and distance to the 300-V point. Then, analyze the findings to determine if these adjustments are reasonable.
4. ***Authorities Unintentionally Providing Data that Result in Excessive Margins of Error.*** Investigate whether authorities are unintentionally overstating data that result in unreasonable design conditions. If data changes are prudent, GPR and ZOI results may be more acceptable.

5. ***Chemical Additives to Lower Ground Resistance.*** These additives help lower grid resistance; however, long-term changes could restore original problems. A cautionary note is that some chemical additives are problematic and may require costly maintenance (reference IEEE Std. 80-2000).
6. ***Telecommunications Channel Time Delays to Increase Fault Duration.*** Excessive time delays in critical telecommunications circuits can lead to extended energy release during a fault event. Care must be taken not to use telecommunications equipment that is subject to long resynchronization time or outages interrupting their performance.
7. ***Administrative Guidelines.*** They should be reviewed periodically to make sure they remain practical, realistic, and appropriate.
8. ***Acquiring Accurate Data.*** Double check and validate data used to calculate GPR and ZOI to make sure expected results are tolerable.

LIGHTNING FAULTS

Lightning strikes on electric power facilities or telecommunications towers can cause GPR and ZOI conditions to occur where HV isolation protection equipment is needed. Lightning strikes can trigger power faults on lines and in substations. For example, a lightning strike on a distribution line will most likely operate a lightning arrester, thus momentarily shorting out the line. Because the lightning triggered the arrester to short out the line, the 60 Hz follow-through current must be stopped by the breaker opening. The GPR will remain active until the power circuit breaker or fuse clears the fault.

A lightning strike has different electrical characteristics than power faults. A lightning strike, for example, has a very fast rate of rise time and its duration is much shorter than a power fault. A power fault's duration is long because it takes time for a relay operation and/or setting to trip a circuit breaker. When a lightning strike occurs on a line, structure, or in a substation, the lightning itself stops without the need of a circuit breaker operation. Lightning strikes can initiate power faults on unshielded transmission lines or have its energy dissipated by the transmission line shielding system.

When a lightning strike initiates a power fault on a transmission line, a phenomenon called back flashover can occur. In a back flashover situation, the initial GPR created by the lightning strike on the structure causes the structure's GPR to exceed the insulation level between the structure and the power conductors, resulting in the tower flashing back to the conductor. Back flashovers are usually prevented by requiring low tower ground impedances. It is sometimes difficult to achieve low tower ground resistances in some soils. Those situations normally require additional ground rods, counterpoise grounding schemes, and periodic assurance testing.

Telecommunication circuits must be protected from the adverse effects of lightning as well as power faults.

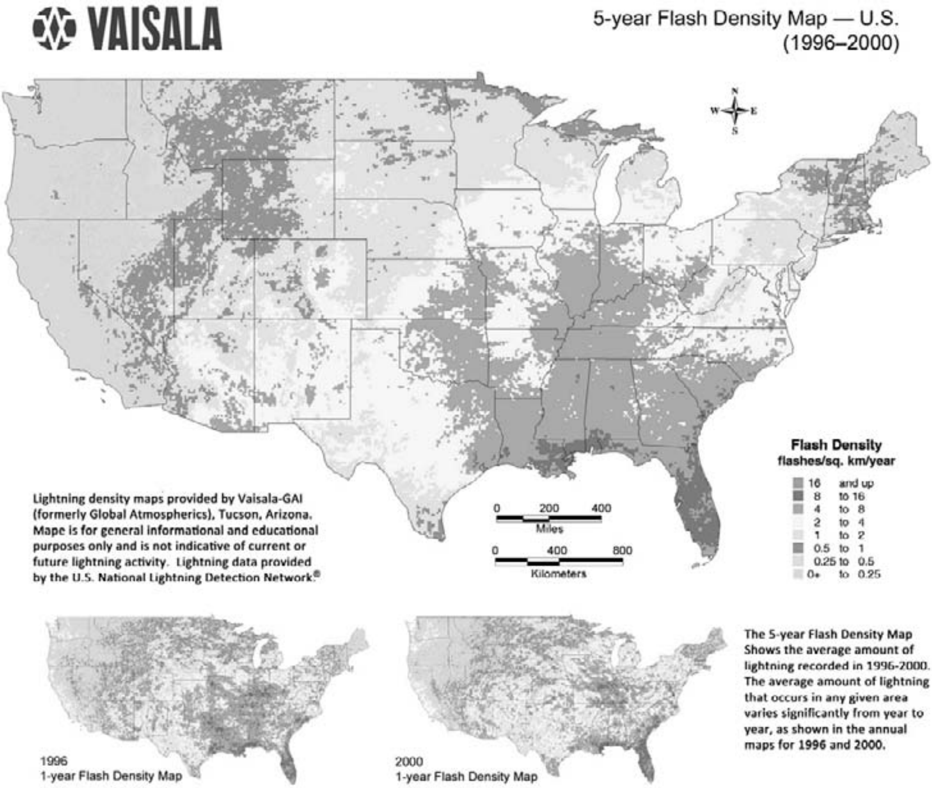
Lightning strikes occur from electrostatic discharges of positively or negatively charged electrical energy that is built up in cloud formations. The three important factors that affect lightning discharges or strikes on power equipment are:

1. Flash density, or probability of occurrence (number of strikes per km^2)
2. Intensity (kA)
3. Rate of change (current rise time in seconds)

The lightning flash density, otherwise called probability of occurrence, is determined by using flash density maps and/or maps showing isokeraunic levels of a region. A typical flash density map for the United States is shown in Figure 3.23.

The isokeraunic level refers to the average number of thunderstorm days occurring per year in a region. The isokeraunic level map for the United States is shown in Figure 3.24. The Internet offers several isokeraunic maps for locations outside the United States.

Lightning currents can range from 10 kA to over 100 kA in the order of 2–4 μs rise time and a 50 μs overall duration. The 50% average lightning current is 30 kA. This high current, short-duration, rapid rate of rise energy impulse can cause a very high and short-lived GPR. Lightning damage to telecommunications equipment and hazards to personnel are likely if they are not properly protected with an HV interface system.



Lightning density maps provided by Vaisala-GAI (formerly Global Atmospherics), Tucson, Arizona. Mape is for general informational and educational purposes only and is not indicative of current or future lightning activity. Lightning data provided by the U.S. National Lightning Detection Network®

The 5-year Flash Density Map Shows the average amount of lightning recorded in 1996-2000. The average amount of lightning that occurs in any given area varies significantly from year to year, as shown in the annual maps for 1996 and 2000.

Figure 3.23 Lightning flash density map—United States. Courtesy of VAISALA.

ELECTROMAGNETIC INDUCTION UNDER FAULT CONDITIONS

This section provides a simple yet good approximation approach to determine the induced voltages and currents on telecommunications cables that parallel power lines that undergo fault conditions. Telecommunications cables receive an enhanced longitudinal induction component of voltage and current when exposed to parallel overhead electric power lines that are under fault conditions.

Note that the total electrical stress on a telecommunications cable is the vectorial sum of the GPR and induced voltage components. Vectorial summation of these components is discussed later in this chapter.

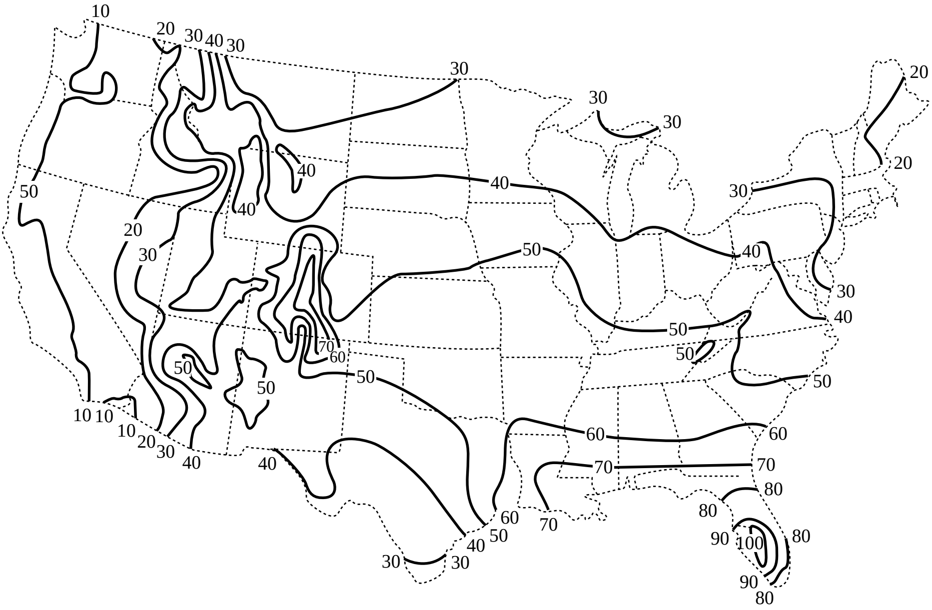


Figure 3.24 Isokeraunic map of the United States.

When a faulting electric power line parallels an overhead or underground telecommunications cable, a potentially dangerous longitudinal voltage is electromagnetically induced in the cable. The magnitude of this induced cable voltage depends on the separation distance between the power line and telecommunications cable, the longitudinal length of parallel exposure, the magnitude of the fault current, and the earth's resistivity.

Telecommunications cable shielding provides excellent protection from electric fields; however, cable shielding provides very little protection from magnetic fields. Therefore, a high rate of changing magnetic fields in faulted power lines can induce damaging high currents into shielded telecommunications cables. Normal power line current flows induce relatively low currents on parallel telecommunications cables that sometimes have to be dealt with because of noise and other service complaints. To minimize induction issues, telecommunications cables should not parallel electric power lines and should be placed perpendicular to power lines whenever possible.

Mutual Impedance

The calculation for determining induction on a telecommunications cable from a nearby power line requires knowledge of the mutual impedance components between the lines. If the lines are not reasonably parallel to each other, the calculation of mutual impedance is broken up into sections where calculating the mutual impedances of each section is then summed for total exposure. This way, fixed angles for each section can be simplified, and calculations are made easier.

The formulas for calculating the external mutual impedance of parallel supply and telecommunications circuits were developed by J.R. Carson (referencing IEEE Std. 367-2002). These formulas are sometimes referred to as Carson's equations. The details of his theories can be found in his research papers dating back to 1926.

The general formula for calculating the induced voltage in an unshielded telecommunications conductor having uniform exposure with a power line is given by the following equation:

$$V = Z_m L(I)$$

where

Z_m is the mutual impedance Z_m in Ω/km.

L is the length of exposure (kft or km). Note that graphs 1, 2, and 3 show length L in feet. IEEE Std. 367-2009 contains graphs shown in meters also.

I is the inducing current supplied by the power utility (amps).

Figure 3.25 shows Z_m and will be used in the following example (note that individual R_m and X_m graphs are provided in IEEE Std. 367-2002).

To interpret the graph in Figure 3.25, one simply uses the horizontal axis for the average distance between the power line and telecommunications line, selects the appropriate earth resistivity curve, and reads the mutual impedance off the left side vertical axis.

Example of Uniform Exposure

Calculate the parallel inductive exposure voltage between a power line and a telecommunications line having the following conditions:

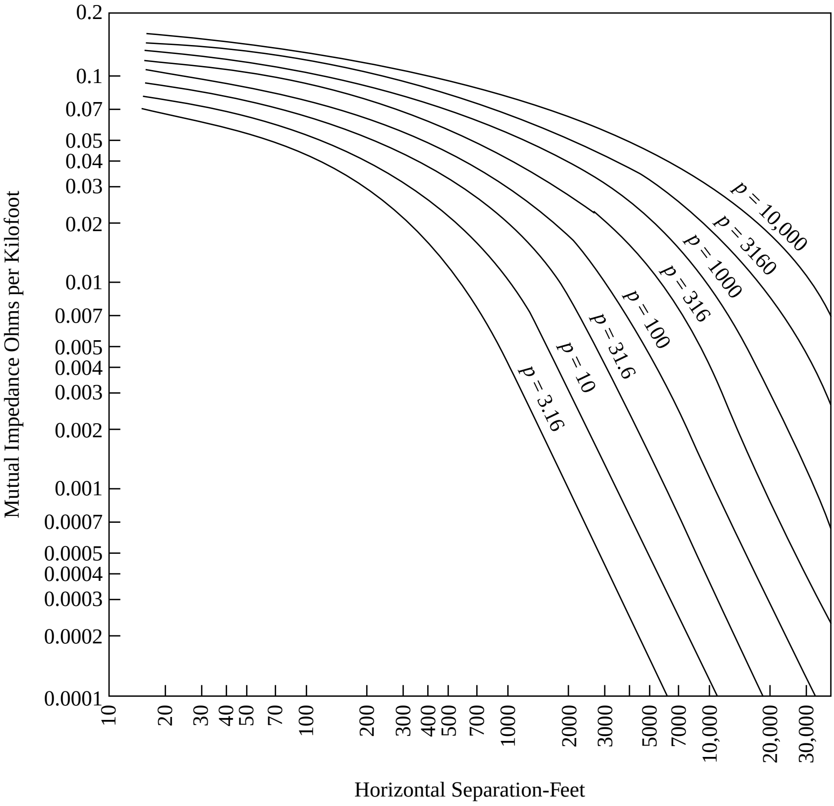


Figure 3.25 Mutual impedance (Z_m).

where

S = horizontal separation (100 ft)
L = length of exposure (15 kft)
ρ = earth resistivity (100 Ω-m)
I = fault current (5000 A)

Using the graph in Figure 3.25 to find the mutual impedance (note that the IEEE standard provides graphs for metric units),

$$Z_m = 0.08\ \Omega/\text{kft}.$$

Accounting for the longitudinal length or exposure distance,

$$Z_m = Z_{\mathrm{m}}L = 0.08 \times 15 = 1.2\ \Omega,$$

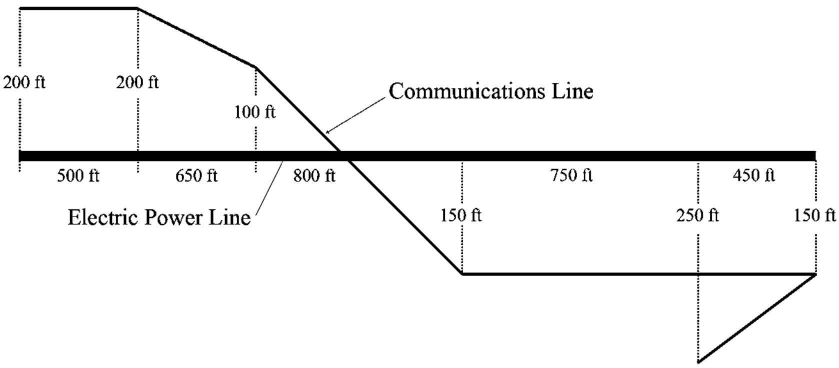


Figure 3.26 Telecommunications line exposure example.

and then applying Carson's equation, the induced parallel voltage is

$$V = Z_m I = (1.2) \times (5000) = 6000 \text{ V}.$$

Example of Nonuniform Exposure (Slant Exposure)

In most cases, the telecommunications line is not parallel to the power line, and separations vary throughout the exposure. In those cases, simply divide the total exposure into acceptable straight-line segments, calculate the induction effects of each segment, and then sum the results. If the telecommunications line segment reverses direction with respect to the power line, then that segment's induced voltage is subtracted from the sum.

Figure 3.26 shows a situation where the telecommunications line and power line are not parallel over the full exposure and there is a cross-section and a reverse section. The following example calculates the total induced voltage of this situation.

As pointed out in IEEE Std. 367-2002 regarding subdividing the telecommunications line into segments, the ratio of maximum separation to minimum separation should not exceed 2. At crossings, the minimum separation should be taken as 15 ft. The mutual impedance for each segment is obtained by taking the average of the separation distances for each line segment where

S = horizontal separation (as shown, feet)
L = length of exposure (as shown, kft)

Table 3.7
Example: Nonuniform Exposure

Section	L (kft)	Average separation (feet)	Z_m (from graph) (Ω)	Zm (= Z_mL) (Ω)	V (= Z_mI) (V)
A–B	0.5	200	0.06	0.03	120
B–C	0.65	150	0.07	.0455	182
C–D	0.8	25	0.15	0.12	480
D–F	1.2	150	0.07	0.084	336
F–E	0.45	200	–0.06	0.027	–108
Total					1010

ρ = earth resistivity (100 Ω-m) (note that GPR expert assumes 100 Ω-m)
I = fault current (4000 A)

Table 3.7 summarizes the results for each section. The summation of each line segment results in an induced voltage of 1010 V under fault conditions.

Corrections for Induced Voltages

Correction for Difference in Line Heights. These calculations are based on the difference between power line height and the telecommunications line height as being 25 ft. If necessary, refer to the correction curves for different heights in IEEE Std. 367-2009 (also available in metric system).

Power Lines with Double-Ended Feed. When the power line is supplied from both ends, the inducing currents act in opposite directions. Therefore, when evaluating the resultant induced voltage for a specific portion of the exposure on the telecommunications line, care should be taken to ensure that opposite signs are used when adding up the net contributions from the power sources.

Fault Location for Maximum-Induced Voltage. For a single-ended feed and reasonably uniform separation, the fault location giving maximum-induced voltage is usually at the end of the exposure remote from the supply feed. This condition provides parallel fault current over the majority of the line.

Shield Factor

The induced voltage calculations discussed earlier on telecommunication cables assume non-shielded cables. A shield factor is used to take into account the shielding action of all grounded conductors (overhead ground wires, rails, metallic pipes, etc.) including metallic sheaths of telecommunications cables when in an inductive exposure environment. The greater the shield factor, the less induced currents are imposed on the cable.

For telecommunications cables with aluminum or copper shields only, the shield factor does not vary much over a wide range of inducing currents. When magnetic armoring is applied over the metallic shield, the shield factor varies significantly and will depend on the flux density in the armoring and the magnitude of the induced current in the conducting shield. Excessive current can saturate the iron, thus limiting its magnetic properties.

Shield Factors for Ground Wires on Overhead Power Lines

The opposing direction currents in the unfaulted phases of a power line can serve to reduce the induced currents in the telecommunications line, thus appearing as a form of shielding. In addition to reduction of induced current from unfaulted phases and from overhead ground wires, further reduction in induced current takes place from the effect of current dissipation into the earth's conductivity through the tower or pole footing impedances (in the form of heating the earth as a resistive load). Near the fault, overhead ground wires might carry large amounts of fault current, which is then dissipated into the earth through adjacent successive grounded towers or poles.

The shield factor for overhead ground or static wires, per IEEE Std. 367-2002, may be estimated according to Table 3.8.

Shield Factors for Continuously Grounded Telecommunications Cables

Aside from the reduction of induced voltages from power line shielding effects (i.e., system neutrals and shield wires), shield factors for telecommunications cables may play a prominent role on reducing induced

Table 3.8
Shield Factors from Power Line Overhead Ground or Static Wires

Overhead ground	60 Hz shield factor	
Wire type	Single wire	Double wire
DC resistance of wires less than 0.2 Ω/mi (0.1 Ω/km)	0.55–0.7	0.4–0.5
DC resistance of wires less than 0.8 Ω/mi (0.5 Ω/km)	0.65–0.75	0.65–0.75
DC resistance of wires less than 1.6 Ω/mi (1.0 Ω/km)	0.8–0.9	0.8–0.9

currents. Such shielding factor contributors for telecommunications cables are as follows:

- *Type of metal shield* on the telecommunications cable. Whether the shielding is copper, aluminum, or has iron properties, the type of shield can have significant impact on the magnitude of induced current.
- *Location of the shield* with respect to the faulted or receptive cables.
- *Earth resistivity* affects the amount of current in the faulted and recipient conductors. When earth resistivity goes up or down, it goes up or down for both power and telecommunications cables, making only minor changes in total affect.
- *Impedance of shielding circuit* should be as low as possible because shielding improves as more grounds are added.
- *Shielding circuit reactance* is dependent on the other components of the system such as coupling capacitance and inductance.
- *Mutual impedance* can be changed by adding induction mitigation components that are designed to effectively reduce induction on the recipient conductor.
- *Frequency* contributes to the impedance of the circuit, and depending on whether fault current (changing frequency component) or normal power flow (constant frequency) current is in question, frequency is usually not a controllable factor.

Refer to IEEE Std. 367-2002 for more information on shielding.

Table 3.9
Alpeth Telecommunications Cable (Jacketed Aluminum Shield Polyethylene, Commonly Used Today)

	DC shield resistance		60 Hz shield factor for given Z_T/L			
Cable size	(Ω/kft)	(Ω/km)				
			1.0	0.2	0	(Ω/kft)
			3.28	0.656	0	(Ω/km)
11 pair 26 gauge	1.34	4.40	0.99	0.98	0.97	
300 pair 19 gauge	0.28	0.92	0.97	0.90	0.80	

Table 3.10
Stalpeth Telecommunications Cable (Jacketed Steel Shield Flooded [Soldered Overlap] Polyethylene Cable)

Primary field		60 Hz shield factor for given Z_T/L			
(V/kft)	(V/km)				
		1.0	0.3	0	(Ω/kft)
		3.28	0.98	0	(Ω/km)
22.9	75	0.95	0.81	0.53	
45.7	150	0.93	0.74	0.47	
68.6	225	0.91	0.72	0.52	

The shield factors for common telecommunications cables are shown in Tables 3.9–3.11.

The shielding factors for steel cables from magnetic fields are typically 0.85–0.9 and are generally better than aluminum, which are typically 0.9–0.95.

Applying Shield Factor

Simply multiply the appropriate shield factor to the calculated induced voltage value to determine the effective induced voltage on the cable.

Table 3.11
Tape-Armored Telecommunications Cable

Primary field					
(V/kft)	(V/km)	60 Hz shield factor for given Z_T/L			
		1.0	0.3	0	(Ω/kft)
		3.28	0.98	0	(Ω/km)
22.9	75	0.84	0.54	0.16	
45.7	150	0.80	0.47	0.13	
68.6	225	0.77	0.44	0.11	
100.6	330	0.74	0.41	0.09	
300.2	985	0.67	0.40	0.11	

TOTAL ELECTRICAL CABLE STRESS

The total electrical stress on a telecommunications cable under fault conditions is the vectorial sum of the GPR and the induced voltage components. During normal operations, GPR is negligible and induced voltage is minimum, and combined, they have relatively negligible effect on telecommunications cable stress. In some cases, the telecommunications cable is in close proximity to the power line, and steady-state induction can have an inverse effect on the communication cable's performance (such as stray currents and noise). Under fault conditions, however, both the GPR and the induced voltage can be high, causing a relatively HV stress on the cable.

This section discusses how the individually calculated GPR and induced voltage are vectorially summed together to obtain the total electrical stress on a telecommunications cable. It is then up to the design engineer to determine if the dielectric strength of the telecommunications cable is adequate to withstand the imposed total electrical stress. Note that in certain situations, either the GPR or induced voltage alone can cause excessive electrical cable stress. For example, induced voltage on a cable can occur without a substation GPR by merely having a cable attached to a power line that is undergoing a fault condition.

Figure 3.27 Vectorial summation of GPR and induced voltages.

Vectorial Summation of GPR and Induced Voltages

For a detailed analysis for metallic telecommunications cables that are subjected to the effects of both GPR and longitudinal induction arising from the same electric supply line fault current, refer to IEEE Std. 487-2007.

The total electrical cable stress is the vectorial summation of GPR and induced voltage according to the following equation:

$$\mathit{Total\ Cable\ Stress} = \sqrt{GPR^2 + \mathit{Induced}^2}.$$

Figure 3.27 shows the graphical equivalent of the total cable stress formula.

Example of Total Electrical Stress on a Cable

Suppose the GPR value is 3058 V, and the longitudinal induced voltage is 1010 V. Find the total cable stress voltage:

$$\begin{aligned}\mathit{Total\ Cable\ Stress} &= \sqrt{GPR^2 + \mathit{Induced}^2}\\ &= \sqrt{(3058)^2 + (1101)^2} = 3220\ \text{V}.\end{aligned}$$

THE ROLE OF PROTECTION ENGINEERS

Whether the protection engineer works in the electric power industry or in the telecommunications industry, working together with full cooperation is highly encouraged. For example, the telecommunications engineer expects realistic data from the power engineer so that GPR and other calculations can be calculated accurately, equipment location distances can be right sized, and safety of personnel is not compromised. On the other hand, the electric power engineer expects the telecommunications engineer to design the telecommunications circuits properly for maximum service reliability and be knowledgeable of the safety practices inside HV environments. Therefore, the telecommunications protection engineer and electric power protection engineer must work together to identify potentially problematic scenarios and determine the proper means for effectively protecting these important telecommunications circuits and assure safe and reliable telecommunications services at all times.

CHAPTER 4

Critical Telecommunications Circuits in HV Environments

LEARNING OBJECTIVES

- Discuss service performance objectives (SPOs) when it comes to service reliability expectations
- Describe how the smart grid applications view circuit reliability
- Apply the proper Class of Service to meet the desired level of performance
- Describe the power company's primary circuit applications and associated Class of Service
- Describe supervisory control and data acquisition and energy management applications and explain the expected type of service

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High Voltage Protection for Telecommunications, First Edition. Steven W. Blume.

GENERAL

This chapter discusses the importance of telecommunications circuits used in electric power systems, their applications, and expectations for the benefit of the telecommunications protection engineer who might not be fully familiar with the critical nature of these important power industry circuits. Further, this chapter discusses the types of circuits, standard protection expectations, and telecommunications terminology for the benefit of the electric power engineer/electrician who might not be fully familiar with telecommunications facilities. Each individual, whether from the telecommunications or electric power industry, should recognize the importance of working together to properly coordinate and protect all the telecommunications circuits used in high voltage (HV) environments (the same is true in other critical circuit industries, such as police, fire, 911, and the military, that utilize telecommunications sites that are vulnerable to power faults and lightning strikes).

Electric power systems require highly reliable telecommunications circuits in various forms and applications to maintain grid system integrity. The most critical telecommunications circuits used in power systems are those involving protective relaying (mentioned in Chapter 2) where it is essential to send transfer trip signals to other substations to open critical circuit breakers stopping the flow of short-circuit energy as fast as possible. Next in importantce are the system control center circuits used to communicate with power plants, substations, and major consumers involving a supervisory control and data acquisition (SCADA) system. These SCADA circuits are also used for alarm monitoring, power grid control, and energy management.

Now, the new “smart grid” energy efficiency management movement is an extension of these SCADA circuits involving high reliability. In addition to high reliability requirements, cyber security is playing a prominent role in today’s telecommunications services involving HV environments.

SERVICE PERFORMANCE OBJECTIVES (SPOs)

When referencing electric power telecommunications circuits, the term reliability is often used to mean circuit availability in time of critical need. Depending on whether a circuit is used for critical protective relaying functions, SCADA, or basic telephone service, the circuit designation, the "SPO," is a key factor when referring to the importance of a telecommunications circuit. Once the circuit's SPO is established and the electrical environmental parameters are identified (GPR, zone of influence, etc.), the circuit design parameters for proper protection, equipment requirements, and installation objectives can be established.

The circuit application and mutual understanding between the subscriber and telecommunications service provider determines the applicable SPO and associated protection equipment requirements. The basic question in determining the SPO is can the circuit be interrupted during a power fault or lightning strike? The answer to this question creates three classes of SPOs, those being Class A, Class B, and Class C as defined in IEEE 487-2007™. Based on the chosen SPO and the electrical environmental parameters, the telecommunications circuits' HV protection equipment can be designed, safely installed, and maintained.

The telecommunications circuit must fall into one of the three following SPOs, sometimes referred to as Class of Service.

- Class A: circuits that must function before, during, and after the fault condition.
- Class B: circuits that must function before and after the fault condition but not necessarily during the fault.
- Class C: circuits that can tolerate delay time for a normal repair to restore service.

SPO Class A (Non-Interruptible Service Performance)

Circuits that must operate before, during, and after the fault are considered Class A-rated. These telecommunications circuits are by far the most critical circuits in power systems and other special needs applications such as 911 call centers. They are mostly associated with protective relay schemes or emergency applications. These circuits have a significant influence on service reliability as explained in the succeeding paragraphs. The failure of a Class A circuit to operate during a critical time, even momentarily, can result in catastrophic equipment damage, potentially a major system disturbance/outage and possibly injury to people, or it can result in dropping critical emergency telephone calls that can result in loss of life. Class A circuits often provide alarm information to control centers when they go out of service so that repairs can be initiated immediately.

The system requirements for Class A service often include redundancy to assure reliability. Redundant circuits usually involve physical separation, frequency diversification, alternative geographic pathways, and/or dual equipment methods of redundancy. They usually involve two completely independent telecommunications systems (fiber, microwave, or power line carrier) and rigorous scheduled/planned maintenance activities just to ensure complete reliability for the equipment connected to these Class A circuits.

It should be noted that Class A circuits are so important to a power company that they (the power company themselves) install Class A circuits on their own telecommunications equipment just to assure reliability and immediate maintenance response to circuit outage alarms. Leased circuits are sometimes avoided due to the critical nature of the circuit application to have spare equipment availability and to insure the sense of urgency with Class A service requirements. Obviously, there are leased circuit providers that meet and exceed the expected service requirements of Class A circuits; however, the aging workforce and downsizing, losing the knowledgeable employees, add to a power company's concern for performance reliability assurance.

SPO Class B (Self-Restoring Interruptible Service Performance)

Class B circuits are less critical than Class A; however, they remain extremely important to the reliable operation of an electric power system or other important application (police, fire, etc.). *Class B implies that the circuit operates before and after the fault but not necessarily during the fault.* The types of power system equipment that rely on Class B performance usually include SCADA, remote metering, automation control (smart grid), and emergency telephones.

These circuits normally self-restore immediately after the fault. The communication circuit protectors such as carbon blocks and gas tubes, discussed in more detail in the next chapter, fire (operate) during power faults and lightning strikes and short out the telecommunications signal during the event, returning the circuit to normal operation immediately after the event clears. Applications that are designed for Class A service cannot operate in a Class B mode. However, the other way is permissible; applications designed for Class B can operate in Class A mode.

SPO Class C (Interruptible, Noncritical Service Performance)

Examples of Class C circuit applications are those circuits that can withstand outages and can wait for normal repair times; they include the following: plain old telephone service (POTS) lines, fax lines, and other ordinary telecommunications not critical to the operation of the power system, telecommunications site, or emergency call center.

One important note regarding POTS circuits used for telephones in substations is that such phone circuits cannot tolerate prolonged outages since they provide emergency telephone service in the event of an emergency such as an injury accident. These telephone circuits, especially at remote locations, could be the only means for communicating help during an emergency. Therefore, telephones in HV environments should be considered Class B, not Class C.

NORTH AMERICA ELECTRIC RELIABILITY CORPORATION (NERC) CRITICAL INFRASTRUCTURE PROTECTION (CIP) STANDARDS

The NERC introduced their CIP standards. NERC standards are recognized for bulk power system reliability and define specific obligations of owners, operators, and users of the North American bulk power systems. These standards include a requirement to reliably provide telecommunications systems including cyber security protection. Ensuring that the SPOs discussed earlier accurately describe the utility's actual telecommunications circuits' performance, they do not, however, completely address cyber security protection requirements of NERC.

The NERC CIP standards are currently composed of nine specific titles as listed in the following:

- CIP-001: Sabotage Reporting
- CIP-002: Critical Cyber Asset Identification
- CIP-003: Security Management Controls
- CIP-004: Personnel and Training
- CIP-005: Electronic Security Perimeter(s)
- CIP-006: Physical Security of Critical Cyber Assets
- CIP-007: Systems Security Management
- CIP-008: Incident Reporting and Response Planning
- CIP-009: Recovery Plans for Critical Cyber Assets

The performance reliability standards described in SPO Classes of Service and the cyber threat protection standards described in NERC CIP standards combined state the expectations of modern telecommunications systems and circuits. The risks for cyber breach include such items as false tripping of important circuit breakers, interrupting Class A protective relay circuits, interrupting Class B SCADA circuits, and other critical telecommunication circuits. The goal for the protection engineer is to incorporate cyber secure telecommunications circuit requirements to the various SPO Classes of service.

PROTECTIVE RELAYING SCHEMES THAT REQUIRE CLASS A CIRCUITS

Regarding power industry applications for Class A service, system protection is vital to the stability, reliability, and integrity of large interconnected electric power systems, not to mention power quality, customer service, and energy efficiency. Several protective relay schemes (similar to those discussed in Chapter 2) depend on telecommunications signals to perform their functions. The term “transfer trip” is commonly used to identify protective relay schemes that incorporate highly critical telecommunications circuits. They often require full operation during fault conditions, thus making them Class A-rated. Figure 4.1 shows substation protection equipment used to transfer trip remotely located

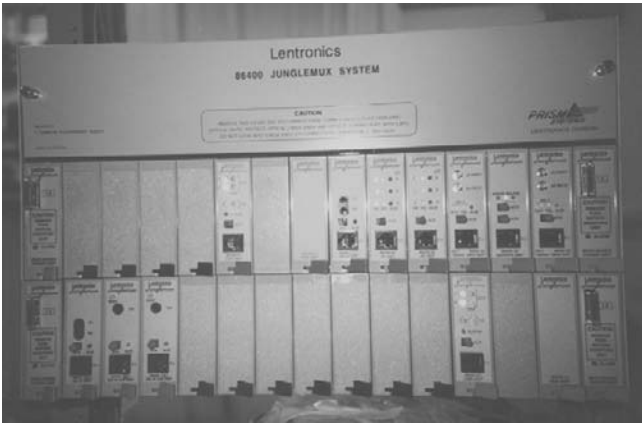

Figure 4.1 Transfer trip equipment.

equipment during a fault. This equipment is connected to other substations via Class A telecommunications circuits.

The following paragraphs explain how critical Class A telecommunications circuits are used in protective relay applications in the power industry. All of the Class A circuit applications listed later are important; the order in which they are presented does not reflect priority. Not all Class A circuits are listed. Some of these relay protection schemes are used in transmission systems including 765 kV.

Zone Relaying

Zone Relaying protection schemes (discussed in Chapter 2) allow transmission line faults that are close to one substation (Zone 1) and far from the circuit breaker at the far end substation of the transmission line (Zone 2) to be cleared as fast as possible. A telecommunications signal is automatically sent from the fast-tripping Zone 1 breaker to the time-delayed far end Zone 2 breaker telling it to defeat the time delay setting and trip immediately. Aside from the actual time it takes for the breaker to open its contacts, the added time delay from the telecommunications signaling equipment is in the order of 4–18 ms (about one cycle in the 60 Hz power frequency). Therefore, with fast signaling speeds and reliable telecommunications, circuit breakers at both ends of a long transmission line are essentially tripped together as the primary protection scheme. Zone 3 protection becomes the backup. The faulted transmission line is then cleared as fast as possible with the help of Class A telecommunications.

Breaker Failure

Breaker failure is another very important and critical protective relaying scheme utilizing Class A telecommunications circuits. As a backup protection scheme, breaker failure relays automatically send trip signals to all breakers that are keeping a failed breaker energized. When a breaker fails to open the faulted power line or equipment, the breaker is said to be in “breaker failure” condition. The only way to protect the power system’s integrity from a breaker failure condition is to de-energize all sources of voltage and current to the failed breaker. This implies that transfer trip signals to multiple remote substations might be sent to de-energize all transmission lines feeding the failed breaker. Thus, highly reliable telecommunications signals are needed to minimize the damage that can result from a stuck breaker experiencing breaker failure condition.

Current Differential or Phase Comparison Schemes

Some of the very high voltage transmission line protective relay schemes use what is called “current differential or phase comparison” protection. This protection scheme breaks down the HV power current sine wave into very small phase angle increments and sends that information to the remote end of the line via a communications path. The magnitude of the current during each phase increment is measured, the measurement is converted into a digital number sample (called quantized), and the digital number is sent to the remote substation where the sample is compared with the local sample. Any significant difference between the two samples will cause the breakers at both ends to trip. This assures high speed or sub-cycle tripping of very high transmission line voltage provided the telecommunications circuit is intact and operational.

Directional Comparison Unblocking Schemes

In a directional comparison unblocking scheme, frequency shift carrier equipment is typically used to provide telecommunications between the two substations connecting the line. This equipment continuously transmits a guard signal on one frequency. When a fault occurs, the protective relay signals the carrier equipment to shift from the guard frequency to the permissive frequency. The receiver at the other end of the line monitors these signals. There is a short transition period in which there is no guard signal and no permissive trip signal received. If the permissive trip signal arrives momentarily, then a normal trip occurs. If the permissive signal does not arrive, then a time window is provided that allows a trip without receipt of the trip signal if the relay itself sees the fault. Notice the importance of needing a Class A continuous circuit during fault conditions.

Mirrored Bits Signaling

Mirrored bits signaling is a protective relay operation assurance scheme that is incorporated into some solid-state protective relays. These relays, for example, swap small packets of data bits back and forth between substations regarding the same transmission line. Data signal integrity proves that the telecommunications channel and protective relays are operating properly; otherwise, alarms are initiated.

Out-of-Step Blocking or Tripping

Out-of-step blocking or tripping protective relay schemes might use telecommunications circuits to send signals to remote substations to block the automatic tripping of certain major intertie connection breakers during a power swing coming from another power utility. It is sometimes more advantageous to block a breaker from tripping if a power swing is detected than allowing the breaker to trip open. Blocking breaker tripping can improve system stability during a foreign power disturbance. The lack of reliable telecommunications could cause the local power system to experience undesirable power system islanding, thus breaking the grid integrity.

Certain power system disturbances may cause loss of synchronism between neighboring utility interconnected power systems. If such a loss of synchronism occurs, it is not only desirable but imperative that the systems separate immediately to avoid widespread outages and equipment damage. An effective mitigating way to contain such a disturbance is through controlled islanding of the power system using out-of-step protection schemes. These complex protective relay schemes require Class A telecommunications service or widespread outages are possible.

Transformer Protection with Remote Breakers

Substation power transformers are often protected by breakers at the far end of a transmission line. A fault in the transformer, for example, may initiate a transfer trip to the circuit breaker at the remote end of the line. This type of protective relay scheme saves the power company money by having the remote breaker protect both the transmission line and the substation transformer. A failure in this Class A telecommunications system could result in the line and transformer not clearing, causing expensive equipment damage due to time delays in backup clearing protection schemes.

Load Rejection Schemes

Telecommunications circuits are sometimes used to send signals to remote locations to trip or drop load. For example, the loss of a generator unit would cause imbalance between load and generation, thus causing system frequency to drop. Load rejection schemes trip load in order to avoid the system frequency drop. Failure of this Class A circuit to reject load can cause frequency instability and likely result in a widespread outage.

Pilot Wire or Line Differential

Pilot wire schemes provide high speed clearing of faults using a telecommunications circuit to compare power line currents at both substations. These pilot wire schemes circulate an actual current that is proportional to the actual line current between substations. Faulty telecommunications circuits having opens, shorts, and/or grounds can be detected and trouble calls initiated. The older pilot wire schemes utilized a continuous copper pair (rated Class A) with no repeaters, multiplexers, and so on, strictly a copper twisted pair between substations.

Audio Tone Protective Relaying

Audio tone protective relaying is a term used to describe any of the power system protective relaying schemes that utilize audio tones to communicate the signaling information between substations. Audio tone equipment can be used for permissive overreaching, transfer trip, breaker failure, and several other protection schemes.

Very secure and reliable signaling schemes are used to assure action through the telecommunications system. In some cases, dual tones must shift frequencies in a certain pattern to trip the remote breaker. Failure to shift frequencies accordingly will not trip the remote breaker. This signaling scheme prevents false tripping, especially during tone injection troubleshooting and maintenance testing. Several audio tone schemes are used for Class A protective relaying and control. Tones are also used to monitor a circuit's integrity by alarming the control center upon loss of tone.

POWER APPLICATIONS THAT REQUIRE CLASS B CIRCUITS

Class B circuits must operate before and after a fault but not necessarily during the fault. Yet, these circuits are considered critical as the applications described below explain their importance.

Electric System Control Centers (ESCCs)

ESCCs such as the one shown in Figure 4.2 operate 24 hours a day, 7 days per week, 365 days per year, and so on and never close, making sure the electric power system within their control area is operating properly, maximizing service reliability, and minimizing energy cost. ESCC system operators monitor, control, balance generation, and

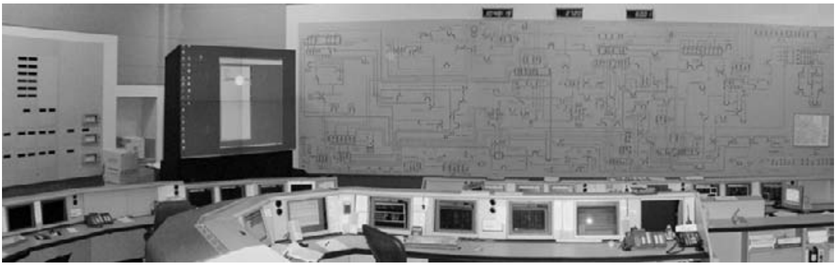

Figure 4.2 Electric system control center.

utilize real-time reports produced by ESCC equipment. System operators are always looking for signs of possible problems (situational awareness) and take immediate action to avoid major system disturbances should an important warning sign occur. Operators are tasked with the responsibility to maintain system connectivity, reliability, and stability, and provide continuous service at the least cost, and SCADA provides that capability.

ESCCs are the nerve centers in the grid operation and depend almost entirely on a reliable telecommunications network. ESCC operators monitor displays of information coming from remote terminal units (RTUs), which, in turn, rely on their telecommunications circuit to feed updated information to the ESCC. A telecommunications circuit failure causes a failure for the ESCC operator's display to update critical information about the status of equipment. Failure to display system updates implies running the system blind and not having any control of the equipment on the opposite side of the telecommunications circuit.

SCADA alarms alert the system operator that a change of state occurred at a substation, generation plant, important energy consumer, or other critical situation information occurring on the power grid. SCADA usually gives the operator full control to change the state back to normal, provided the power fault, if any, has cleared. If a circuit breaker trips due to a power fault on the line, for example, an operator receives an alarm from one of the SCADA's RTU that the circuit breaker is now open. The operator, via SCADA, closes the breaker waiting to see another SCADA alarm come in stating that the breaker status is now closed. This feedback indication technique is inherent in the SCADA system. This two-way telecommunication is made possible by the telecommunications circuits.

One of the unfortunate situations that occurred during the wide-scale New York blackout was the failure of some telecommunications circuits to update ESCC operators. Some telecommunications circuits became inoperative when critical telecommunications equipment became unpowered in the outage (lack of DC backup power). The control operators thought some substation breakers were closed when in actuality, the breakers were open, not allowing power to flow. The center's main computer did not update the operator's screen due to lack of SCADA updates. Incorrect grid operation decisions can happen, making matters worse in situations similar to this. SCADA circuits not only have to restore after a fault (Class B) but must have battery backup in case alternating current (AC) power is lost. Furthermore, with NERC CIP enforcement, cyber security provisions must be incorporated.

The main reason why SCADA circuits are not Class A is because the ESCC's main computer scans its RTUs sequentially. A typical scan of all remotes might take a few seconds, and displays are therefore updated every few seconds. Momentary communications circuit outages might miss an update; however, the update will occur on the next scan. Should a power fault or lightning strike take out a SCADA telecommunications circuit for an extended period of time (i.e., hours), ESCC operators not knowing the correct status could aggravate the system disturbance and outage situation. If they know there are problems with telecommunications circuits, they might send employees to those RTU locations or perhaps activate their backup control centers.

SCADA is also used for the power company's energy management system (EMS). The EMS provides system control operators with several software tools to help them look ahead at possible system conditions (i.e., determine worst-case scenarios in real time) should something else go wrong with the power system. The EMS provides prediction capability, state-of-the-system sensitivity analysis, state estimation should field crews need major equipment outages for maintenance, and so on. When the ESCC main computer isn't properly updated, inaccurate results occur on the software tools.

When problems occur on telecommunications equipment or control center equipment, system operators must occupy backup control centers in order to resume monitoring and control functionality of the power system. Most backup control centers have full functionality and backup emergency generators with uninterruptible power supply (UPS) systems and redundant Class B telecommunications circuits.

International Electrotechnical Commission (IEC) 61850 was established for the standard design of electrical substation automation devices. This standard defines specific signal protocols, data mapping, high interoperability between different equipment vendors, storing of data, and testing requirements for electric utility SCADA systems. Therefore, as a minimum, SCADA circuits must perform to IEEE Class of Service (i.e., "B"), NERC cyber security, and IEC 61850 for equipment compatibility. The HV protection of these telecommunications circuits for circuit reliability is integral to these other performance and security requirements.

Figure 4.3 shows the equipment comprising the SCADA system, including the control center, RTUs, and telecommunications equip-

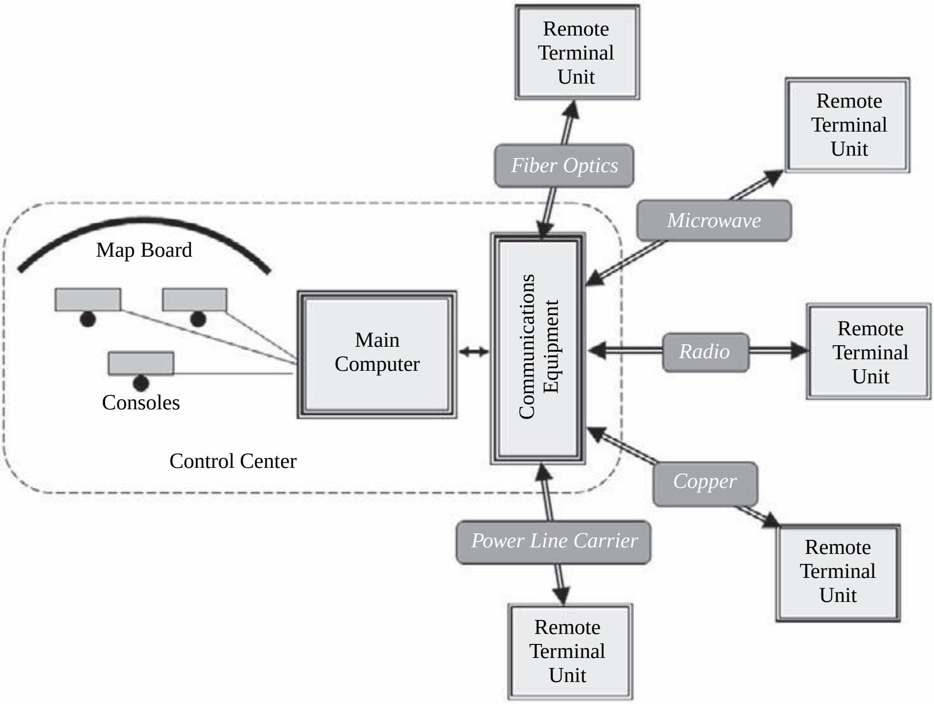

Figure 4.3 SCADA system.

ment. Notice the map board, the main computer, and the various telecommunications systems that depend on the information coming from all RTU telecommunications circuits.

Other Class B Power Circuit Applications

Each electric utility has several special telecommunications circuits that require reliable service. Some examples of other Class B applications are below.

Remote Control, Indication, and Metering

Electric power companies frequently use dedicated Class B circuits to control emergency generators, intelligent electronic devices (IEDs), power switches, motor-operated disconnect switches, and interruptible power devices such as transfer switches and several other important controllable devices. Remote indication and metering applications are also very common among electric utilities. Hydropower plants might need them for turbine gate position, water level indication, security intrusion, and so on.

Advanced Metering Infrastructure (AMI)

AMI is a spin-off from automatic meter reading (AMR) and is part of the smart grid movement. AMR used telecommunications circuits to automatically read data from electric, water, and/or gas meters and transfer those data to centralized data centers for billing and/or analysis. AMR saved companies money by minimizing meter reader employee costs and obtained useful consumption information that led to improved energy conservation, billing plans, and more accurate load growth projections.

Utilities quickly took advantage of two-way telecommunications and moved toward advanced metering and demand control technologies under the label of AMI. AMI continues to use leased telecommunications circuits; however, many systems also incorporate wireless communications. Class B, and even Class C, telecommunications circuits are becoming more and more integrated into power system operations for AMI.

Outage Management and Demand Management Systems

Power utilities are using two-way telecommunications circuits to expedite damage assessment, eliminate fault dependent outages, and enable unmanned intervention of power operations. Dynamic load management helps building energy management (BEM) systems utilize real-time information from the power companies to reduce their energy cost. Graphical information systems (GIS) communicate with the utility's EMS and outage management system to identify outage location, probable equipment at fault, number of customers affected, and so on. These communications circuits are not highly critical (Class A) but are considered to have Class B reliability requirements.

Notice how all Class B circuits located in HV environments require high voltage protection (HVP) for reliability in the event of a power fault or lightning strike!

Class C Circuit Applications

Class C SPO implies that the circuit application can withstand normal service restoration, including calling for service repair, testing, and technician travel time. These are low priority applications. Power company circuits of Class C include a very limited number of phones, metering devices, and data recorders. Most metering circuits convey energy consumption information and can be delayed to a reasonable amount of time. Long metering circuit outages could result in consumer complaints from unexpected billing amounts and incorrect generation cost and control assessments.

Note that situations arise where electric utilities order a simple phone circuit for a substation and a Class C POTS circuit is installed. Cooperation should occur between telecommunications and power services to inform each other that a circuit is going into an HV environment. Otherwise, an unprotected circuit (including Class C) could be installed in an HV environment and be vulnerable to damage and personnel injury.

POWER COMMUNICATION SERVICE TYPES

IEEE Std. 487-2007 provides excellent general descriptions of most communication service types used in the power industry. Circuit types are categorized by whether they require AC or DC signals, continuous copper wire (no multiplexing), AC tones signaling, and what they are used for (SCADA, protective relaying, etc.). Some of the older communication circuits that require metallic conductors end-to-end are also discussed. Electric utilities realize that the availability of all-metallic circuits is passé or obsolete, making it very difficult to obtain continuous copper circuits unless they are installed privately.

Modern telecommunications circuits can only pass analog AC tones, digital in the form of analog tones (i.e., modems), digital carrier systems (T1, high speed digital subscriber line [HDSL], etc.), or, now, Internet protocol (IP)-based telecommunications. These changes in telecommunications technology over recent years have made the importance or significance of “service types” more or less obsolete. However, some modern digital telecommunications systems have issues with synchronization that can have an impact on Class A and B circuits. Some types of digital equipment (HDSL, T1, etc.) reboot during fault conditions, causing momentary circuit outages sufficient to preclude Class A operation.

Some of the more popular telecommunications circuits used in the power industry today are described in the next section (refer to IEEE Std. 487-2007 for more detailed descriptions and other pertinent information). Keep in mind that these circuits must be properly protected.

POTS

The functionality of simple two-wire twisted pair copper circuits that are used for basic dial tone telephone service are referred to as POTs circuits. They provide bidirectional, full-duplex, voice band telecommunications services with a limited frequency response of 300–3400 Hz. They are sometimes referred to as “subscriber loop” circuits and are typically powered by –48 VDC by the central office (CO) equipment.

Private Branch Exchange (PBX)

Some companies use private telephone systems (similar to public telephone systems except owned and maintained by the private company) and need an extension to an HV location (substation). This is a very common application. Most PBX systems have dial tone. It is possible, however, to have dry pairs (i.e., non-dial tone) from the PBX location to an HV location. This non-dial tone line could also be used for other applications, such as metering.

Automatic Ringdown

A dedicated private utility nonswitched service between two or more specific telephone stations is called “automatic ringdown.” Service is provided the moment the phone is off-hook, and uses abbreviated dialing to activate the ringing generator at the far end. When a station goes off-hook, the equipment rings the other station(s). This is similar to a hot phone between control centers for fast connections to convey emergency information quickly.

Four-Wire T1 Carrier

T1 services are very popular in HV environments. Wireless cell sites and power companies use them for data and multiple phone lines. These four-wire full-duplex facilities with dedicated transmit and receive pairs operate at 1.544 Mb/s.

Four-Wire and Two-Wire HDSL

HDSL is a repeaterless extended data service operating as full-duplex 1.544 Mb/s data rate over four-wire or two-wire twisted pair facilities.

Two-Wire Asymmetrical Digital Subscriber Line (ADSL)

ADSL is an analog POTS telecommunications service providing both voice and data. ADSL is a method of combining low frequency voice signals (under 4 kHz) with high frequency data signals of up to 8 Mb. Data uses high frequency analog modems (tones) to communicate the high speed data rates.

Modem Signaling: 56 kb/s POTs

Analog data modems connect between locations using POTS the same way telephone calls are established. Once the modem establishes the connection, the modem negotiates data rate based on line quality and modem capability. Power companies often use these circuits for SCADA.

The service types that are described in detail in IEEE Std. 487-2007 are still used by several telecommunications and power companies. However, some of these service types may not be available, though their definitions are listed below for reference purposes.

Service Type 1

Service Type 1 are private line services requiring either DC transmission or AC and DC transmission. They are used for the following applications:

- Basic telephone services using a private line, voice telephone, and CO exchange trunking service.
- Teletype, telemetering, SCADA, and so on.

Service Type 2

Service Type 2 are private line services requiring AC or DC transmission or both, used for pilot wire protection relaying or DC tripping.

Service Type 3

Service Type 3 are private line services requiring only AC transmission used for telemetering, supervisory control, data, and so on.

Service Type 4

Service Type 4 is a private line service requiring only AC transmission used for audio tone protective relaying.

Reference to these service types is becoming obsolete because they refer primarily to the older type of telecommunications services.

SMART GRID AND CYBER SECURITY

Smart grid refers to having the electric power grid utilize digital technology to improve efficiency of power grid's generation, transmission, distribution, and consumption. Smart grid technology utilizes two-way telecommunications circuits of all types (copper, fiber, wireless, and power line carrier) and applies SPO Classes A, B, and C as an integral, strategic part of the telecommunications network. Dependency on reliable and now cyber secure telecommunications systems has never been higher. Mixing the critical need for Class A and B services, smart grid is now adding more dependency and security to the telecommunications network serving over the nation's power grid. The smart grid movement is gaining a strong power industry foothold because many governments see it as a way to address energy independence, energy demand reduction, and electrical operations efficiency. With years of needing more large-scale power plants, transmission lines, and energy conservation tactics to keep up with demand, smart grid deployment is being implemented everywhere to help cover all these needs.

Smart grid concepts and technologies overlay on the ordinary power grid to make it more efficient and at the same time, to address load growth requirements. A smart grid delivers electricity to consumers while using two-way digital telecommunications to control load consumption in industrial, commercial, and residential buildings. Smart grids incorporate smart meters, voltage/frequency sensing equipment, intelligent electronic devices (IEDs), and many other technologies and devices, all with the need for reliable telecommunications. It also uses telecommunications circuits for automatic metering reading and customer information telecommunications to save operating costs.

A smart grid is made possible by applying sensing, measurement, and control devices with two-way telecommunications. These devices and circuits communicate important information about grid condition, remote operation of switching devices, and making the power grid system dynamic and responsive to planned and unplanned changes in grid conditions. SCADA is the foundation system for smart grid.

Distributed Generation (DG)

DG refers to having several small and large independent generators connected to a power system. DG is a practice that is growing fast. Residential and commercial solar and wind emergency power generators that are used during peak energy demand times and strategically placed independent generators help improve power grid voltage control and at the same time reduce system losses due to being close to the load centers. Transfer trip telecommunications for DG is also used if the independent generator is feeding into a fault and can be used to block a generator that is trying to return to online status following a fault event. Similar to the power system, control centers operate multiple power plants remotely by using telecommunications. Increased dependency on reliable Class A, B, and C services is growing.

Utility Automation

The IEC standard for utility automation, IEC 61850, states that reliable messaging is essential. For example, an electronic message initiated by a device (such as a protective relay and power quality monitoring device) is broadcasted on a telecommunications network to signal that an event has occurred. Receivers of the message are programmed to react in some manner as a response. The responses could be circuit breaker trips, blocks, change settings, or others. This broadcast message (sometimes referred to as a "GOOSE" message) usually stays within the substation network. However, it could be used across a wider network, such as between substations or between a substation and a power plant with the growing use of Internet with cyber security.

Basically, all circuits and systems associated with IEC 61850 telecommunications within a substation and (if applicable) between substations need reliable telecommunications. The use of IEC 61850 capabilities in the substation and the more and more protective relay functions adopting IEC 16850 will be transmitted via reliable telecommunications circuits. This puts several equipment items not normally thought of as "telecommunications" in the power world into the equation such as Ethernet hubs, switches, cables, and the like.

The bottom line is that smart grid two-way telecommunications, especially those circuits and applications under IEC 61850 require reliable telecommunications set forth by proper HV protection under power fault and/or lightning strike conditions.

IP in the Smart Grid

IP (synonymous with the World Wide Web) is now becoming one of the greatest shifts in the power industry. IP is widely used in the electric power industry. Utilities are embracing this technology for smart grid applications. Circuit reliability and security become critical when power companies depend more and more on IP technology.

CIP

CIP is also becoming a major component in reliable telecommunications networks for power companies. Government-enforced mandates for cyber secure networks are also becoming a key element in utility telecommunications. Not only are utilities needing reliable telecommunications such as Class A and B, they are required to have these circuits cyber protected. Will there be a new class of SPO’s cyber security?

CHAPTER 5

High Voltage Protection Equipment

LEARNING OBJECTIVES

- Explain the concepts, characteristics, and application of shunt protectors
- Describe how mutual drainage reactors are used to minimize longitudinal induction
- Describe and apply the three levels of protection
- Discuss the design objectives for individual components used in high voltage interface (HVI) systems
- Explain when high voltage (HV) isolation protection should be used instead of shunt protection
- Describe where shunt protectors should not be used
- Describe the equipment associated with copper cables crossing the zone of influence (ZOI)
- Describe the equipment associated with optical fiber cables crossing the ZOI
- Explain how older isolation systems work and discuss their limitations
- Describe the differences between high dielectric cable and general purpose cable

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High Voltage Protection for Telecommunications, First Edition. Steven W. Blume.

GENERAL

Proper high voltage protection for telecommunications (HVPT) involves several specific design considerations for reliable telecommunications service under fault conditions and safety of personnel during installation and maintenance. This chapter starts out by describing the common types of telecommunications protection system components available and used with regard to the industry standards and best practices. It describes their functions, ratings, and proper applications. The chapter ends with an explanation of the three levels of telecommunications circuit protection that are based on ground potential rise (GPR) values. Chapter 6 is devoted strictly to Level III protection dealing with HV isolation.

BASIC SHUNT PROTECTION

Most telecommunications circuits are protected against HV transients using shunt-type protectors. Shunt protectors are electrically connected across copper pair wires and earth grounding conductors. These shunting devices operate (fire) when the circuit transient peak asymmetrical voltage (PAV) exceeds the threshold value of the device. When PAV reaches approximately 300 V or greater, these shunt devices fire and all conductors connected to shunt protectors (i.e., tip, ring, and ground) get connected together and grounded. Thus, all wires connected to shunt protectors are temporarily grounded together during a GPR event. The shunt device later opens after the fault clears, no longer connecting all wires together, and the circuits are ideally restored back to normal.

One of the primary concerns for properly designing and installing HVPT equipment of all types and conditions is to avoid situations where shunt protectors are used in high GPR environments where protector firing (operation) causes high GPR voltages to be connected to sensitive electronic equipment at the other end of the cable. Improperly applying shunt protection can result in dangerous situations. The purpose of this chapter is to help the reader know when to apply shunt protectors and when to apply isolation protection.

The following section discusses the purpose and design parameters of the more common types of shunt protectors. After the individual components are discussed, they are grouped into levels of protection with explanations. For more information on shunt protector specifications, performance characteristics, and wiring practices, refer to IEEE Std. 487-2007™.

Circuit Protectors

Circuit protectors are used to stop HV transients from lightning strikes and nearby power faults from damaging sensitive electronic equipment that is connected to the copper cable pairs. Circuit protectors are available in different styles, but their main purpose is to short out (zero potential) the telecommunications circuit pair to ground during a transient voltage event. Shorting out the circuit pair during transient situations essentially blocks transient voltage from entering the input terminals of sensitive electronic devices. There is a limit to the amount of transient voltage at which the shunt protector system is designed to work, typically 1000 V GPR. GPR in excess of approximately 1000 V could cause protector failure and other equipment damage (this is explained in more detail later in this chapter).

Brief descriptions of the common style shunt circuit protectors are described in the following:

- Carbon block protectors are composed of two carbon blocks with an air gap between that sparks over at a particular voltage. Depending on the gap separation, spark over voltages vary. They typically have a nominal 60 Hz root mean squared (rms) spark-over voltage rating of 350 V, a peak rating of 500 V, and a surge peak spark-over voltage rating of 700 V.
- Gas tube protectors (also known as discharge tubes) are a ceramic or glass envelope containing metal electrodes surrounded by inert gases that rapidly conduct high currents when the flashover voltage rating between the electrodes is reached. Gas tubes are similar to carbon block protectors; however, gas tube types normally have higher current ratings. They offer almost infinite open-circuit impedance under normal conditions and very low impedance during firing conditions. Gas tubes fire at a nominal voltage of approximately 300 V rms. Note that the flashover or breakdown voltage drops a small amount after every occurrence.

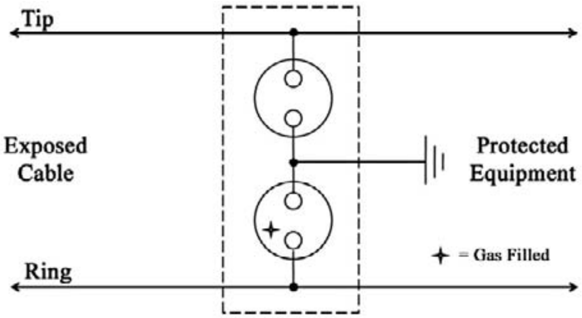


Figure 5.1 Dual two-element gas tube protector.

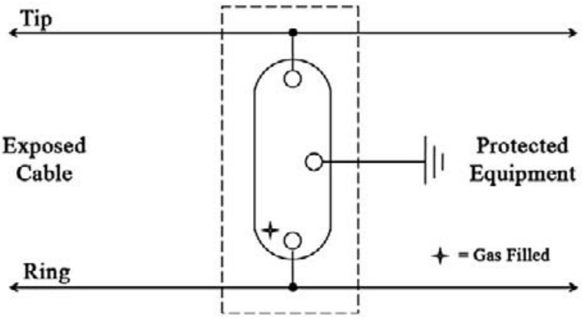


Figure 5.2 Three-element gas tube protector.

Figure 5.1 shows the dual two-element gas tube protector, and Figure 5.2 shows the three-element gas tube protector. The three-element protector is preferred over the dual two-element protector because it minimizes transverse currents under fault transients when one protector fires faster than the other (hence better balance characteristics).

- Solid-state protectors shown in Figure 5.3 are of newer technology than gas tubes and carbon blocks. These protectors provide both high speed voltage limiting and sensing functionality. Solid-state protectors fire at approximately 300 V rms.
- Solid-state hybrid protectors as shown in Figure 5.4 combine the functionality of both gas tubes and solid-state protectors. The solid-state protectors fire first and are last to release the circuit. The solid-state protectors start clamping over voltage at approxi-

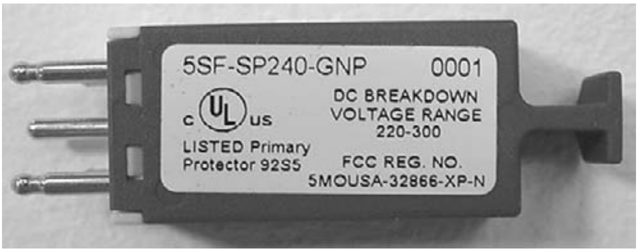


Figure 5.3 Solid-state protector.

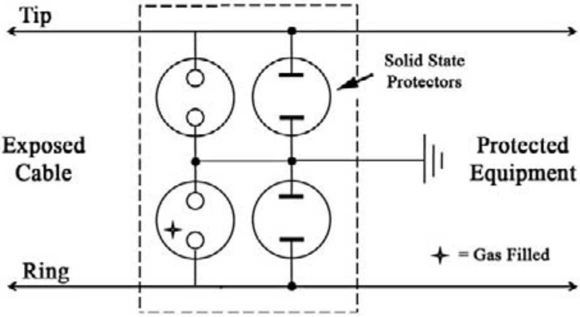


Figure 5.4 Solid-state hybrid protector.

mately 2 ns and are limited to 100 A. The gas tube portion is rated approximately 5000 A. These hybrid connectors offer fast action and high current ratings.

- Spark gaps (not shown) come in fixed and adjustable styles and have two electrodes with air dielectric spacing. They can be adjusted to coordinate with power system exposure by selecting electrode material and shapes. Charts are used to determine the flashover voltage compared with its gap length.

Mutual Drainage Reactors (MDRs)

Drainage reactors, sometimes called “mutual drainage transformers” or “MDRs,” are noise mitigation devices that provide a path to ground for extraneous longitudinal currents on a pair of telecommunications conductors without significantly disturbing the metallic signal path. In other words, they are used to cancel undesirable induced currents from an adjacent power line. Figure 5.5 is an example of an MDR

Figure 5.5 Mutual draining reactor. Courtesy of Positron Inc.

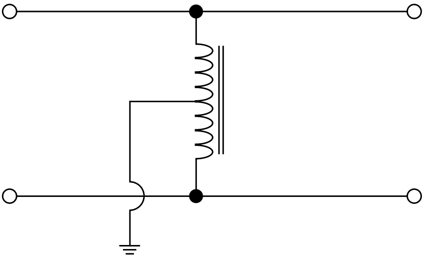


Figure 5.6 Mutual drainage reactor.

(longitudinal implies that the telecommunications cable parallels the power line for a relatively long distance). These units are made of two coils wound on a single magnetic core. When the two coils are connected in series across the conductors of a telecommunications pair with the center point grounded as in Figure 5.6, the configuration presents high impedance to differential mode signals and a low impedance to ground for common mode signals. Differential mode signals imply voice and data, whereas common mode signals implies alternating current (AC) power station hum, longitudinal induction and balanced current.

"Direct drainage" is the term sometimes used to refer to this configuration (Fig. 5.6). Direct drainage is also used to help force the simultaneous firing of shunt protectors that are also connected to the same telecommunications circuit pair.

Most MDRs are inductive and are typically used only in voice frequency applications. The inductance could impact the high fre-

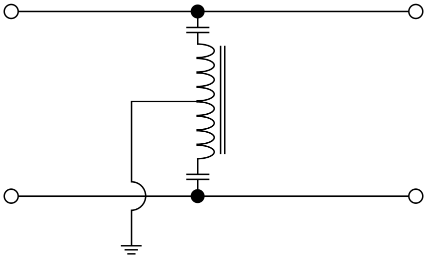


Figure 5.7 Gap drainage protector.

quency signal of some digital circuits. As a best practice, MDRs should be used on Class A voice circuits to minimize common mode noise and improve circuit reliability especially during power fault events.

The configuration in Figure 5.6 works well with totally AC signals. When both AC and DC span power are present on the pair, a drainage reactor with a gap protector in each leg should be used; see Figure 5.7. The gap blocks the DC currents from the low impedance ground. When the gap protector fires, it allows draining of the common mode signals while enabling DC power circuits to still function after the event clears. Another way to block DC power is to use blocking capacitors instead of gap protectors. The blocking capacitors block DC and still pass high frequency AC (that being the power fault or lightning event).

A note regarding dedicated copper cables crossing the ZOI where the shield is not grounded at the substation ground grid: Drainage might be required at the remote end (300-V point and central office [CO] mainframe) if the available fault current at the substation is very high (high induction onto the telecommunications cable), when the induction voltage exceeds 300 V peak and Class A services are present, or when induction exceeds 1000 V peak and no Class A services are present.

LEVELS OF PROTECTION

All telecommunications circuit pairs must be protected to the highest class/level needed at the HV location. IEEE Std. 487-2007 classifies telecommunications circuit protection into three basic levels depending on the magnitude of GPR and protection equipment isolation capability.

The IEEE Std. 487-2007 standard levels of protection are as follows:

1. ***Level I.*** GPR voltage is less than 300 Vpeak asymmetrical (VPA). When the GPR is less than 300 VPA, shunt protectors are not supposed to fire and all service performance objectives (SPO) Classes A, B, and C apply. Regarding Level I Class A protection, this 300 VPA constraint applies to both power faults and lightning strikes.
2. ***Level II.*** GPR voltage is greater than 300 and less than 1000 VPA. The GPR is greater than the firing voltage level of a shunt protector and is less than the presumed insulation failure voltage of the device. When the tip and ring short to ground, the telecommunications signal is disabled. This is not acceptable for Class A circuits and is acceptable for only Class B and C circuits. Unless the shunt protector is damaged, these protectors return to open-state (short-removed) condition soon after the HV event is cleared.

   Another important factor to note regarding Level II protection is the limitation of the protector block insulation strength or the maximum peak voltage withstanding rating between connection terminals (pins, studs, screws, posts, strip, or other form of twisted pair conductor termination). Several termination blocks have flashover ratings of approximately 1000 V. In other words, should the GPR significantly exceed the isolation flashover voltage rating of the block (wire next to wire terminals), the protector block itself could be damaged by exceeding its insulation strength. This applies to the copper cable termination blocks, protector sockets, and the protectors themselves.
3. ***Level III.*** GPR voltage is greater than 1000 VPA.

When GPRs are greater than 1000 V, HV *isolation* equipment is required. There are several ways to provide HV isolation from high GPRs. The two HV isolation systems discussed in this book are fiber and copper cables crossing the ZOI. There is nothing stopping one from using other forms of HV isolation such as radio, microwave, satellite, and power line carrier.

Most copper-based HVI systems can provide circuit isolation up to approximately 90 kV asymmetrical peak. Fiber-based HVI systems approach infinite isolation values when their copper/fiber interfaces are properly installed.

Note that GPR voltages in excess of 1000 V could damage shunt protectors and blocks. Therefore, it is not recommended to install standard telecommunications shunt protectors on installations having GPRs in excess of 1000 V (hence, Level III). GPRs that are much greater than 1000 V could severely damage equipment and potentially cause injury to personnel. Further, they are an attractive nuisance, meaning that inexperienced telecommunications technicians might use the CO side shunt protector block for testing purposes, not knowing that a dangerous situation might arise should there be a power fault or lightning strike occurrence at the same time.

Basic Protection Level I

Basic Protection Level I applies to cable stress situations having a combined GPR and induced cable stress below 300 VPA. Level I protection can accommodate all SPO Classes of service (A, B, and C).

Environments that have virtually no GPR or induction concerns (i.e., under 300 V) and are not in any ZOI often do not use shunt or isolation circuit protection. However, basic (i.e., shunt-type) protection is required by the National Electric Code (NEC®) at buildings, residences, and other communications facilities. The telecommunications service provider might have a standard practice to install shunt-type protection at all important locations or circuit types such as office buildings, long distance loops, four-wire data circuits, and so on regardless of the GPR or cable stress voltage. Having Level I conditions implies that no pair-to-pair or pair-to-shield dielectric failure/breakdown is expected to occur in cables or equipment exposed to 300 VPA or less.

A major problem occurs when companies standardize on protecting important locations or circuit types and they inadvertently end up in a high GPR location. The equipment is destined to failure.

Figure 5.8 shows the diagram of the IEEE Std. 487-2007 Level I protection for all SPO Classifications. Note the gapped shunt protection on both ends of the general use cable circuit. (Note 2 on the IEEE

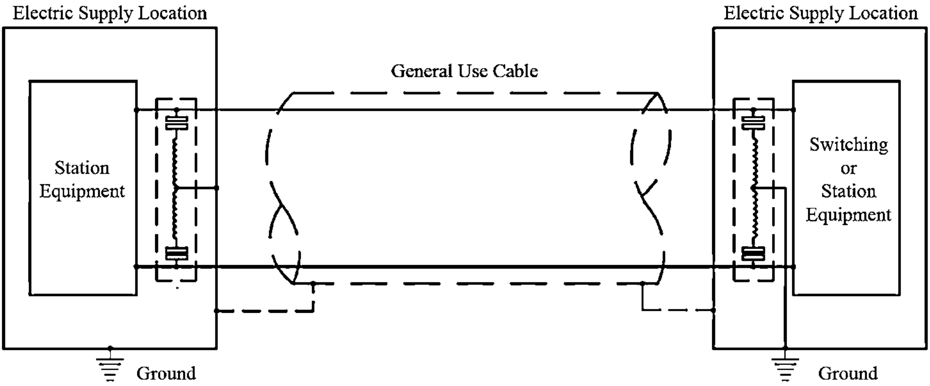


Figure 5.8 Basic protection level I equipment plan.

standard drawing states, "Some telephone administrations may require that shields of all general use cables be grounded at electric supply locations. If that is the case, then current carrying capacity of the shield conductor under power system fault conditions should be considered.")

Basic Protection Level II

Basic Protection Level II applies to cable stress situations having a combined GPR, and induced voltage of 300–1000 VPA. Level II protection can accommodate SPO Class B or Class C services.

The IEEE Std. 487-2007 recommends basic protection level II equipment configuration shown in Figure 5.9 if the GPR or cable stress voltage is greater than 300 and less than 1000 VPA. This scheme should provide a suitable safety margin below voltage and current levels that would otherwise cause telephone-type protectors to fail. Since shunt protectors are recommended for Basic Level II protection and GPRs can exceed 300 V, then this scheme only applies to SPO Class B or Class C.

Experience has shown that the protective devices at Level II will recover after a fault and will restore the circuit to normal. Furthermore, the current through the conductors during the fault should not cause damage to the conductors or to the cable's insulation.

Some authorities allow the upper limit to be 1500 VPA if shunt protection is used. This is sometimes the case at the junction of the

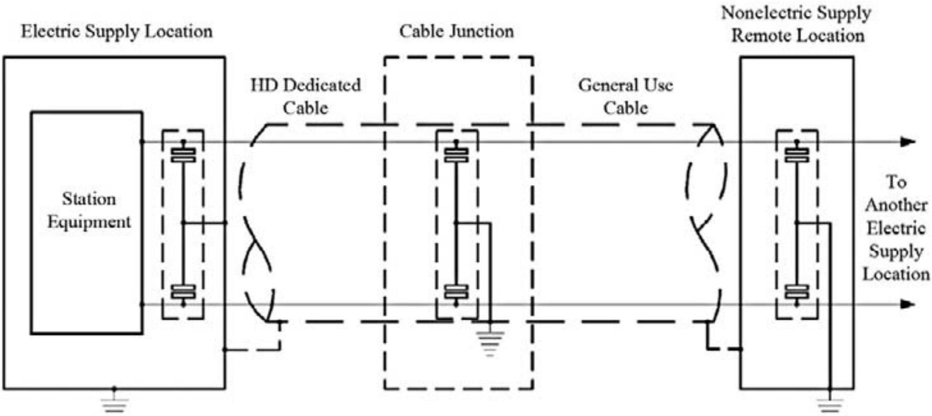


Figure 5.9 Basic protection level II equipment.

dedicated and general use cables. The upper limit of 1000-V peak is suggested if remote shunt protection is not used.

Figure 5.9 shows the basic protection equipment for Basic Protection Level II. Notice the use of high dielectric dedicated cable. Notice the shunt protection at both ends of both the dedicated high dielectric and general use cables. (Note 2 on the IEEE drawing states "Some telephone administrations may require that shields of all general use cables be grounded at electric supply locations. Current carrying capacity of the shield under power system fault conditions should be considered.")

Basic Protection Level III

Basic Protection Level II applies to cable stress situations having a combined GPR and induced voltage above 1000 VPA. Level III protection can accommodate all SPO Classes of Service (A, B, and C).

Level III requires HV isolation equipment.

Level III protection has circuit integrity for all SPO Classes (A, B, and C). Level III protection can use various means of isolation, fiber optics (IEEE Std. 1590-2009™), copper wire HVI (IEEE Std. 487-2007), and wireless radio circuits. Only fiber and copper Level III systems are discussed in this book. (Note that Level III protection can be used for all levels of protection, including Level I.)

From a *copper cable across the ZOI* standpoint, Level III protection configurations consist of an HVI device at the electric supply location (ESL) and a dedicated high dielectric telecommunications cable used across the ZOI to the remote location (300-V point). The dedicated and general use cables are normally connected together at the remote location (300-V point). Mutual drainage protection may also be required at the 300-V point. When the remote location is another ESL, another HVI system may be required.

From an *all dielectric optical fiber cable across the ZOI* standpoint, Level III protection configurations consist of a copper-to-fiber junction (CFJ) at the remote location (300-V point) and an optical electrical interface (OEI) at the ESL (this is explained in more detail in Chapter 6).

The station side of the HVI can be located at either the edge of the station ground grid (fence) or in the control building provided that it is located as part of the ground grid. Wiring between the HVI and the station terminal equipment should be short to minimize exposure to inductive interference, switching transients, and/or differential ground grid voltages. Secondary protection (shunt protectors) may be installed on the station side of the HVI when the station terminal equipment is located more than 100 ft from the HVI (details on HVI installations are discussed later in Chapter 6).

Whether copper cables are crossing the ZOI or all dielectric fiber cables, the ZOI should not contain other telecommunications system equipment such as splice cases, multiplexers, regenerators, or terminals unless properly designed. For example, necessary splice cases should be all dielectric and not grounded. Design engineers planning to use electronic equipment located inside the ZOI must use special caution powering the devices utilizing copper wires to distant sources (CO battery). This arrangement might create touch and step issues as discussed in Chapter 7. Some telecommunications service installations use optical fiber systems to avoid powering electronic equipment issues. Other installations use the more reliable power passive transformer-based systems to avoid powering requirements altogether.

Lightning arresters are frequently used to protect the HVI device from extreme GPRs resulting from extreme lightning strikes. In these rare events, the telecommunications facility or power station ground grid GPR may exceed the HVI isolation capability and the lightning arrester helps distribute the peak lightning energy through additional ground connections at remote facilities.

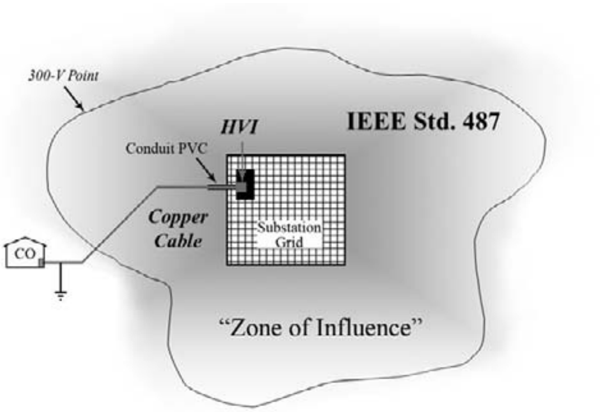


Figure 5.10 Level III protection using copper across the ZOI.

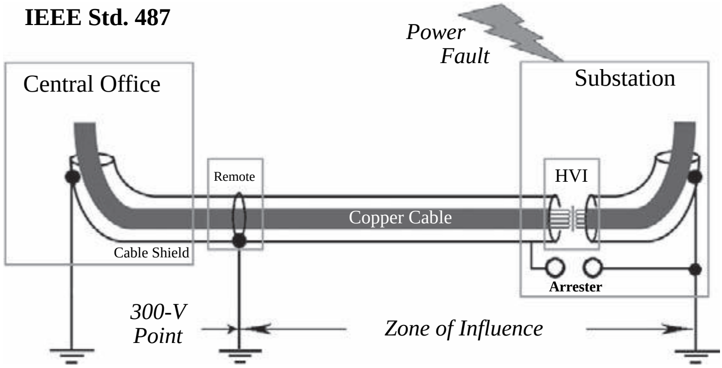


Figure 5.11 Level III copper cable protection equipment.

Level III: Copper across the ZOI

Figure 5.10 shows the basic isolation protection configuration for communication circuits utilizing copper cables across the ZOI. Figure 5.11 shows the basic building blocks for copper HVI systems. Figure 5.12 shows more details on the equipment requirements needed at the substation or ESL and the CO. Figure 5.13 shows the Level III protection concept between two ESLs (substations).

When copper cables are used, IEEE Std. 487-2007 is the recommended practice. This recommended practice calls for using a minimum

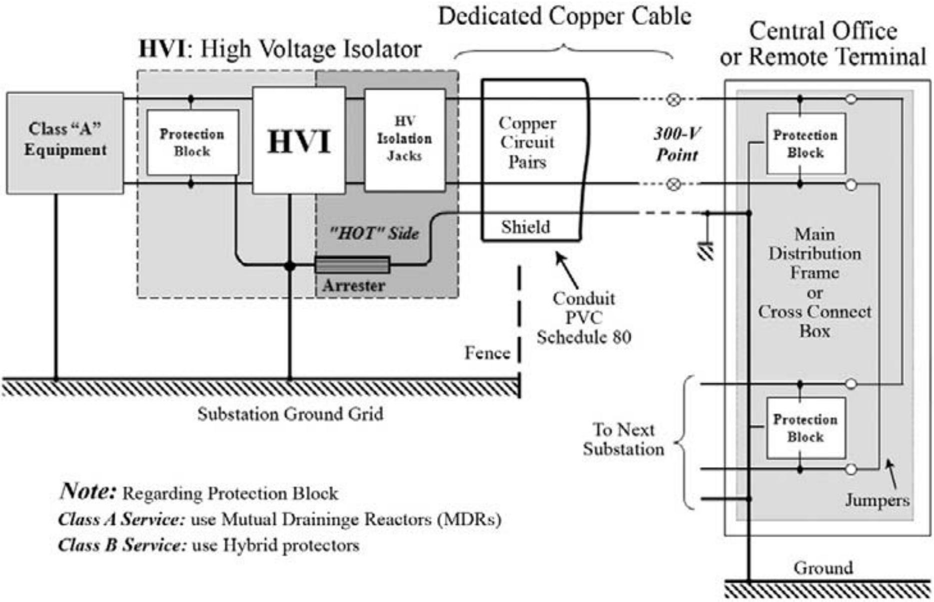


Figure 5.12 Level III equipment detail station and CO.

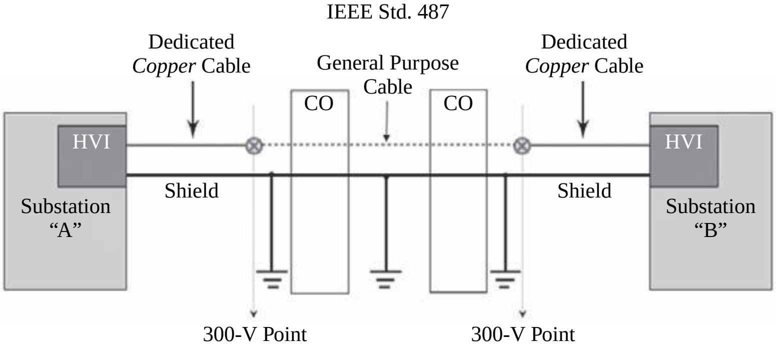


Figure 5.13 Level III protection between two substations.

of 10 ft of Schedule 80 polyvinyl chloride (PVC) conduit outside the fence for the dedicated copper cable (see Figs. 5.10 and 5.12).

Dedicated Cables versus General Purpose Cables

The purposes for using dedicated copper cables across the ZOI are to provide high dielectric strength cables (instead of general purpose insulation rated cables), maintain isolation from other noncritical non-

GPR-related telecommunications services and to demark from the normal outside cable plant construction practices. The dedicated cable should only contain those circuit pairs serving the ESL. To be effective, the dedicated cable should be extended from the power station to just beyond the 300-V point locations. General use cables can be connected to dedicated cables outside the 300-V point of the ZOI. Preventive measures should be taken to assure that unused pairs in the dedicated cable are not used or connected to general use cables without proper protection coordination. The dedicated cable should be clearly marked to avoid misuse of the cable.

The dedicated cable is different from the general use cable with regard to dielectric strength. The dielectric strength is factory test rated at approximately 20 kV DC core-to-shield and 5 kV DC pair-to-pair. For aerial construction, double-jacketed air core cables are appropriate. For underground construction, gel-filled high dielectric strength waterproof cable should be used. Regardless of the type of dedicated cable construction, the outer plastic jacket will be relied upon to maintain the isolation of the metallic shield from earth potential.

Regarding construction practices, the shield must remain isolated and ungrounded throughout its length across the ZOI. The metallic shield must be kept insulated from the ESL's ground grid at all times. Nonmetallic splice cases must be used to maintain isolation from the earth potential. The support strand and associated lashing wire should be bonded and grounded to other cable strands, vertical grounds (pole grounds), and power neutrals according to normal construction practices. However, aerial cables attached to delta power line configurations shall not share strand and lashing bonds and grounding. Aerial cables on delta power lines shall have separate vertical grounds. This avoids power faults from using aerial telephone cables as high current ground paths.

The nonmetallic splice cases inside the ZOI should be located as far as possible from the electrical supply location. The individual splices themselves should be of the in-line type self-sealing plastic connectors. Connectorized wire splices should be avoided since they offer lower conductor to conductor insulation characteristics than carefully placed individual in-line splices.

Lastly, aerial telecommunication cables should not be used in HV locations, especially near the substation, mainly due to grounding, GPR, and safety issues.

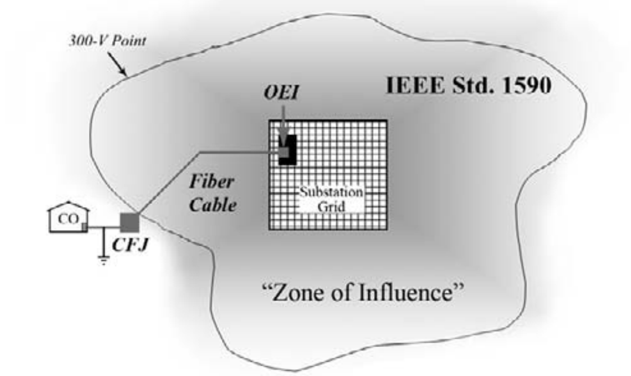


Figure 5.14 Level III protection using fiber across the ZOI.

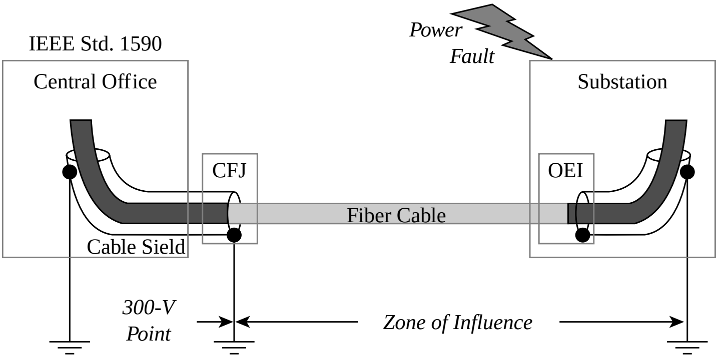


Figure 5.15 Level III optical fiber cable protection equipment.

Level III: Fiber Across the ZOI

Figure 5.14 shows the basic isolation protection configuration for communication circuits utilizing optical fiber cables across the ZOI. Figure 5.15 shows the basic building blocks for fiber HVI systems. Figure 5.16 shows the optical fiber cable Level III protection concept between two substations.

When optical fiber cables are used across the ZOI, IEEE Std. 1590-2009 applies. Note the location of the copper to fiber transition outside the ZOI. This is referred to as the CFJ. The transition back from fiber to copper at the ESL is referred to as the OEI.

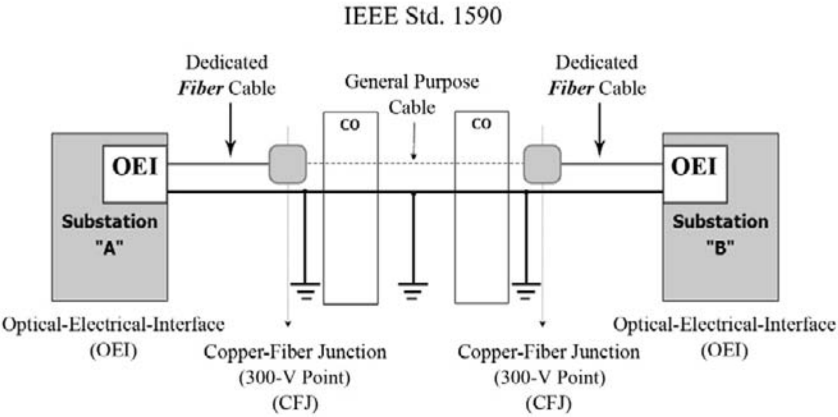


Figure 5.16 Level III protection between two substations.

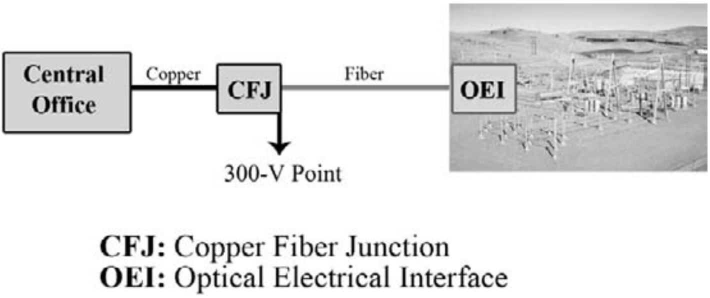


Figure 5.17 Fiber HVI to substation.

Figure 5.17 shows the basic fiber HVI system connecting a CO to a substation. Figure 5.18 shows the basic fiber HVI system connecting a CO to a wireless cell site on a power transmission structure.

Benefits for Using All-Dielectric Optical Fiber Cables

All-dielectric fiber optic cables are recommended across the ZOI to serve these ESLs. These optical fiber cables should have a nonmetallic strength member (i.e., nylon, fiberglass, or equivalent) and must not contain any metallic parts. All optical fiber cable support hardware should also have all-dielectric properties. Note that if metallic support strands are used or the fiber optic cable is lashed to existing copper cables, care must be taken to avoid grounding the strand or anchors a

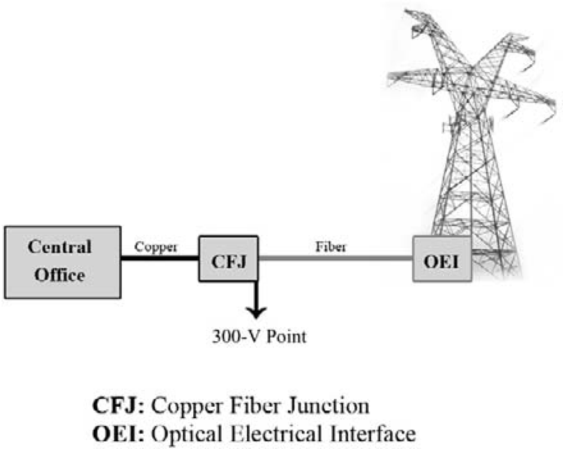


Figure 5.18 Fiber HVI to cell site on power tower.

minimum of 15–20 m (50–60 ft) of the ESL ground grid to reduce the risk of touch potential voltage problems. The use of strand insulators with adequate voltage rating is required by the National Electrical Safety Code (NESC) (American National Standards Institute (ANSI) C2-2007) Rule 279.

Regarding locating all-dielectric optical fiber cables buried underground, there should not be any continuous metallic wires placed alongside or near the optical fiber cable. Optical fiber cable locating provisions should be done with electronic devices (such as frequency-based) or passive reflectors external to the optical fiber cables.

The recommended practice for using optical fiber cables that have metallic members is IEEE Std. 487-2007, where they are treated as copper cables crossing the ZOI.

Older Isolation Systems

Several older-style Classes A and B HV isolator systems are still in use today. Their theories of operation are discussed below.

Isolation Transformers

An old-style isolation transformer is shown in Figure 5.19. These isolation transformers have symmetrical windings, which are used to decou-

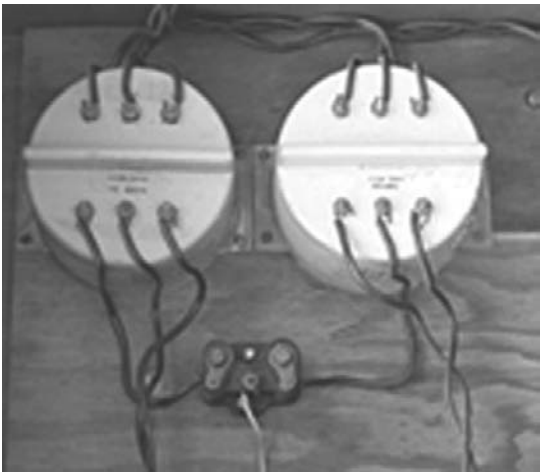


Figure 5.19 Older style isolation transformer.

ple or isolate two electrical telecommunications circuits (CO and station). Isolation transformers couple AC signals using electromagnetics without electrically connecting the circuit conductors. Isolation transformers block the transmission of DC signals from one circuit to the other but allow AC signals to pass. They also block interference caused by ground loops.

The older isolation transformers are normally used for GPR values up to about 50 kVPA (and probably not that high; 20 kVPA is more appropriate). Their power ratings range from a few milliwatts to several hundred watts with frequency capability ranging from 17 Hz up to the megahertz range.

This type of isolation transformer device can be used to provide GPR isolation and drainage if a balanced center tap device is used. The center tap on the power station side may be connected to the ground grid to provide direct drainage. Care must be taken to not create ground loops that result in undesirable hum or noise.

Isolation transformers that are combined with a highly insulated reed relay-type circuitry can be used for DC signaling circuits (see Fig. 5.20). A split-winding transformer in conjunction with an HV relay provides signaling and balanced impedances. The relay coil is connected to the center taps of the power station side. Capacitors are used to pass AC signals and block DC for relay operations.

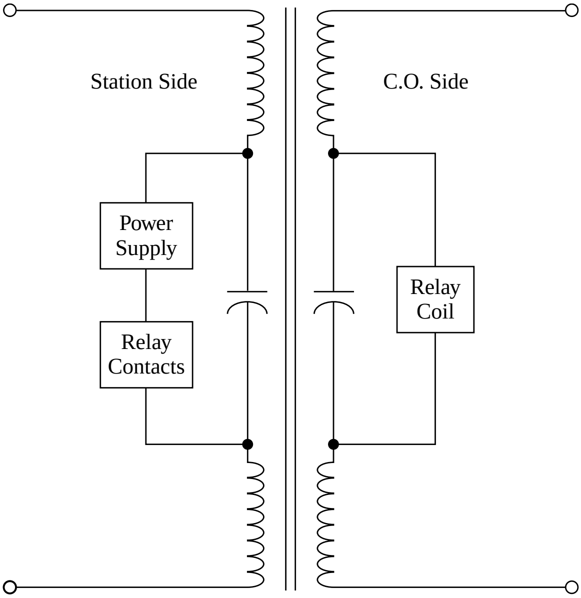


Figure 5.20 Isolating transformer with high voltage isolation relay.

Neutralizing Transformers (NTs)

NTs, sometimes called neutralizing reactors (NRs), are used to cancel or neutralize undesirable voltages arising from the power station's GPR, longitudinal induction, or both. The NT essentially stops the adverse effects of GPR voltage by introducing a counter GPR voltage during the power fault event, thus neutralizing the voltage on the telecommunications conductors. When a GPR event occurs, the station ground grid is elevated in potential with respect to remote ground. This potential appears across the NT's primary winding, thus creating voltage. The primary voltage is induced into each secondary winding in opposite polarity to the potential created by the GPR in the secondary windings themselves, thus equalizing, neutralizing, or canceling the potential. In other words, the NT has the telecommunications wires internally coiled in opposite directions from the cable shield conductor, thus providing GPR cancellation between the coiled shield conductor and twisted pair conductors internal to the transformer. A picture of an old-style NT is shown in Figure 5.21.

One of the disadvantages of NTs is that they must be placed in series with the GPR and are subject to core saturation, thus limiting their overall GPR capability.

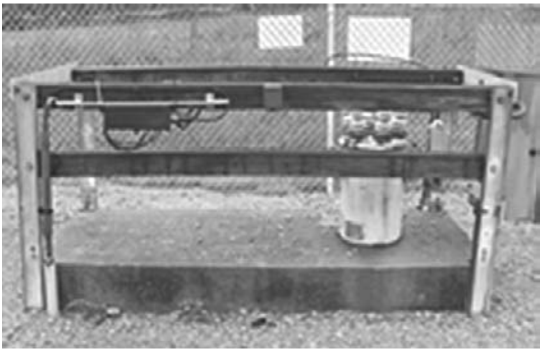
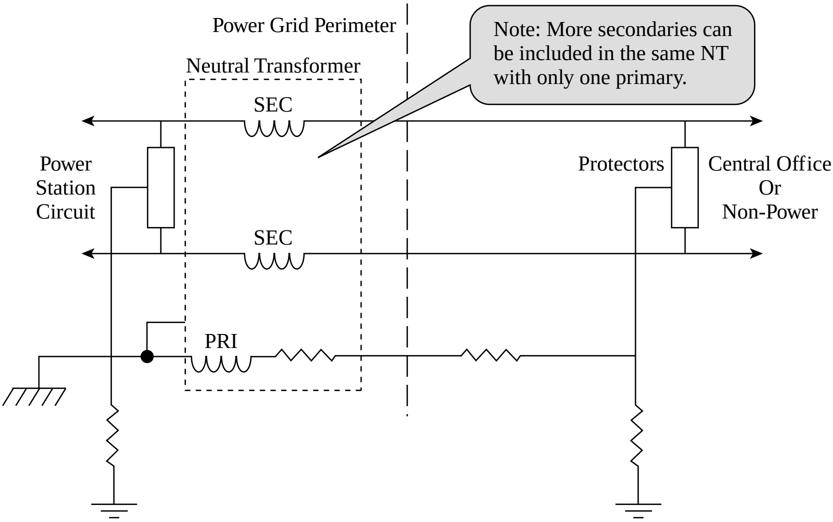


Figure 5.21 Neutralizing transformer.



Note: More secondaries can be included in the same NT with only one primary.

Figure 5.22 Three-winding neutralizing transformer.

Three-Winding NT

Figure 5.22 shows the schematic diagram of a three-winding NT that provides protection by establishing a primary or exciting voltage from the current flowing between the power station ground grid and remote ground (from outside the ZOI) and the windings of the twisted pair conductors (secondary side). As long as primary reactance remains high relative to the primary winding's external circuit resistance (determined by transformer design), the majority of the GPR develops across the primary winding. The GPR will be coupled into each secondary winding with proper magnitude and polarity to neutralize the common mode voltage of the telecommunications conductors. Hence, the differential mode signals continue to pass through the NT.

The instantaneous voltages that develop across the NT primary and secondary windings cancel during the power fault or lightning strike. The NT operates similarly when neutralizing longitudinally induced voltage.

In contrast to the isolation transformer, in which the disturbing voltage is applied across the primary to secondary dielectric and no longitudinal common mode current flows through the transformer windings, the NT primary winding is placed in series with the GPR voltage.

Two-Winding NRs

Figure 5.23 shows a two-winding NR, sometimes called a two-winding NT. These NRs are similar to the three-winding type of NT, except that their primary or exciting winding is omitted. The two-winding NR is self-excited through the cable capacitance (to ground) and the capacitance and current, limiting resistance to ground on the station side of the reactor. The disturbing voltage is induced directly into the signal conductors and is effectively canceled or neutralized from the inverse voltage developed through the reactor windings and external capacitance.

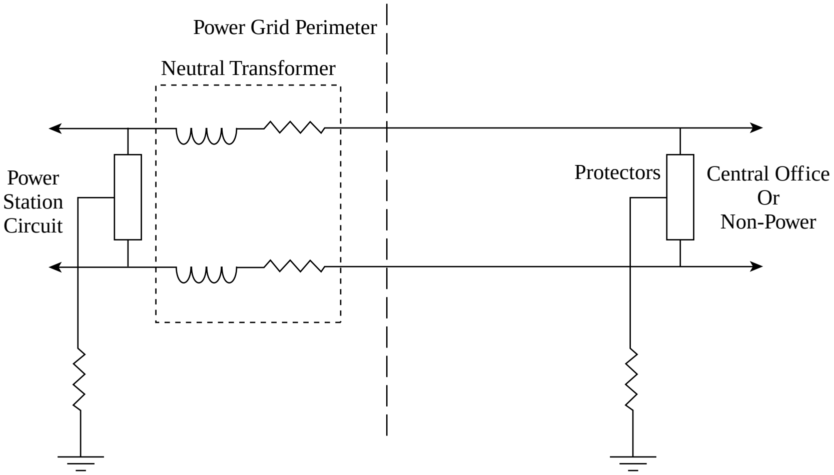


Figure 5.23 Two-winding neutralizing transformer.

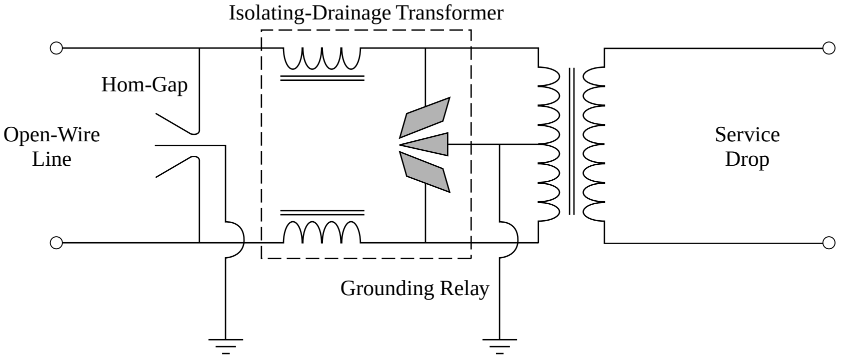


Figure 5.24 Open-wire or hotline protector.

Multi-pair NRs are available for low voltage GPR applications. High GPR applications (4 kV and above range) require adding external capacitance for proper reactor excitation. Therefore, two-winding NRs are usually limited to 4 kV GPRs, and three-winding NTs have higher GPR ratings. Standard design specifications have been prepared for 2.0, 2.5, 3.0, 4.5, 6.0, 7.5, 9.0, and 12 kV NTs. The NRs are usually limited to 4.0 kV.

Open-Wire or Hotline Protector

Open-wire or hotline protectors such as those shown in Figure 5.24 are used in Class B circuits that are subjected to high values of induced voltages and currents and in situations not requiring DC continuity. These protector units use combined isolating and drainage transformers in conjunction with a grounding relay and horn gaps. The horn gaps provide a shunt path to ground for power faults and lightning strikes, causing the circuit to be inoperative during the firing duration (i.e., Class B-rated). The grounding relay helps remove noise from longitudinal induction from cables paralleling power lines.

Other Protection Devices

Depending on the telecommunications and power company practices, other protection devices or protection schemes might be used on telecommunications circuits in HV environments. The following devices may or may not be used in Level I, II, or III protection systems.

- Heat coils operate similar to a fuse and are often used in COs as current limiting devices. They are rarely used in customer locations, especially in HV environments.

  Heat coils are made of thinner gauge or special material wire (compared with general plant cable conductors) and melt under designed specified high current conditions and therefore break the signal connection between the CO and the remote location when overstressed. Some heat coils have spring-loaded plastic covers that break away for fast visual indication when the heat coil opens. Heat coils are sometimes used with gas tubes to protect circuits when the GPR is too low. They typically have a continuous current rating of 350 ma for a period of 3 hours. They can operate (fuse open) when exposed to currents in the order of 500 ma for under 3 min.
- Fuse links consist of a small link of cable sized two to four gauges smaller than the cable pair and functions as a fuse or weak link in the cable. They are designed to melt open the circuit when shorts are created by other protection devices. Fuse links are often used at the 300-V point between the general use cable and the dedicated high dielectric strength cable.

SPECIAL CONSIDERATION FOR NEARBY FACILITIES

Telephone subscribers in close proximity to electric power stations may require special HV protection on their facilities if exposed to nearby high GPR situations. Shunt-type protectors may be required at these copper services to help equalize potentials within the general area.

When a general use cable with a grounded shield is routed through an area subject to GPR, supplemental protection may be necessary to avoid cable damage. To reduce voltage stress on the cable during a GPR event, shunt protection might be required at strategic locations along the general purpose cable path when the pair-to-pair or pair-to-shield voltage difference exceeds the 1000 V peak. It may be also necessary to unground splice cases, cross-connect blocks, even cabinets, and use nonmetallic cabinets that are in close proximity to power stations.

CHAPTER 6

Level III HV Protection Equipment, Installation, and Testing

LEARNING OBJECTIVES

- Describe the purpose of the individual high voltage interface (HVI) components used in copper cables crossing the zone of influence (ZOI) systems
- Explain how to properly design and install a complete copper HVI system
- Explain when, why, and how lightning arresters should be installed at an HVI location
- Discuss the differences and purpose for using high dielectric cables across the ZOI
- List and explain the critical copper HVI design factors
- Discuss how to strategically install a copper HVI (which end first)
- Discuss how to test, maintain, and inspect a copper-based HVI
- Explain how to properly design and install a complete fiber-based HVI system

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High Voltage Protection for Telecommunications, First Edition. Steven W. Blume.

- Describe the important design and location aspects of a fiber-based HVI system
- Discuss the powering options for either fiber or copper HVI systems
- Explain the HVI grounding differences between wireless cell sites and power stations
- Discuss alternating current power neutral issues and solutions
- Explain the meaning of single point or master ground at cell sites
- Describe the hybrid HVI system used with 911 call centers adjacent to antenna towers

GENERAL

The components, design, installation, and maintenance of Level III protection using copper and optical fiber cables across the zone of influence (ZOI) are discussed in this chapter. Level III protection involves complete circuit isolation from power fault and lightning strike energy while maintaining reliable telecommunications services. Where shunt protection encourages the grounding power fault and lightning energy to the electric supply station's grounding electrodes during ground potential rise (GPR) events and the telecommunications circuits cease operation, Level III protection isolates the energy from the telecommunications circuits while maintaining telecommunications. There are special situations where shunt protectors are used in conjunction with Level III protection and those situations will be discussed later in this chapter.

This book was written primarily to explain the collection of concepts and best practices for safe and reliable high voltage protection for telecommunications (HVPT) systems from several key references and industry expertise. The IEEE standards that are referenced in this book should be reviewed for more detail behind these discussions.

The order at which this chapter covers Level III HVI installations is first copper HVI, then fiber HVI, then wireless sites on power towers, and then nonpower facilities having critical telecommunications circuits that are also vulnerable to lightning and need reliable communication circuits.

One very important design objective for any Level III protection system is to properly match the high voltage (HV) environment's protection requirements (i.e., GPR, induction, and cable stress voltages) with the dielectric strength or insulation value of the HVI equipment itself and providing a reasonable margin of safety. Level III copper cable HVI systems insulation value can be as high as roughly 90 kV peak asymmetrical (VPA), whereas optical fiber cable HVI systems approach infinite isolation values and margins of safety are not necessary provided that the installation is correct.

LEVEL III COPPER HVI COMPONENTS

The basic installation concepts and recommended practices for copper cables across the ZOI are discussed in this section. Please refer to the IEEE standard IEEE Std. 487-2007™ and equipment manufacturers' installation manuals for additional information and details.

The primary goal for all telecommunications HV isolation systems is to *maintain adequate insulation all the way from the 300-V point to the station ground grid with no weak links!* Failure to maintain adequate insulation from GPR at a point between the remote ground and the electric supply station that breaks down and causes equipment or service failure represents a weak link. An example of a weak link is having the central office (CO) side of the HVI cable adjacent to the station side cable when a GPR event occurs causing the two cables to flash, thus interrupting service with equipment damage and hopefully, no injuries to nearby personnel. Having the two cables within striking distance presents a weak link in maintaining proper insulation. Copper HVI systems must maintain a minimum of 6 in. of air gap between both sides of the HVI. The CO side cable should be housed in Schedule 80 PVC conduit to provide an additional approximately 100 kV of isolation to the CO cable. Shortcuts in the system layout or component ratings could create weak links, inviting failure.

General Layout of a Copper-Based HVI

Figure 6.1 shows the basic layout of a copper HVI system with the essential components. The components making up the HVI might

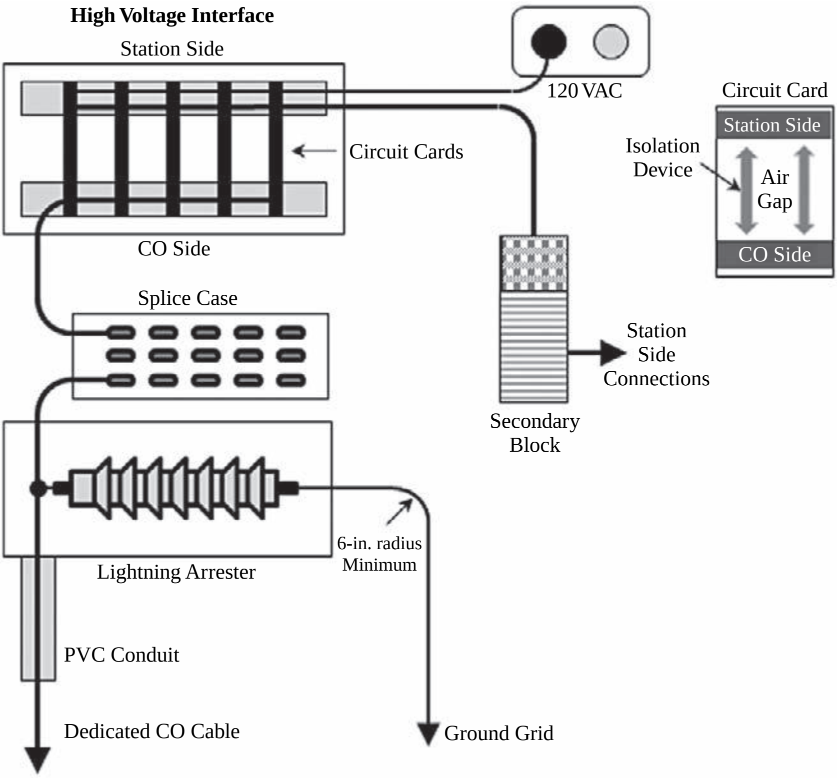

Figure 6.1 Copper HVI system.

include a card shelf, HV isolation jacks (in this example, a splice case), secondary protection block, lightning arrester, and a dedicated high dielectric cable. The actual HV isolation occurs across the air gap between the station side and the CO side of the HVI. The circuit cards plug into the HVI shelf and bridge the air gap. The isolation device on the circuit card and its associated electronic components provide the means for communicating signals across the air gap. Depending on the manufacturer, there are several types of circuit cards available, usually each card having a specific type of telecommunications service. Usually, the telecommunications service needed for telecommunications dictates the type of isolation card used across the air gap in the HVI shelf. Each specific circuit card slot in the shelf corresponds to the dedicated CO cable pair(s) and the termination points on the secondary block.

A direct current (DC) or 120 V of alternating current (AC) power source might be required to power the station side of the cards, and span power might be used to power the CO side of the cards. Note that station power is never used to power the CO side of a card, and the CO side span power is never used to power the station side of the cards. Complete electrical isolation is required between the CO and the station sides of the HVI.

Note that the CO side copper cable must be kept a minimum of 6 in. away from the station side copper wires in order to maintain the HV isolation level available from the HVI. Some copper HVI installations have painted lines to clearly identify the two sides, CO and station. The recommended 6-in. air gap provides roughly 100 kVPA insulation value.

Isolation Shelf

The picture in Figure 6.2 shows a copper HVI shelf with cards manufactured by Positron Inc. Notice the circuit board cards bridging the CO side electronics (bottom) from the station side (top). Different cards are used for different telecommunications services. This manufacturer requires that the station side cable and external power be connected to the top right part of the shelf and the CO cable be connected to the bottom left part of the shelf. It should become obvious that a copper HVI system is installed correctly because there should always be a

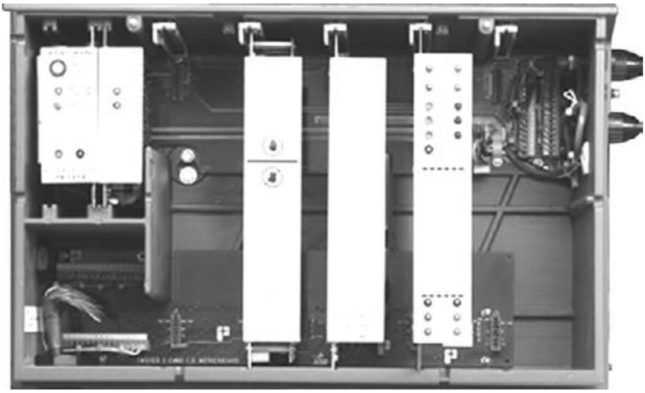

Figure 6.2 HVI shelf. Courtesy of Positron Inc.

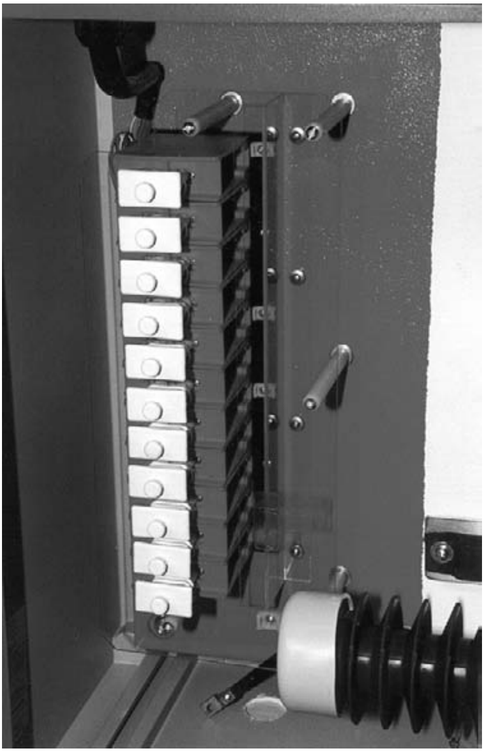

Figure 6.3 High voltage isolation jacks.

minimum of 6 in. of clearance between anything connected to either side.

HV Isolation Jacks

HV isolation jacks, similar to those shown in Figure 6.3 (manufactured by Tyco ADC), are frequently used instead of splice cases for the convenience of telecommunications circuit testing. Depending on the plugs inserted into these HV jacks, basic troubleshooting can be accomplished. For example, depending on the type of plug inserted into a jack, a circuit open, short, and even tip-ring reversal can be accomplished. The use of these HV jacks and plugs provides troubleshooting flexibility that is not provided when using splice cases.

All dedicated cable pairs that are used should be terminated on HV isolation jacks, allocating one jack per cable pair. The unused pairs should be capped and tie-wrapped back. For convenience, the jacks should be numbered from top to bottom, with the top jack being number 1 and the last jack being the last pair utilized in the cable. These jacks are available in screw-down or wire-wrap connections.

Regarding the plugs, the tip or pointed part of the plug is referred to as the "tip" conductor, and the ring conductor just after a small insulator is referred to as the "ring" conductor. There is a third conductor on this type of connector just after the ring and insulator that is called the "sleeve." The sleeve conductor is not used in this system. It normally connects to ground.

Splice Cases

Cable splice cases (sometimes called closures) protect splices from mechanical and environmental damage. Closures are used in aerial, direct-buried, underground, and in-building applications. The size of the closure is based on the number of cable pairs or splices.

When splicing telecommunications cables crossing the ZOI, it is recommended that only nonmetallic splice cases with rubber boots and seals are used. There should be no metal connections to ground anywhere in the ZOI. The telecommunications cable shield or sheath should not come in contact with the earth at any point when inside the ZOI. These nonmetallic splice cases, if needed, should be as close to the 300-V point as possible.

Figure 6.4 shows a typical splice case that is attached to the HVI unit instead of the HV jacks mentioned earlier, connecting the short HVI pigtail to the incoming telecommunications cable. Figure 6.5 shows a nonmetallic splice case that can be used inside the ZOI.

Regarding the actual conductor splices in the splice case, use only individual splice connectors. Avoid using "modular connectors." They offer low dielectric strength due to the close proximity of adjacent wires on the terminal strip. Splice each wire individually and position the individual splices such that separation is provided for additional insulation.

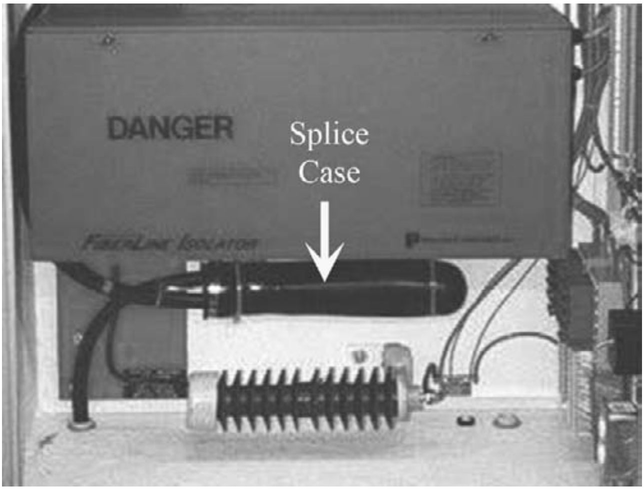

Figure 6.4 Nonmetallic splice case at HVI.

Figure 6.5 Nonmetallic splice case inside ZOI. Courtesy of Corning.

Secondary Protector Modules

The device shown in Figure 6.6 is called a "secondary protector module" and is installed on the station side of the HVI. (Note that telecommunications companies often use these modules throughout their general plant for Protection Levels I and II.) They are referred to as secondary since they are connected on the station side of the primary Level III HVI.

Secondary protection modules (SPMs) provide several functions. They provide a termination point (or demarcation) for the station side wires connecting to the HVI. They provide a termination point for the station's protective relay, supervisory control and data acquisition remote terminal unit (SCADA-RTU), metering, phone, and data equip-

Figure 6.6 Secondary protector module.

ment. They provide shunt protection for transients or unbalanced voltage conditions appearing on the station side of the primary HVI. (Note that voltage transients can appear on the station side of the HVI if there are station ground grid equipotential issues, especially when long station side circuits are used over 100 ft.) Five-pin balanced solid-state protectors versus dual three-pin are recommended for improved circuit balance operational characteristics.

SPMs also provide a convenient access point for testing and troubleshooting on the station side of the HVI. Different plug types may be inserted into the jack to perform various circuit tests.

Lightning Arresters

Lightning arresters (i.e., surge arresters) are used in the complete HVI protection system to help shunt excessive peak lightning energy to remote ground facilities. Lightning strikes, as opposed to power faults, can have very high voltage and current spike rise and fall time characteristics. The lightning strike impulse energy is intense compared with the longer duration power faults. In some cases, the GPR voltage peak (although very short in duration) can exceed the dielectric strength of the HVI equipment and potentially cause damage if it was not for the lightning arrester. The lightning arrester serves as an HV shunt protector for the HVI, thus shorting excessive energy to earth ground and remote grounds. This contradicts the reason for using Level III isolation by providing a shunting mechanism during extreme GPR conditions. However, only the peak of the lighting energy is dissipated by these additional grounds; most of the energy is dissipated by the station ground grid.

There are multiple reasons why lightning arresters are used in HVI installations:

- They bypass excessive lightning energy to avoid damaging the HVI.
- They help place HVI equipment failures outside the control building, thus lowering the chance for injury should a person be standing near the HVI equipment at time of extreme lightning.
- It provides a convenient termination point for the copper cable shield instead of leaving it unterminated. The CO copper cable shield connects to one end of the lightning arrester and the other end of the lightning arrester connects directly to the substation ground grid.

There are two basic types of HV lightning arresters, metal oxide and gap. The older gap-type arresters were constructed with porcelain glass and vulnerable to catastrophic failure should the dissipation energy exceed its rating. For that reason, these older gap-type porcelain lightning arresters were mounted outside the control building in self-contained cabinets. The newer metal oxide (or gapless)-type arresters have inherently better energy dissipation characteristics, are considered non-fragmenting, and are now placed alongside the HVI or within the same cabinet as the HVI.

Metal Oxide Surge Arresters

Finely crushed zinc oxide compound and other selected metal oxides are mixed, pressed, and heated into discs of dense material. These discs offer high resistance at low electrical stress levels and very low resistance at very high electrical stress levels. A picture of a metal oxide-type lightning arrester is shown in Figure 6.7.

This type of arrester is commonly used on electric utility's distribution system. They are selected based on the maximum continuous operating voltage (MCOV) that can be applied to the arrester terminals on a continuous basis without having conduction (high resistance

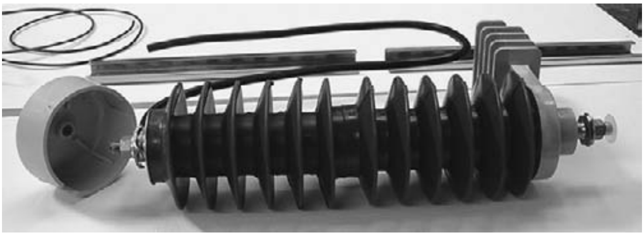

Figure 6.7 Metal oxide lightning arrester.

mode). The MCOV rating is typically the maximum root mean squared (rms) line-to-ground voltage of the power system. The arrester's rated voltage, usually in kVrms, is typically 20–30% higher than its MCOV (the actual continuous line-to-ground operating voltage). In other words, when the line-to-ground voltage is 20–30% higher than the continuous voltage rating of the arrester, the arrester starts conducting (low resistance mode). The arrester's voltage rating may be applied to the arrester on a temporary basis (e.g., 30 min) to accommodate temporary over voltage conditions. Most of the time the arrester does nothing. In the extreme lightning strike event, the arrester limits the voltage across the HVI, thus protecting it.

The lightning arrester rating that is of interest in HVPT design is the conduction leveling voltage rating. This is the line-to-ground voltage that the arrester tries to maintain during its conduction. For example, a 15 kV distribution class lightning arrester that is normally used with an HVI tries to limit the overvoltage condition to approximately 56 kV, whereas 10 kV distribution class arresters try to limit voltage to 48 kV. The 10 kV arresters are not encouraged; however, they could be used in conjunction with the older copper cables that have lower dielectric strength.

It is common practice to provide a 20–40% protection margin between the lightning arrester conduction or hold voltage and the protected equipment insulation rating. Therefore, the 15-kV arrester having a conduction voltage of approximately 56 kV is sufficiently protecting an HVI unit that is rated 90 kV. The arrester should conduct and limit voltage well before the HVI equipment is damaged.

Lastly, should the extreme lightning strike cause the arrester to fire and the remote grounds of the telecommunications cable draw lightning energy sufficient to damage the cable, cable/equipment failures tend to be located outside, away from personnel.

Figure 6.8 Lightning arrester in cabinet.

Gap-Type Surge Arresters

These older-style arresters are made of porcelain bodies consisting of internal spark gaps connected in series with either silicon carbide or metal oxide valve and variable resistive elements. When the specified voltage occurs across the gaps, the gaps arc and close the electrical circuit path between the CO cable shield and station ground (ground grid). The arcing inside the gap arrester heats up its limited internal space, and excessive heating from high energy and long-duration lightning strikes can cause arrester failure and damage. Arrester manufacturers incorporate valve elements to vent excessive heat energy out of the gap arrester. Excessive heat can cause catastrophic arrester damage and that is why these older units are normally installed in cabinets outside the control building. Figure 6.8 shows a metal oxide lightning arrester in a stand-alone cabinet.

High Dielectric Cables

High dielectric insulation-type copper cables are recommended (IEEE Std. 487-2007) for crossing the ZOI. High dielectric cables help ensure that the voltage gradient in the earth during a power fault will not create an arc between the earth and the shield or core communication pairs. High dielectric implies the insulation between the outside jacket and the shield and the shield to the actual conductor bundle core is greater than that normally used in general purpose cables. The main difference between general purpose cables and high dielectric cables is the insulation ratings between conductor to conductor (insulation around each wire in a pair), the core (group of conductors) to shield insulation, and the shield to outside earth (jacket) insulation levels.

The U.S. Department of Agriculture (USDA) for Rural Utilities Service's (RUS) Bulletin 1751F-815 addresses the subject of electrical protection of outside plant requirements for high dielectric cables. This document addresses the surge dielectric strength for lightning protection for plastic-insulated cable (PIC).

RUS Bulletin 1751F-815 shows the following engineering design recommendations:

	Surge dielectric strength	
Insulator type	Conductor-to-conductor (kV)	Core-to-shield (kV)
Solid gel-filled	20	35
Gel-filled, expanded	15	25

The standards that reference high dielectric cables include the following:

- ANSI/ICEA S-84-608-2002
- CFR 755.890—RUS
- ANSI/ICEA S-85-625
- Telcordia GR-421-Core
- RUS (Rural Electric Administration, REA) Bulletin 1753F205 (Specification Polyethylene [PE]-39) and Bulletin 1753F208 (Specification PE-89)

REA and RUS: PE-39 and PE-89 standards are considered functionally equivalent. The difference between the two is the method used to insulate the copper conductors. All other materials in the two cable types are basically the same.

- PE-39 cables are manufactured with "solid" insulated conductors, that is, the polyolefin insulation is applied as a solid layer over the copper conductor. These cables typically have lower attenuation and higher dielectric strength than PE-89.
- PE-89 cables are manufactured with "foam skin" insulated conductors. Foam skin insulation is applied as a dual layer over the copper conductor. The inner layer is "foamed" (expanded) polyolefin and the outer layer is solid polyolefin. These cables are smaller and lighter than PE-39 cables.

  Example: (see Fig. 6.9) Addison Foam Skin Insulated and LAP Sheathed Jelly Filled Cable RUS (REA) PE-89

Table 6.1 summarizes typical insulation levels between general use and high dielectric cables.

Figure 6.9 Insulated gel-filled cable. Courtesy of Addison Cables.

Table 6.1
High Dielectric Insulation Strength

Dielectric location	Typical general use cables minimum (kV)	High dielectric cable 22 gauge
Conductor to conductor	1–3	5
Core to shield, single jacket	3–5	15
Core to shield, double jacket		20

COPPER HVI SYSTEM DESIGN

Before discussing proper design and installation requirements for copper-based HVI systems, one should first realize where the potential hazards lie and what is required to mitigate those potential hazards. One good way to explain or visualize the hazards is to view a person standing on the ground grid in a substation control building and in front of a copper-based HVI system when a power fault occurs and a GPR is created. Suppose the incoming telecommunications CO cable is 6 in. away from the station side wiring (correct installation). The CO cable's shield is connected to a remote ground located outside the ZOI. During the fault, the station side of the HVI is at GPR value (say 15 kV) and the CO side of the HVI is at remote ground value (say 300 V). In other words, the substation ground grid is at GPR potential (15 kV) and the cable's shield is at 300 V. Therefore, the person standing on the substation's ground grid or control building floor would be in jeopardy if that person touches the shield of the incoming telecommunications cable. The person could be subjected to the difference of potential (in this case, 15 kV – 300 V = 14.7 kV). Hence, in a substation one might warn "danger low voltage!" While on the station's equipotential zone at GPR potential, the jacketed telecommunications shield presents a dangerous 300 V. Voltage difference or potential is relative, and either way, whether it is "danger high voltage" or "danger low voltage," the hazard still exists.

Keep in mind that the probability of a fault occurring at the same time a person is touching both sides of the HVI is extremely low. Because of the possibility that a fault or lightning strike could occur at any moment, the person must wear rubber personnel protection equipment (PPE), isolating them from a potential hazard. This is explained in more detail in Chapter 7 on safety.

Design Factors

Assuring that key design factors are properly administered will accomplish two things: first, provide continuously insulated telecommunications wires from GPR between the electric supply location (ESL) and remote ground and, second, help a person recognize good installations from bad ones. The following design factors should help assure good copper HVI installations.

- The HVI should be located on the station's ground grid. In some cases, the ground grid is extended outside the station's fence to improve equipment access without having to go inside the station and still be considered on the station's ground grid. Therefore, the HVI can be mounted outside the fence and still be part of the station's ground grid.
- Make sure the HVI supporting structure is adequate to support the weight of the cabinet or that ample room exists on a wall panel installation.
- Make sure the CO cable and the station cable conduits are of proper type (PVC vs. metal) and are properly placed to meet clearance specifications. The CO side conduit should be PVC schedule 80 from the HVI to 10 ft outside the station fence. Station side conduit, if used, should be metal type. Never place CO cables inside metal conduit.
- Run long station side cables (excess of 100 ft) in metal conduit or use a number 2 copper bonding conductor alongside the telecommunications cable as recommended in IEEE Std. 487-2007. The bonding conductor should be grounded at both ends to minimize voltage drop across the station grid during a GPR event. It is not harmful to use PVC conduit on the station side with the bonding wire; however, metal is recommended to help equipotential objectives.
- Consider using small cooling fans on the HVI if there is a concentration of high component-type circuit board cards in the shelf or cabinet.
- Confirm that power supply voltages and power ratings are correct for the job and take into consideration future growth.
- Confirm that HVI battery backup is provided if any Class A and B circuits are involved. Note that transformer isolation does not require power; that makes them Class A-rated.

Preconstruction

The following pointers are presented to heighten safety procedures during construction activities, thus minimizing touch and step potential exposure.

- First of all, telecommunications personnel should never enter an HV location (such as a substation) without being escorted by power company personnel.
- Perform as much work off-site as possible. For example, install equipment on wall boards, inside enclosures, and wiring off-site to assure no exposure to potentially harmful GPR voltages.
- Mount the new HVI equipment (wall boards, cabinets, etc.) at the substation with the dedicated cable disconnected at the remote ground end and insulated from any contact to metal objects. This eliminates dangerous low voltage (LV) potentials from being transferred on the CO cable to the HVI should a power fault or lightning strike event occur during station equipment installation.
- Complete all wiring and bonding on the HVI at the substation location prior to bonding and splicing the dedicated cable to the general use cable at the 300-V point location.
- Once the 300-V point is terminated, all copper safety procedures discussed in Chapter 7 must be followed.
- Never work on HVI equipment when power company personnel are performing switching activities. Switching is the term used to change the configuration of the electric power system or to isolate equipment for safe working conditions. Switching involves power company personnel in the field communicating with system control center personnel. Switching is required to open or close disconnect switches, circuit breakers, and so on for planned maintenance, emergency restoration, load transfer, and/or equipment isolation. Power company personnel place tags on equipment to identify equipment that is not in normal status. Switching can be very time-consuming due to the nature of repetitive telecommunications during the "switching orders" conversations. Wait for switching to be finished before commencing work on HVI equipment. Allow the power company personnel to make certain it is safe to proceed. Make sure the power company employees know what telecom activities are to take place.

300-V Point

It is important to ensure that the following steps are taken:

- Keep the dedicated cable disconnected until all construction activities are completed at the ESL.
- When connecting the dedicated high dielectric strength cable to the general use cable at the 300-V point, be sure to use proper rubber PPE as discussed in Chapter 7 on safety.
- Ground the shield of both the general use cable and dedicated cable at this location using PPE. Touching the shield from the station cable could expose oneself to GPR transfer potential. Also, there might be a difference in potential between the dedicated cable that is now terminated and the grounded general purpose cable.

CO Side of the HVI

The CO side of the HVI involves equipment that is normally connected via copper cable to remote ground or 300-V point. If the remote end is terminated (grounded), rubber gloves and standing on a rubber insulation safety mat (PPE, discussed in Chapter 7) are required when working on this equipment. If this is new construction and it is possible to have the remote ground side of the cable disconnect, do so. This eliminates the possibility for LV appearing at the HVI should a fault occur.

The CO side of the HVI consists of the dedicated telecommunications cable, the cable attachment to the lightning arrester, HV isolation jacks (or nonmetallic splice case), and the pigtail cable from the CO side of the HVI. When installing this equipment remember the following:

- Use plastic PVC Schedule 80 conduit (preferably 4-in. diameter) from 10 ft outside the substation ground grid or fence to the CO pigtail cable connection termination at the HVI.
- Make sure the conduit is sealed or provides good water drainage
- The dedicated cable (from remote ground location) should be connected to HV isolation jacks or nonmetallic splice case connecting to the pigtail of the HVI.

- Maintain a minimum 6 in. air gap clearance between CO side cables and metal parts that are in contact with the station side of the HVI or any part of the station's equipotential ground grid. Several installations have painted border lines (often red or yellow) on backplanes or cabinets to quickly identify both sides of the HVI and to assure a 6-in. air gap boundary is provided at all times.
- Watch out for grounded mounting bolts or hardware that come in close proximity to the CO side of the HVI.
- Never use shunt protectors or standard 66 blocks on the CO side of the HVI.
- Use lightning arrestors if lightning strikes are possible in the area.
- Never use sharp bends in the lightning arrester ground wires or connection to the CO cable shield.
- When attaching the lightning arrester to the CO cable, strip only an area about 4 in. where it is to be clamped to the lightning arrester. Do not strip the insulation or cut the cable in any other area of the CO cable.

Station Side of the HVI

The station side of the HVI consists of power company telecommunications and protection equipment and wiring that is essentially at substation ground potential during a GPR event. Because of the equipotential zone created by the station's ground grid, it is technically safe to touch this side of the HVI while in the substation. The equipment connected to this side of the HVI is normally secondary circuit protector blocks, interconnection/quick-disconnect blocks, substation circuits, and the station side of the lightning arrester. Factors to consider when designing access to the station side of the HVI are the following:

- All ground connections must be installed on the station side of the HVI, including the card shelf, secondary connector block, and lightning arrester. These grounds are to be connected to the station's ground grid. Figure 6.10 shows the ground wire connections to the HVI (station side only) and secondary protector block.
- Figure 6.10 also shows the station side power company telecommunications circuits connections at the punch down terminals of

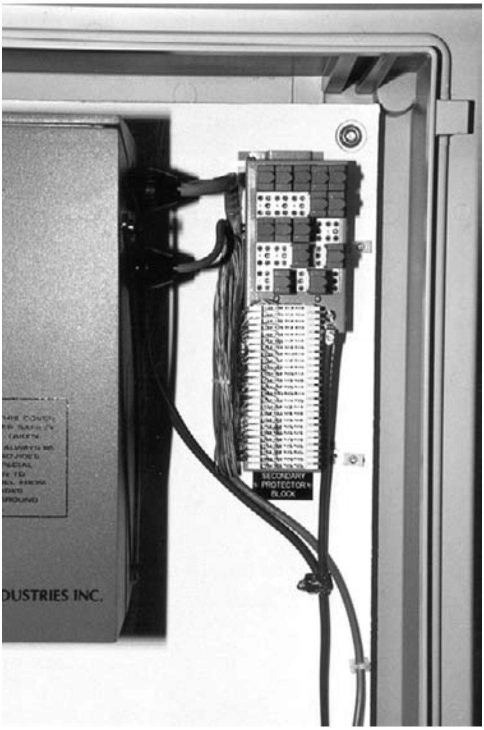

Figure 6.10 Station side circuit connections.

the secondary protector block. Note in Figure 6.10 the red shunt protector plugs and spaces where plugs are missing. The plugs allow circuit signals to pass and the white empty five-pin sockets (without shunt protector plugs) are open where circuit continuity for signals does not exit. These blocks are designed to provide circuit continuity when protector plugs are inserted. These blocks can help troubleshooting procedures by providing inline access points.

- The HVI cabinet must be connected to the substation ground grid. A ground wire must be installed between the HVI ground bus bar and the substation ground grid, keeping the wire length as short as possible (less than 6 ft total external to the HVI). Never use sharp bends in the arrester ground wire. Bends should always be greater than 90° with a radius of 6 in. or more. Note the wide radius arrester ground wire bend in Figure 6.11. The ground wires should be of a minimum gauge number 6.

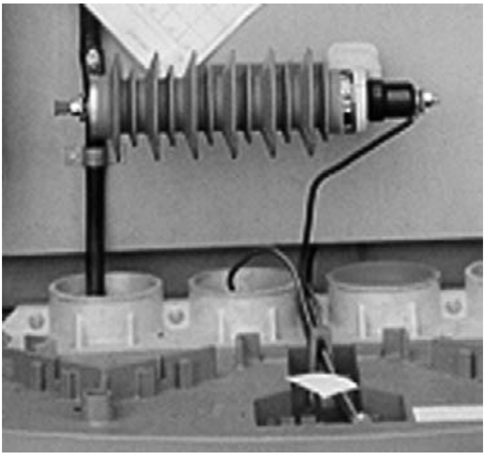

Figure 6.11 Lightning arrester ground connections.

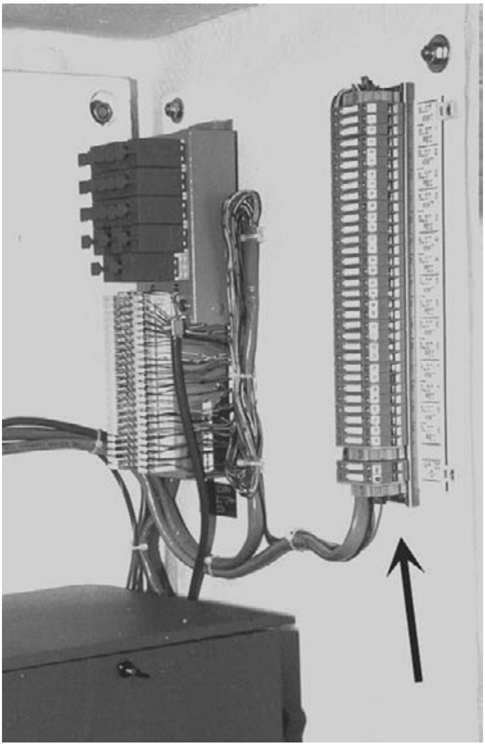

Figure 6.12 Station side circuit disconnect block.

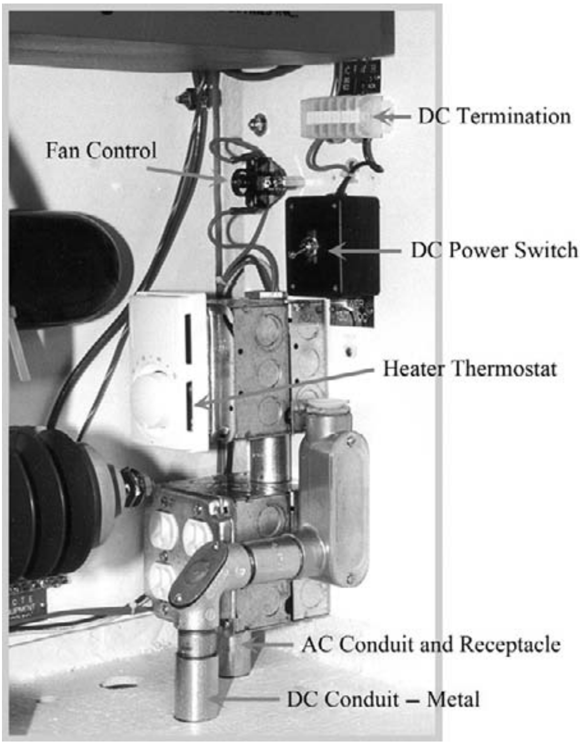

Figure 6.13 AC and DC power fixtures.

- Figure 6.12 shows an installation where the power company used a station side quick-disconnect block. This style block provides a convenient disconnect feature for maintenance and troubleshooting. They can also accommodate fuses.
- HVI systems that depend on the station's battery supply (24 VDC, 48 VDC, or 125/130 VDC) should have a separate load center DC breaker (typically 5 A maximum), a convenient DC terminal strip (with on/off switch), and a dedicated metal conduit (typically 3/4 in.). Figure 6.13 shows the DC circuit metal conduit, on/off switch (black box), and DC terminal strip (cream color) above the switch.
- HVI systems that require external 120 VAC power supplies should have a 20-A service. Figure 6.13 shows the quad AC power receptacle to be used for powering external AC power

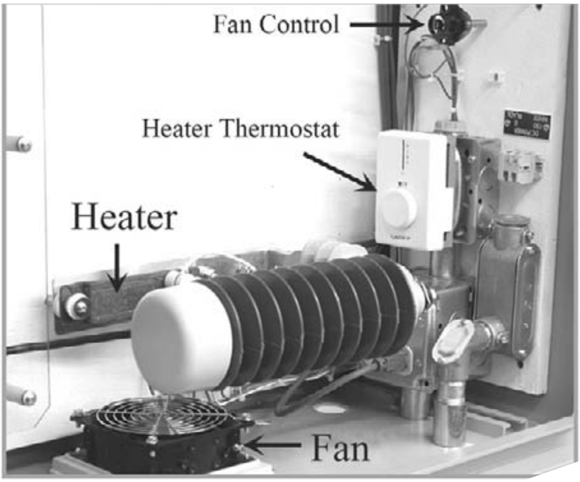

Figure 6.14 Environmental control.

supplies. Caution: This receptacle should NOT be used for powering portable test equipment for testing the CO side of the HVI. A GPR event will place full GPR potential across the test instrument and could catastrophically damage the instrument and possible injure the technician. Only use battery-operated test equipment on the CO side of the HVI.

- Convection cooling is adequate in most situations. However, fans may be needed if there are several high density circuit cards requiring station power (refer to HVI equipment manufacturer for design specifications when to use fans). Figure 6.14 shows a fan at the bottom of the HVI cabinet for improved air circulation.
- Figure 6.14 also shows a heater strip (behind the lightning arrester), thermostat control (right side with white knob), and the fan control (small black component on top right side). This arrangement is used to control the environmental conditions inside the cabinet. Normally, the heater is set around 50° ± 5°F and the fan around 95° ± 5°F.

Figure 6.15 shows filtered air vents for improved air circulation when fans are used.

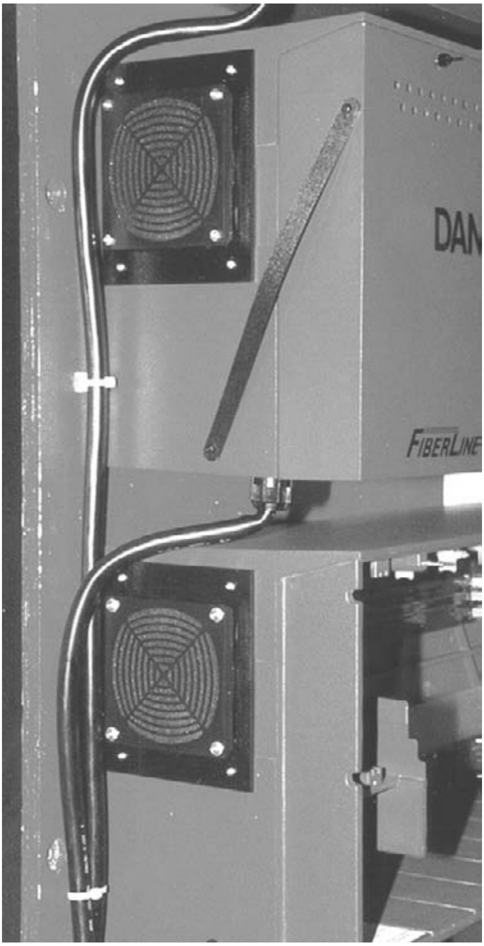

Figure 6.15 HVI-filtered vents.

The Complete HVI Assembly

The following photos show complete units ready for installation. A complete basic HVI cabinet with environment controls is shown in Figure 6.16.

A complete HVI 8-ft backplane design is shown in Figure 6.17.

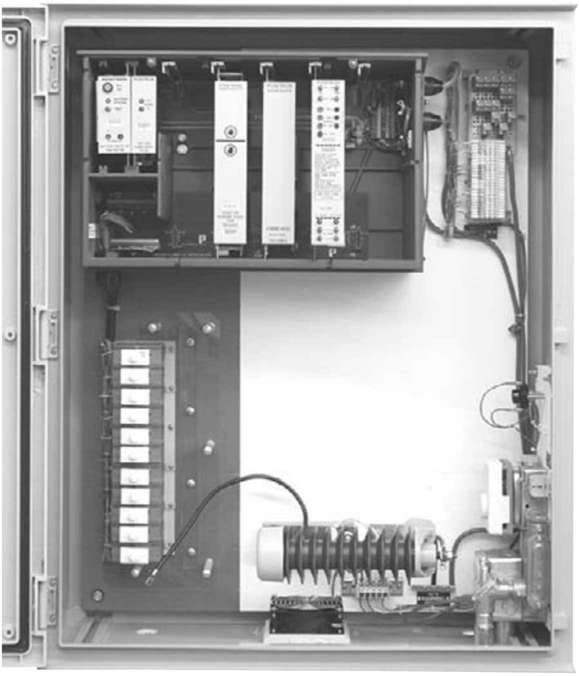

Figure 6.16 Complete basic HVI cabinet. Courtesy of Positron Inc.

COPPER HVI INSTALLATION EXAMPLES

Several examples of actual copper-based HVI installations are provided in the following sections. The features are noted for reference. The intent is to point out the qualities and cautions in these real installations.

300-V Point (Remote Ground)

First, the 300-V point, commonly referred to as the "remote ground." Figure 6.18 shows a very clean installation of a pedestal enclosure where the dedicated cable connects to the general use cable.

Station Equipment

A station HVI installation is shown in Figure 6.19. Note the HVI shelf on the top seciton of the National Electrical Manufacturers Association (NEMA)-rated fiberglass cabinet. Notice the CO cable and nonmetallic

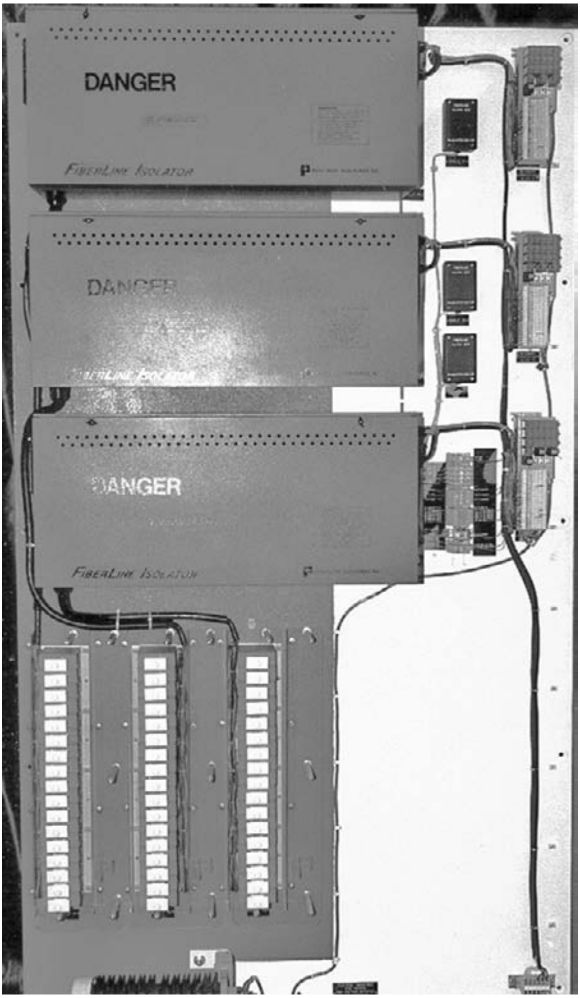

Figure 6.17 Complete HVI backplane. Courtesy of Positron Inc.

splice case at the bottom left corner inside the cabinet. The station equipment is located at the right bottom section of the cabinet with the lightning arrester between the CO and station sides of the installation. There is a minimum 6-in. gap between the CO and the station equipment.

Although this HVI installation is located outside the substation fence, it is mounted above the station ground grid and provides easy

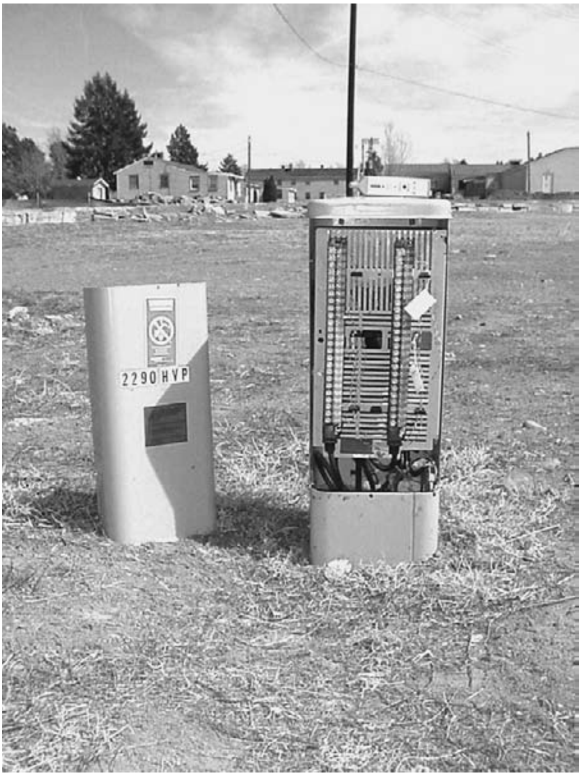

Figure 6.18 300 volt point (remote ground).

Figure 6.19 Station copper HVI.

access without a technician needing to go inside the substation perimeter fence. Gravel is provided to help insulate people from touch and step potential. The nonconductive pad for standing further isolates one from touch potential. Note that although gravel and nonconductive pad are provided for touch and step potentials, it is still dangerous to touch the CO side with one hand and the station side with the other. Hand-to-hand touch potential is possible. The same is true with test equipment; you cannot connect test equipment across the CO and station sides of the HVI.

Figure 6.20 shows basically the same cabinet but at a different location: a pole-mounted structure. Notice the station side secondary protector block and the copper pair punch down block. Figure 6.21 shows the same type of installation, this time using a fiberglass pedestal

Figure 6.20 Station copper HVI—pole mount.

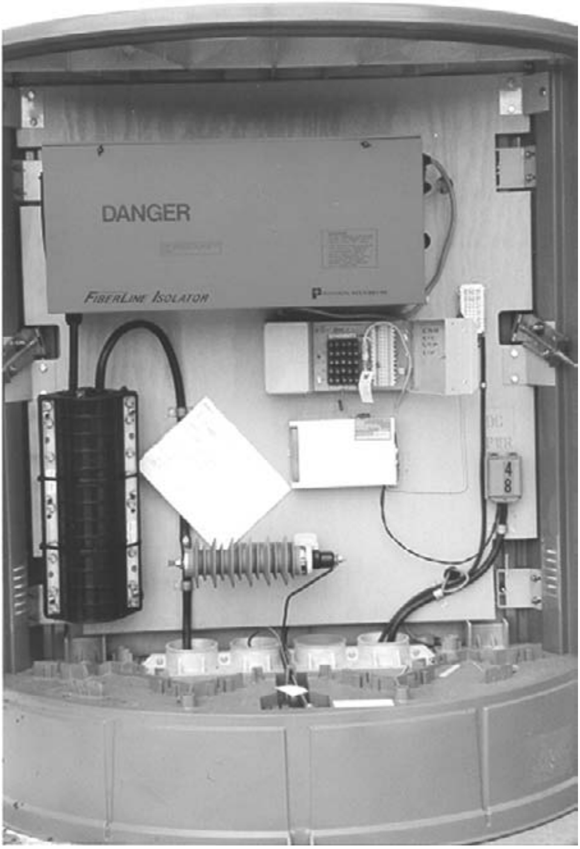

Figure 6.21 Station copper HVI—pedestal.

configuration. Notice the lightning arrester connections: very clean, short, and ample space is provided.

COPPER HVI SYSTEM INITIAL TESTING

The proper use of rubber gloves, mats and blankets, PPE, and so on is required during the testing of the HVI. PPE is discussed in Chapter 7. The following procedures can be used for testing and maintaining copper HVI systems.

The following steps outline a safe method for testing a new HVI installation:

- Step 1: Verify that all circuit cards are removed from their respective slots.
- Step 2: Ensure that all station side circuit connections are intact and functional.
- Step 3: Insert the test card into each shelf slot and verify equipment power is functioning properly prior to circuit card insertion. If a test card is not available, measure voltages on the appropriate pins on the secondary protection block.
- Step 4: Test all station side pairs from the HVI to the power telecommunications equipment using appropriate test instruments. This is done in two steps: between the secondary protector block and the power telecommunications equipment and between the secondary block to the test card in the HVI shelf. Repeat these tests for each shelf slot and each pair connecting to the power telecommunications equipment.
- Step 5: Test all CO side pairs for shorts, grounds, and opens between the shelf slots, using a test card, and the CO termination main distribution frame (MDF) or any other available test pint that is beyond the 300-V point.

  Caution: Never connect AC-powered meters in a substation while testing CO side circuits. Power fault GPR could catastrophically damage the test instruments and injure personnel. Only use battery-operated test instruments.
- Step 6: With proper PPE in place, plug in each card and test each circuit all the way through from the MDF to the power telecommunications equipment. If the circuit ultimately connects substation to substation or substation to other power company facility, then test functionality end to end.

  Circuits that do not test end to end could have a wiring rollover (tip-ring reversal), short, open, crossover, and so on, and the circuit card should be removed, test card inserted, and circuit analyzed from HVI test card to station equipment or test card to CO mainframe.
- Step 7: Turn circuits over to operations.
- Step 8: Inspect annually.

COPPER HVI MAINTENANCE AND INSPECTION

A properly installed HVI system requires very little maintenance. However, the importance for reliable HV transmission system protective relaying relies on Class A and SCADA on Class B protected telecommunications circuits being periodically inspected and performance-tested. These telecommunications circuits require immediate action should a malfunction occur or any infraction is found. Recommended inspection intervals may vary from service provider to service user. Again, these circuits are of utmost importance and reliability must be assured through periodic inspections and testing.

Physical Inspections

Physical inspections should be conducted at least once per year to assure reliable performance. The following tips should help physical inspections.

- *Substation HVI visual*: Look for possible corrosion at ground connections, loose hardware, loose cords, nicked wires, rodent or other damage, debris, and infringement on 6-in. CO-station gaps. Look for better ways to route wires should physical changes occur in the control building from new construction.
- *Remote 300-V point and/or CO*: Inspect CO mainframe for proper termination equipment, circuit identification tags, proper protectors, drawing accuracy, reporting phone numbers, and so on.
- *Review trouble records*: Make sure all temporary trouble repairs have been made permanent and long-lasting.
- *Review cable records*: Periodically verify that all Class A and B circuits are clearly marked and tagged and computer messaging screens have noted the critical nature of these circuits on the telecommunication’s maintenance documents. Make sure the notes accurately state who to notify at the power company should maintenance be performed.
- *Periodically verify that the shortest circuit path exists between telecommunications circuit end points:* Over time, new

construction projects provide new cables and possibly shorter distances become end points. Shorter paths mean less maintenance.

Common Mistakes with Copper HVI Installations

- Do not use 66 blocks or other low dielectric terminations on CO side of HVI.
- Do not allow station side wires to touch, cross over, or be within 6 in. of CO side wires and equipment. A quick solution is to use Schedule 80 PVC conduit as an insulator. Make sure mounting bolts do not infringe on the 6 in. gap.
- Do not let external power supply AC cords cross over CO side cables.
- Make sure high dielectric dedicated cables are used between the HVI and the 300-V point.
- Do not use nonshielded cable drops into substations. Most drops are not insulated for GPR and can fail upon power fault.
- Do not depend on shelf heaters to warm equipment in extreme cold weather. Heaters are mainly for moisture control.

Periodic Testing

- *HVI testing:* Test each circuit for proper performance approximately once per year, including test tone levels, alarm indications, signal levels and reserve margins, frequency response, and environmental control settings (i.e., heater, fans, etc.).

Engineering Evaluations

- *Expected GPR* should be reviewed (recalculated) against design parameters (i.e., distance to 300-V point) approximately once every two years. This would include review of available fault current, changes to substation ground grid resistance, and changes in soil condition (drought/wet years). Correct any deficiency.
- *Field testing* and measurements of station ground grid resistance to provide valuable information about expected circuit conditions under fault situations.

- *Future growth*: Reevaluate GPR and ZOI conditions before a station's physical expansion; reevaluate all parameters should new circuits be proposed, fault currents increase, and so on.

FIBER HVI SYSTEMS INSTALLATION

This section of the book addresses the proper use of fiber optic cables crossing the ZOI according to IEEE Std. 1590-2009™. The optical fiber cable connects the 300-V point and the electrical supply location. Fiber is popularly used because of its inherent isolation properties. The main factor regarding fiber HVI systems is the location of the copper-to-fiber junction (CFJ). The CFJ must be located outside the ZOI or possibilities exist for someone to be standing on earth potential that comes in contact with the remote transfer potential carried through the cable's insulated shield conductor. This book does not address situations where the CFJ is located inside the ZOI where very special adaptations are needed such as insulating the CFJ. Readers are directed to IEEE Std. 487-2007 should they consider installing the CFJ inside the ZOI.

This section of the book also addresses optical fiber cable installations to wireless cell sites. Wireless cell site equipment is often located at the base of HV power structures (transmission line towers), the antennae are located above or below the energized power conductors, and the optical fiber cable crosses the ZOI. Fault-producing GPRs are usually caused by a power line insulation failure (flashover) or lightning strikes. The lightning energy is distributed though the tower grounding (shield) conductors and is distributed to adjacent tower grounds producing GPRs at those ancillary locations where other cell sites might be located.

Design Factors

The following general design factors or considerations are part of fiber HVI systems.

- Location of the CFJ is critical and should be outside the ZOI. The important factor is to keep the copper outside the ZOI to eliminate the possibility of transfer potentials. The shield conductor of copper cables connecting CFJs that are well within the

ZOI can transfer LV remote ground potentials to the CFJ location where higher earth surface voltages exist, creating a safety hazard.

- There are many ways to power the CFJ: CO span power from the copper conductors, high intensity-led laser light that is converted to electrical energy by a photo detector, solar/wind power charging a battery backup supply, and AC power if available.
- The optical electrical interface (OEI) is normally powered by AC or DC sources that are available at the ESL. DC power is required for increased reliability if the HV AC power does not have a backup generator and is out of service for any reason.
- There are recommended practices to isolate the neutral at the ESL when powering the equipment with 120/240 VAC electrical service. The National Electric Code (NEC®) code requires grounding the AC neutral at the service location; however, isolating the neutral via isolation transformers, neutral blockers, or leaving it disconnected has the benefit of not transferring GPR energy to neighborhood electrical services.
- Electrical induction in copper cables may be a factor to consider. Location of the CFJ should take into account GPRs generated by longitudinal induction.
- The use of all dielectric optical fiber cables across the ZOI is the preferred practice. The use of optical fiber cables with metallic members or the placement of metallic conductors with all dielectric optical fiber cables for tracking purposes is not recommended. The reader is asked to refer to IEEE Std. 487-2007 should copper tracers or shielded optical fiber cable be desired.
- The locations of touch and step potentials are confined to the CFJ location only (discussed in more detail in Chapter 7). The touch and step potentials will be minimal if the CFJ is outside the ZOI.

Preconstruction and Construction

Similar to copper HVI systems, one should do as much preconstruction as possible off-site. Although there is less concern for electrical safety with fiber HVIs, considering the remote possibility of any electrical equipment failure or other unexpected accident occurring while exposed to construction or maintenance activities should be avoided for safety prevention whenever possible. Cabinet construction, equipment testing, chassis wiring, and any other construction activity that can be completed off-site is recommended to be performed off-site.

Location of CFJ

Since one side of the CFJ is copper, the CFJ needs to be located outside of the ZOI. Since the location of the CFJ is outside the ZOI, shunt protectors can be used in accordance with general plant design and construction practices. However, shunt protectors on Class A service should be avoided simply due to the possibility that a 300-V potential is likely to occur at the CFJ location during a power fault, thus causing Class A services to be momentarily interrupted.

Powering the CFJ

There are several ways to power the copper to fiber telecommunications equipment housed at the CFJ. Most of these options are listed below:

- Some CFJ HVI equipment is powered directly from the copper pairs coming from the CO. This is referred to as “span power.”
- Some CFJ equipment is powered by express pairs. Express pairs are dedicated pairs for the sole purpose of bringing 48 VDC power to the CFJ. This is not always supported by telecommunications service providers since they are easily mistaken for faulty pairs during testing.
- Power over fiber is another available option. This option converts high power laser light energy from the OEI into DC power at the CFJ.
- Locally powered AC–DC supplies are viable options when the CFJ is located where AC power is available.
- Locally powered solar cell or small wind turbine systems with battery backup are viable alternatives.

Whatever source of CFJ power is used, battery backup, emergency generator, and/or uninterruptible power supply (UPS) systems should be considered.

Powering the OEI

The most common method for powering the OEI is the use of station power or utility service power. Battery backup power should be used.

Utility AC power can have issues regarding its service neutral. For example, the NEC requires grounding the neutral at wireless cell site locations. However, a power fault GPR at the OEI location can transfer to the utility service transformer, causing a secondary GPR to develop a distance away from the cell site. The transferred GPR energy at the service transformer location can also transfer energy to other nearby electric utility customers, thus causing collateral damage. As explained earlier in this book, neutral isolation or 120 VAC power isolation transformers should be used to prevent collateral damage.

Applicable Codes and Compliance

The wireless cell site or any ESL requires that all applicable building codes be implemented and compliant. These codes might involve the NEC, the National Electrical Safety Code (NESC), and possibly other local ordinances or special compliance requirements.

FIBER HVI INSTALLATION EXAMPLES

Several examples of fiber HVI installations are provided in the next few sections. The special characteristics of each photo are pointed out for reference purposes.

CFJ

Figure 6.22 shows a CFJ installed on the side of the right of way or power line corridor. Notice the gravel for added safety should there be an issue with the copper cable transfer potential.

Figure 6.23 shows another CFJ installation; this time equipment is mounted on a support structure. Notice the copper CO cable on the bottom

Figure 6.22 CFJ fiber. Courtesy of RLH Industries, Inc.

Figure 6.23 CFJ fiber—support structure. Courtesy of RLH Industries, Inc.

Figure 6.24 CFJ fiber—with solar power. Courtesy of RLH Industries, Inc.

left of the cabinet and the optical fiber cable coming out of the top of the HVI and routed around to the bottom right side of the cabinet. The shunt protector block is provided in the middle of the back plane board.

- A CFJ with solar power assist is shown in Figure 6.24.
- A CFJ feeding a wind farm is shown in Figures 6.25 and 6.26.

OEI

Figure 6.27 shows an OEI next to a power tower having wireless cell site equipment. Notice the grounded fence post (for equipotential) and gravel for added isolation from touch and step potential. Since this electric supply station has an equipotential mat, the gravel serves as added insulation (secondary).

Figure 6.28 shows the OEI at wind farm-2. Notice the secondary protector block and the ground bus bar. Also note the minimum lengths of the grounding conductors.

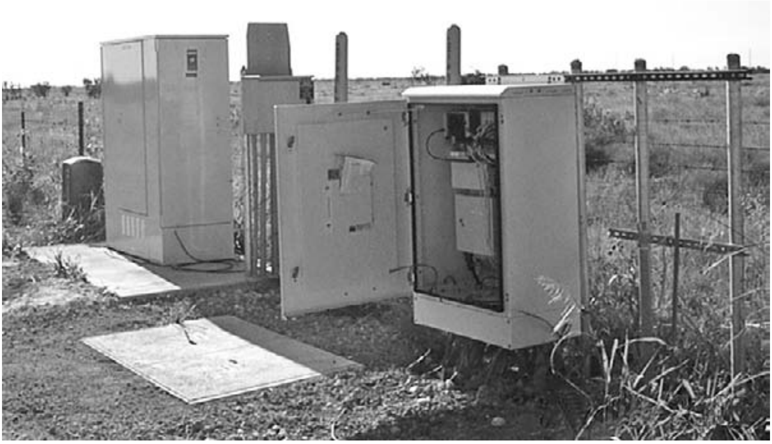

Figure 6.25 CFJ fiber—wind farm-1.

Figure 6.26 CFJ fiber wind farm-2. Courtesy of RLH Industries, Inc.

WIRELESS SITES ON ELECTRICAL POWER TOWERS

Installing HVI equipment at wireless cell sites mounted on power towers is similar to substation installations; all are considered ESLs. Figure 6.29 shows a wireless cell site on a power transmission tower. Notice the antenna mounted at the tower's waist, monopole in the

Figure 6.27 OEI—wireless cell site on power tower. Courtesy of RLH Industries, Inc.

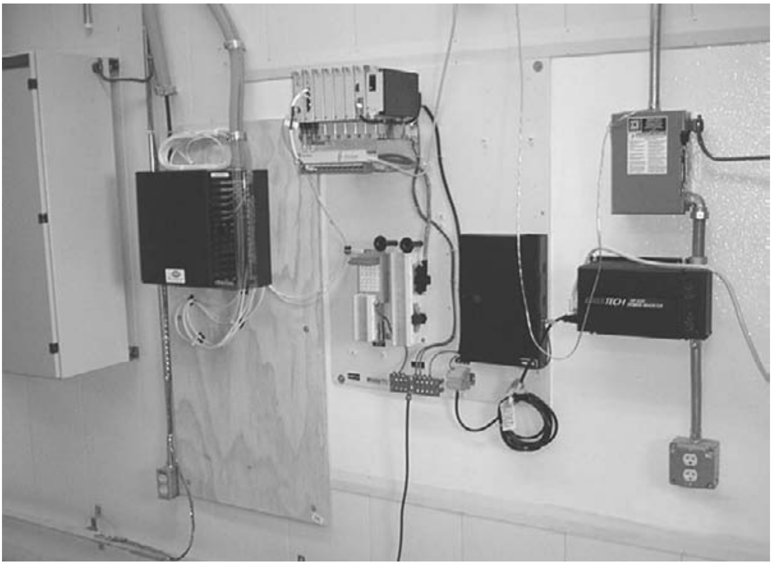

Figure 6.28 OEI—wind farm-2 substation.

Figure 6.29 Wireless cell site on power transmission tower.

center for antenna feed lines, and telecommunications equipment mounted at the footing. Some power companies do not allow the extra equipment weight on the tower structure (as the tower might not be designed for it) requiring self-supporting monopoles, while other power companies may approve antenna feed lines attached to tower structures.

A well-designed installation requires protection coordination of tower and equipment grounding, AC power feeds, and telecommunications cables protection and grounding.

Design Factors

The following design factors should be taken into consideration when designing or upgrading a wireless cell site on a power tower:

- Power transmission structure grounding designs normally require actual tower ground resistance measurements to be 10 Ω or less. A power company will install extra ground rods and copper counterpoise conductors to achieve this requirement. This requirement prevents lightning back flashover situations as discussed earlier. This can lead to extended ZOI situations.
- The base transceiver station (BTS) grounding system should utilize the “master ground” (sometimes referred to as “ground mecca”) or “single-point grounding” system. All telecommunications equipment, secondary protectors, ice bridges, and so on should use this single-point grounding system to minimize potential differences and eliminate ground loops.
- A gap grounding ring should be used inside a building to minimize ground loops.
- A wire mesh under the BTS equipment should be used to minimize touch potential.
- The ice bridge (if used) should be bonded to the ground connection between the tower and master ground.
- The concrete slab should have its rebar grounded to the mat. The porous nature of concrete helps lower the station ground resistance and the equipotential objective.
- The fiber telecommunications cable should enter the BTS site in PVC conduit. The conduit should extend beyond the fence a minimum of 3 ft.
- Secondary protectors on the OEI should be bonded to the master ground junction.
- Special circumstances might require isolation of the 120/240 VAC power source neutral (discussed in more detail later in this chapter).
- The 120/240 VAC power source panel needs to be grounded to the BTS equipment grounding conductors. A ground rod might be required by local code. If a rod is required, the rod should be bonded to the ground conductors at the service entrance location.

The AC power conduit should be PVC and extend outside and beyond the fence a minimum of 3 ft.

Station Grounding

Figure 6.30 shows the recommended grounding plan of a wireless cell site on a power transmission structure. Notice how the wireless equipment ground, fence, gate, rebar in concrete slab, and ground grid are all connected together to form a zone of equipotential and that the ground grid is connected to the power tower at one location. Under this arrangement, the wireless site is essentially bonded to the power tower ground grid. The power tower GPR is then transferred to the wireless equipotential zone. Therefore, the wireless equipment, ground mat, fence, and so on will all rise to approximately the same potential. Touch and step potentials safety concerns are minimized. Note that the fence posts are also grounded to the ground grid. It is important to place gravel around the tower to minimize touch potential.

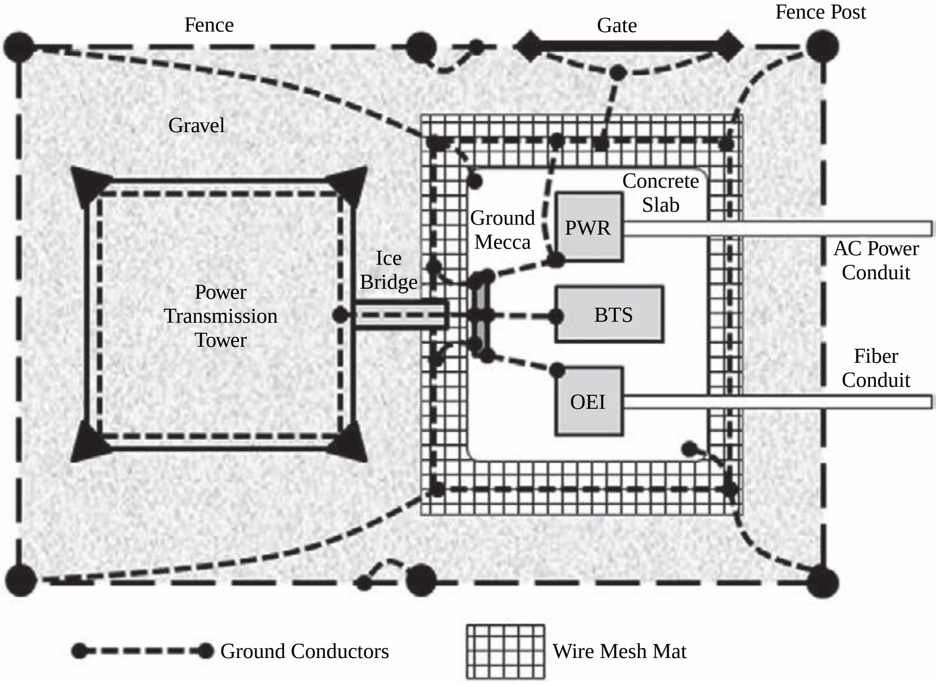

Figure 6.30 Wireless cell site grounding on power transmission tower.

Electrical Power Supply

One of the issues regarding the installation of telecommunications equipment at electric power towers is the required grounding of the incoming AC power service neutral and at the same time, having the need to isolate the AC power neutral from transfer potential similar to floating the shield on a copper cable across the ZOI.

The utility power to a wireless site is often provided by a single-phase 120/240 VAC secondary service from a distribution transformer that has its center tap neutral-bonded to the primary multi-grounded neutral (MGN). The service neutral at the wireless site is also grounded per NEC. This power supply AC neutral that is grounded at both ends presents a path for the transfer potential during a power fault or lightning strike at the tower. This is similar to the need to isolate the shield wire at a substation when a copper cable crossing the ZOI HVI system is used. If the GPR is of sufficient magnitude and the neutral is not isolated at the wireless site, equipment damage and safety hazards can exist in the distribution line's MGN that can affect other commercial and residential services. This contradiction of code rules versus practical applications needs to be addressed, especially if equipment damage has occurred.

There are possible solutions to improve this situation which might still meet code rules; for instance, do not connect the neutral at the site's station entrance equipment, provide an isolation transformer at the site's station entrance equipment, or temporarily open service power (including the neutral) during the GPR event. The first option (do not connect the neutral) is not in compliance with the NEC.

Isolation transformers, such as the one shown in Figure 6.31, can be used to solve this electrical issue. This method calls for installing

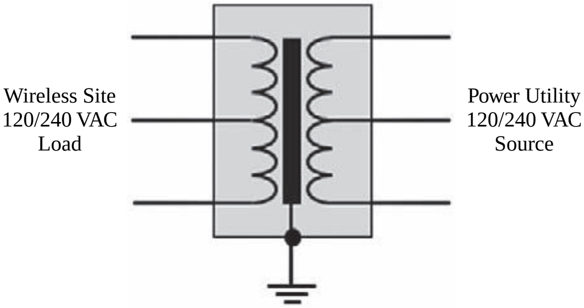

Figure 6.31 Isolation transformer.

an isolation transformer in series with the service power at the site to isolate the neutral from a direct connection back to the service transformer MGN on the distribution line. In other words, this concept requires the power company's wye-grounded distribution system to be stepped down from the primary voltage to 120/240 VAC secondary (the normal situation) and then brought underground (preferably) to a 120/240 VAC grounded neutral isolation transformer at the BTS site. Note in Figure 6.31 that the isolation transformer's neutral is not solidly connected to the secondary 120/240 service on either side. This design allows the wireless BTS equipment to have a grounded neutral electrical system. It also provides isolation from HV transfer potentials to the distribution MGN where other services are provided. Note a well-grounded MGN reduces the transfer potential, provided very low ground rod resistances and low soil resistivity exist.

Another possible solution is to use a disconnecting switch at the BTS site that temporarily opens the AC power source during the GPR event. Note that temporarily disconnecting AC power from the telecommunications equipment requires the use of battery backup power to power the BTS equipment.

In any event, a separate and dedicated distribution transformer and service wires should be used at a wireless site. This dedicated service transformer should not be used to provide AC service power to nearby non-wireless site residential and commercial locations.

PROTECTION AT NON-POWER COMPANY LOCATIONS

The purpose of Level III HVI equipment is to isolate power fault and lightning discharge energy from entering sensitive telecommunications equipment. This section discusses protection equipment requirements when lightning is the most probable cause of GPR and not power faults. These sites are not in close proximity of HV substations, transmission, or distribution power lines. These sites include high altitude telecommunications sites, 911 Public Safety Answering Point locations (PSAPs), stand-alone wireless cell towers, or other lightning strike susceptible facilities having critical telecommunications services. These telecommunications sites normally have an adjacent radio antenna tower that is frequently struck by lightning.

These sites follow the strict building code requirement of NEC where Level II (1000 V GPR or under) protection is required. There are several references outside this book that address proper grounding at these locations such as the NEC (NFPA 70-2008—NEC), NESC (Accredited Standards Committee C2-2007), and the Standard for the Installation of Lightning Protection Systems (NFPA 780-2000).

This section provides possible protection and grounding enhancements that are needed to improve telecommunications reliability during lightning strike activity. The enhancements apply to antenna structures, telecommunications equipment grounding, buildings, and enclosure grounding.

The standard means of providing lightning protection on a telecommunications circuit at this type of facility is the gas discharge tube (GDT) or other shunt protector. These protectors are designed to shunt most current to ground during a lightning strike. When shunting devices are used to protect equipment from GPR, they also offer a parallel energy discharge path through their copper cable core conductors to remote telecommunications equipment where more shunting protectors might be located. High GPRs can cause equipment damage by not having a zone of equipotential and having remote ground locations during a GPR event.

A well-designed stand-alone installation, from a lightning protection point of view, requires protection coordination of 120/240 VAC power service (as discussed earlier), single point grounding, proper interior grounding, and proper telecommunications cables protection and grounding.

Single-Point Ground Reference

Starting with the equipotential design requirements of the station ground grid, the spacing of ground electrodes can cause significant differences in earth potential during a GPR event. When a single-point reference grounding arrangement is utilized and lightning strikes the tower, see Figure 6.32, GPR potential differences occur between grounding electrodes, potentially causing equipment damage. Note the different grounding electrode locations where potential differences can exist because of the non-equipotential grounding design.

Figure 6.33 shows the single-point ground reference concept using a master ground bar arrangement. The majority of lightning energy will

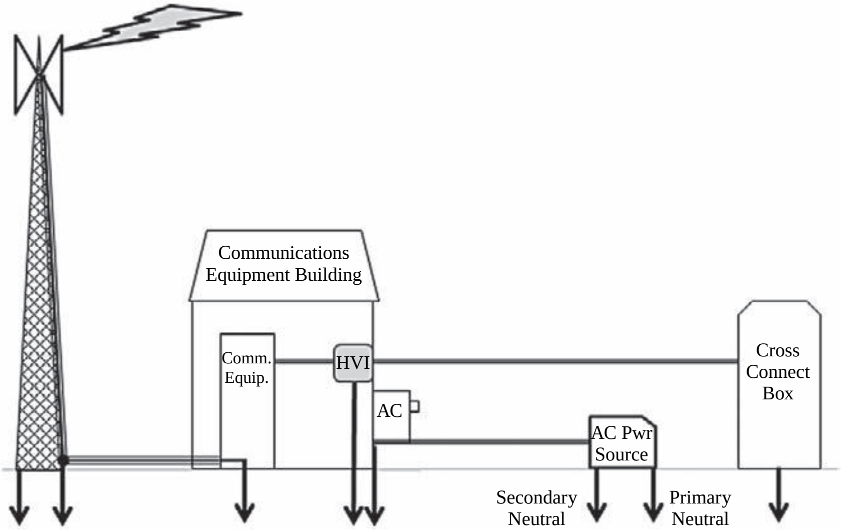

Figure 6.32 Problematic GPR grounding.

travel down the tower and into the earth through the tower grounding electrodes while the telecommunications equipment experiences a zone of equipotential.

Improved performance can be achieved by providing an equipotential grounding system with a “master ground bar” as shown in Figure 6.33.

Interior Equipment Grounding

Lightning strike currents can create strong electromagnetic fields around the grounding conductors. Equipment exposure to these electromagnetic fields can produce undesirable voltages and currents from induction. Interior equipment ground rings are often used to bond all equipment together inside the building. This ring is not continuous; there is a gap in order to block loop currents. The ground ring is then connected to the master ground bar for equipotential benefits.

Hybrid Isolation HVI and NEC Grounding

There are special occasions where an existing NEC grounded facility that has an adjacent antenna tower vulnerable to lightning experiences

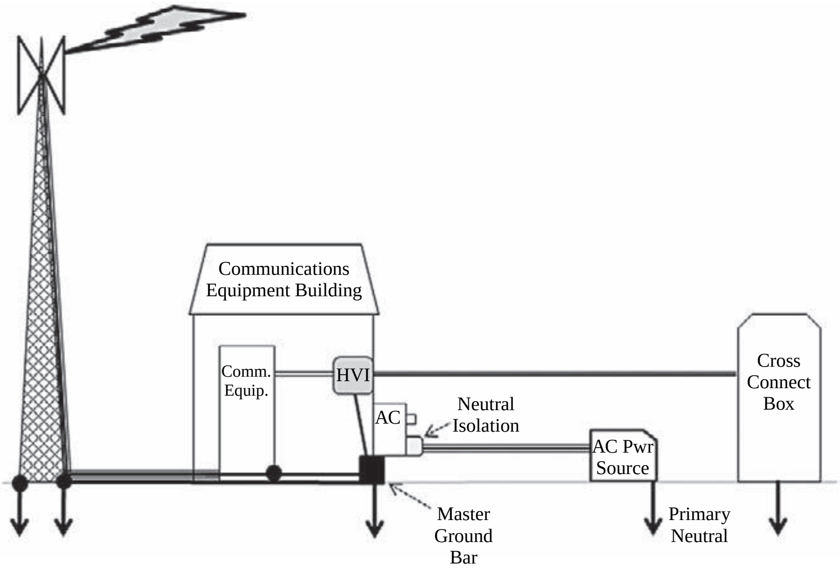

Figure 6.33 Desirable grounding.

telecommunications equipment damage after lightning strike events. In particular, the sensitive electronic circuits that connect to outside telecommunications service conductors experience damage. The problem is that local GPRs cause the local equipment grounds to rise in potential and flash back to the incoming telecommunications circuit pairs (similar to back flashover of a power company's transmission tower). The twisted pairs in the telecommunications cables are connected to delicate circuit board electronics in the facility (e.g., 911 call center equipment) that do not have insulation specifications designed for GPR voltages. Figure 6.34 is an example of a PSAP site having an antenna tower vulnerable to lightning.

Figure 6.35 shows the application of an insulation-type HVI that is used to isolate the remote copper pairs from back flashing the sensitive electronic equipment. Notice that only the critical telecommunications pairs are isolated. The drawing shows the shunt protectors according to NEC requirements, but the sensitive 911 equipment is isolated from the GPR differential. Isolating the telecommunications service conductors from the sensitive circuit board electronics using isolation instead of shunt protection helps resolves equipment damage problems with this situation.

Figure 6.34 PSAP example.

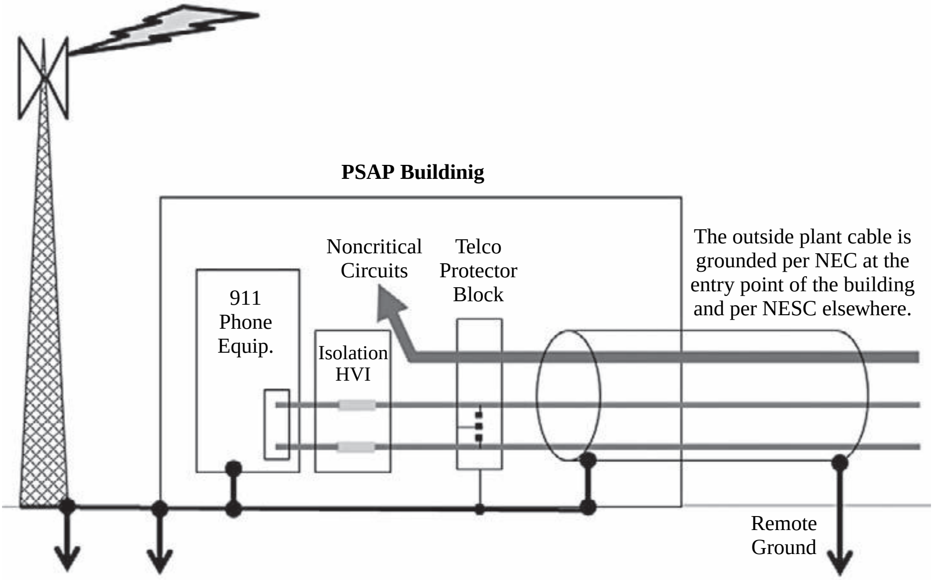

Figure 6.35 PSAP isolation HVI.

Service Performance Objective (SPO)

Applying NEC (NFPA 70-2008—NEC) with shunt circuit protectors and not applying IEEE Std. 487-2007 recommendations rules out Class A service at these high lightning-prone GPR locations due to the possibility of firing the shunt circuit protectors. Improved site grounding measures may minimize equipment damage; however, shunt protectors are still likely to fire and Class A service is not provided. PSAP facilities that have critical 911 circuits that are adjacent to an antenna tower might have emergency calls dropped during a lighting strike on the antenna tower event. This requires the caller to call back. Using the hybrid approach as shown in Figure 6.35 provides Class A service while staying in compliance with the NEC.

CHAPTER 7

Personnel Safety Working with HV Protection Equipment

LEARNING OBJECTIVES

- Discuss "personal protection" when it comes to electric power systems safety
- Explain how one can be safe by "isolation"
- Explain how one can be safe in a "zone of equipotential"
- Discuss "ground potential rise"
- Explain why it is very important to know about "touch" and "step" potentials
- Explain human vulnerability to electricity and current levels
- Discuss how line maintenance is performed safely when lines are "energized" or "de-energized and grounded"
- Explain what is meant by "switching"
- Discuss "safety hazards" around the home

High Voltage Protection for Telecommunications, First Edition. Steven W. Blume.

ELECTRICAL SAFETY

The main issues concerning electrical safety in high voltage (HV) environments are the invisible nature of the hazardous situations and the element of surprise. One has to anticipate, visualize, and plan for the unexpected and follow all proper safety rules before, during, and after the HV event occurs. Then, gain safety procedure confidence habitually and consistently when working around electricity. Those who have experience in electrical safety plan for the unexpected. There are several methodologies and personal protection equipment (PPE) devices available that make working conditions around electrical equipment safe.

The proper practices and safety equipment related to HV protection for telecommunications (HVPT) services are explained in this chapter. The theories behind those practices are also discussed. Having a good fundamental understanding of electrical safety principles is very important and is effective in recognizing and avoiding possible electrical hazards.

The efforts of many individuals, companies, organizations, and universities worldwide have contributed to the renowned IEEE Std. 80-2000™ Guide for Safety in AC Substation Grounding. This IEEE standard was developed to provide guidance and information pertinent to safe grounding practices in substation design. This standard covers varying soil conditions, ground grid design recommendations, tolerable, expected, and actual potentials, resistance measurements, and several other ground grid design and safety essentials.

ELECTRICAL PROTECTION PRIORITIES

Generally speaking, the purpose for electrical protection in HV environments follows these priorities:

1. ***Safety of Personnel.*** Safety of personnel is most important. Design, construction, and maintenance of the high voltage interface (HVI) systems primarily address the safety of personnel. General safety rules and procedures during construction and maintenance activities are usually pointed out in company handbooks. Make sure the technicians involved in the HVI

project have read the company's safety rules to confirm compliance.

2. ***Damage to Property.*** Second in priority is damage to property. The HVI installation is designed to minimize damage to property. Make sure the HVPT equipment is properly installed according to industry standards.
3. ***Damage to Equipment.*** Although equipment damage is a concern, HVI equipment is selected and designed to provide priorities 1 and 2 protection.

TOUCH AND STEP POTENTIALS

During a lightning strike or power fault event in a substation, the entire substation rises to a high potential, and anyone standing on the ground grid during that event should experience no touch or step potential because of equipotential grounding. Touch potential as shown in Figure 7.1 is the difference between the voltage magnitude of a person (or animal) touching an object and the magnitude of voltage at the person's feet. Touch potential can also be viewed as the difference in voltage between two potentials (i.e., hand to hand). Equal potential means zero

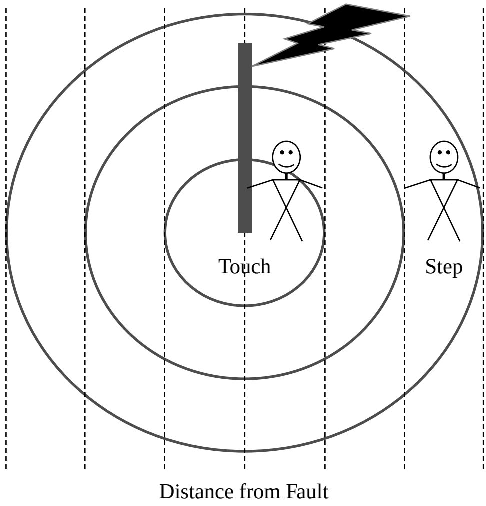

Figure 7.1 Touch and step potential.

or minimal voltage exists between the two potentials, making it safe to touch. Rubber gloves are used to provide isolation between touch potentials. Step potential is the difference in voltage between a person's (or animal's) feet.

Shoes, gloves, and other articles of clothing plus gravel and rubber mats help insulate a person from touch and step potentials. Approved, tested, and properly used rubber safety products provide isolation from potentially hazardous touch and step potentials.

Principles of "Equipotential" Safety

Substations are built with a large quantity of bare copper conductors and ground rods connected together and buried about 18–26 in. below the surface. Metal fences, structural steel, major equipment tanks, racks and frames, and all other metal objects requiring an electrical ground reference are also connected to the buried copper conductors. This elaborate interconnected system of conductive metals forms what is referred to as the station ground grid.

This ground grid provides a safe working environment that is sometimes referred to as equipotential grounding. Usually, a copper conductor is buried outside the fence perimeter approximately 3 ft (1 m) from the fence to extend the ground grid for additional safety. Usually, 2–4 in. of clean gravel is placed on top of the station soil to serve as additional isolation from currents flowing through the earth and surface voltage profiles that exist during fault conditions. Figure 7.2 shows the ground grid concept.

There are two main reasons for having an effective grounding system: first, to provide a solid ground path for fault current to flow back to the energy sources to trip circuit breakers (i.e., system protection); second, effective grounds provide a zone of equipotential for safe working environments (i.e., personnel protection). The effective ground grid causes high fault currents to trip circuit breakers faster than less complicated or minimum station grounds. Thus, an area of equipotential minimizes the risk of someone experiencing a current flow situation during a lightning strike or power fault. Theoretically, everything a person touches in a zone of "equipotential" is at the same voltage, and therefore, no current flows through the person. As a comparison example, suppose you were in an airplane flying above the earth at 30,000 ft. Everything inside the airplane seems normal. The same is true in a properly designed substation equipotential ground grid

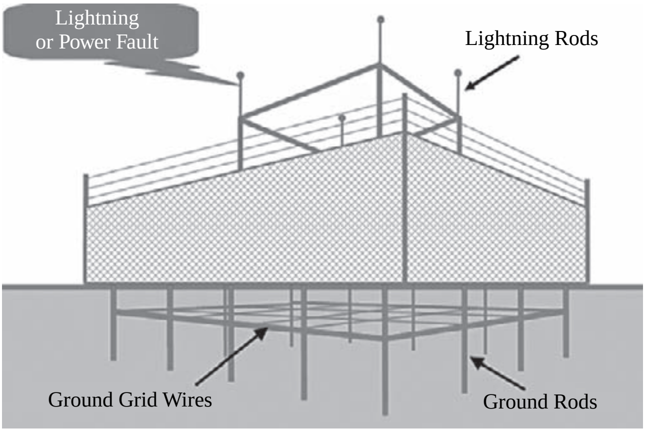

Figure 7.2 Substation ground grid.

under fault conditions having a ground potential rise (GPR) of 30,000 kV.

Personal Protection

Personal protection refers to the use of proper clothing, insulating rubber goods, or other safety tools that isolate oneself from electrical shock. The uses of insulation protection equipment or working in a zone of equipotential are known methods for reliable electrical safety. All one has to do is follow proper safety procedures that have been around for many years.

Human Vulnerability to Electrical Current

Before discussing personal protection in greater detail, it is helpful to understand human vulnerability to electrical current. The level of current flowing through the body determines the seriousness of the situation/injury. Note that the focus is on current flow through the body, not voltage. Yes, a person can come in contact with a potential difference (i.e., touch or step potential) can experience a shock. A potential difference across parts of the body can cause current to flow between the body parts. It is the magnitude of current flowing through the body parts that determines the magnitude of the injury.

Testing back in the early 1950s showed that a current in the range of about 1–2 mA (0.001–0.002 A) flowing through the human body is considered the threshold of sensitivity. As little as 16 mA (0.016 A) can cause the loss of muscle control and a person could lock on to the contact situation. As little as 23 mA (0.023 A) can cause difficulty breathing, and 50 mA can cause severe burning. These body current levels that cause personal injury are relatively small when compared with normal household electrical load. For example, a 60-W light bulb at full brightness with a rated voltage of 120 V draws 500 mA of current, way above human safety threshold.

The residential ground fault circuit interrupter (GFCI) similar to those used in bathrooms opens the circuit if the differential current reaches approximately 5.0 mA (0.005 A). The GFCI opens the circuit breaker well before dangerous current levels are allowed to flow through the human body. The conclusion is humans are very vulnerable to relatively small electrical currents. Therefore, it is of utmost importance that persons working in areas known to have touch and step potentials be properly trained in using PPE.

Principles of "Isolation" Safety

A person can be safe from electrical hazards through the use of proper rubber isolation products such as rubber gloves, shoes, blankets, and mats. Proper rubber goods allow a person to be isolated from touch and step potentials that would otherwise be dangerous. Rubber gloves, shoes, blankets, and mats among other rubber isolation products are commonly referred to as PPE. Electric utilities test their rubber goods PPE frequently to insure that safe working conditions are provided for their employees. Occupational Safety and Health Administration (OSHA) 1910.137 states the rules and regulations for utilities to properly test and manage PPE.

Figure 7.3 shows the cotton inner liners, insulated rubber glove, and leather protector glove used in maintaining HVPT equipment. PPE is also used by the electric power industry for live line maintenance activities where exposure to actual live line conditions is continuous. In the case of HVPT applications, the HV is not present continuously; the use of PPE is for the highly improbable sudden power fault GPR events. In HVPT work, one has to assume the equipment is live or energized, yet in reality, the undesirable event is random and unexpected. PPE protection must be worn at all times as a precautionary measure.

Figure 7.4 shows HV-insulated boots, insulated blankets, and mats for personal protection from step and touch potentials.

Figure 7.3 Insulated rubber gloves.

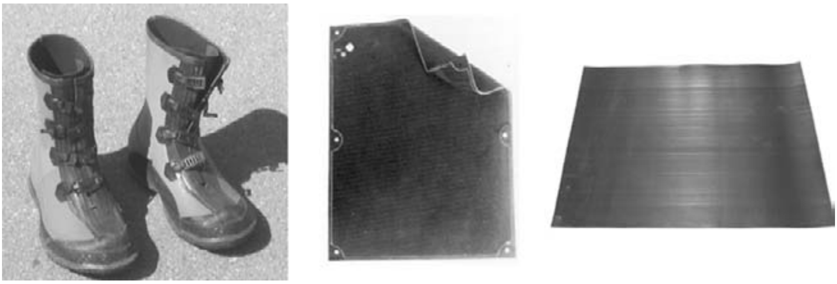

Figure 7.4 Rubber insulated boots, blanket, and mat.

Every electric utility has extensive and very detailed safety procedures regarding the proper use of rubber goods and other safety-related tools and equipment. Adherence to these strict safety rules and equipment testing procedures by power and telecommunications utilities help ensure that workers are safe.

When it comes to telecommunications industry personnel working on HVPT equipment, electric power companies expect telecommunications workers to know the safe working procedures around HVI equipment in HV environments, and they are expected to have in their possession at all times properly tested PPE that is ready for use on the job site.

Safety Regarding HVI Equipment

Copper HVI systems pose more concern for proper safety practices than fiber HVI systems. The main areas of concern for a copper HVI

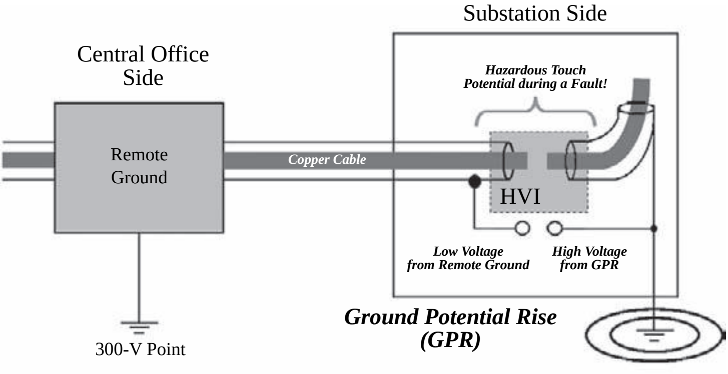

Figure 7.5 Copper HVI, PPE required.

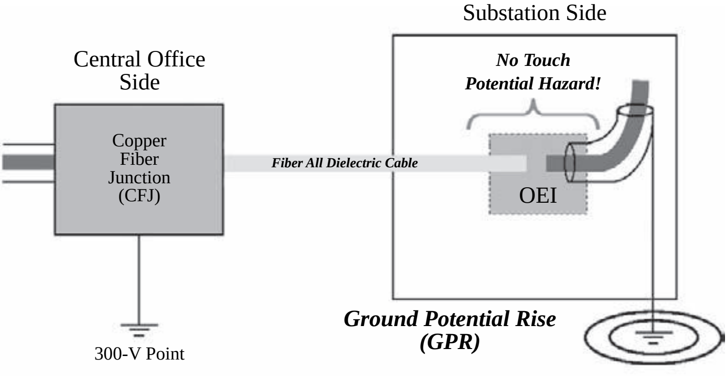

Figure 7.6 Fiber HVI, PPE not required.

system is at the HV environment location where both the GPR and remote ground (300 V) potentials exist across the HVI interface simultaneously as shown in Figure 7.5. Figure 7.6 shows a fiber HVI system in comparison, having copper on one side and fiber (a glass insulator) on the other side. Fiber HVI systems do not require PPE during construction or maintenance if they are properly installed.

PPE is required when working on copper HVI systems, mainly when the technician is exposed to both potentials simultaneously, that is, during an unexpected power fault or lightning strike. The following situations require PPE at all times:

- When removing/installing cards, one's hand can bridge the insulation gap between the station side of the card and the central office (CO) side of the card.

- Anytime when accessing the CO side of the HVI (CO cable, HV insulation jacks, splice cases, etc.). Working with gloves is cumbersome, at best, and sometimes, mistakenly avoided. That practice of not using PPE, especially when working on the CO side of the HVI at the HV location, is completely unacceptable. PPE should be worn at all times when accessing the CO side of an HVI.
- When working on equipment at the 300 V point. A power fault at the substation can transfer a dangerous voltage to the 300 V point.

One of the main advantages of fiber HVI systems is electrical safety. Since the potential difference between the 300-V point and the full GPR does not exist at the same location (i.e., across an HVI interface as in copper HVI systems), optical fiber systems are inherently safe, provided they are properly installed.

Fiber HVI systems can pose electrical safety problems when the copper-to-fiber junction (CFJ), which should be located outside the 300-V point, is in fact located in the zone of influence (ZOI). Should a CFJ be installed inside the ZOI, then PPE is required. The safety concern is that a GPR will produce a dangerous touch and step potential between the well-grounded general telecommunications equipment outside the ZOI and the copper location inside the ZOI. PPE is needed when working on the CFJ if located inside the ZOI.

Personal safety, the prevention of equipment damage, and the reliability of critical telecommunications equipment are the goals of proper high voltage protection for telecommunications.

Glossary

Base transceiver station (BTS): A unit or component of the cell site composed of all radio transmission and receiving equipment.

Bonding: The permanent joining of metallic materials to form a low resistive electrical path for current to flow. Bonding usually refers to connecting metal objects together to form an equipotential. Normally, bonding is done with a number 6 solid copper wire.

Carbon block protector: An assembly of two or three carbon blocks and air gaps designed to a specific breakdown voltage. These devices are normally connected for telecommunications circuits to provide overvoltage protection and current paths to ground during overvoltage conditions.

Drainage transformers, units, or reactors: Center-tapped inductive devices designed to relieve conductor-to-conductor and conductor-to-ground voltage stress by draining extraneous currents to ground.

Electric supply locations: Any building, separate space, or site in which electric supply equipment is located that may be subjected to the effects of ground potential rise (GPR) from power system fault currents. This includes generation, transformation, conversion, switching, and delivery facilities.

Fuse links: These consist of a small link of cable sized two to four gauges smaller than the cable pair and their function is as a fuse or weak link in the cable. They are designed to open the circuit from shorts created by the other protection devices to block long duration overcurrents.

Gas-filled protector (gas tubes): Gas tubes are similar to carbon block protectors in operation except that the electrodes are metal-sealed in a ceramic or glass envelope containing inert gasses to rapidly conduct high currents. They provide almost infinite impedance across the line until triggered by an overvoltage.

Grounding: This implies establishing a low resistance path of metallic objects to the true earth ground reference. Grounding usually refers to providing an electrical path to true earth.

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Heat coils: Heat coils have a continuous current rating of 350 mA for a period of 3 h. However, they can operate in the order of 500 mA when exposed to overcurrent for under 3 min. Heat coils are normally used in central offices to act similar to a fuse to protect the circuit from sneak currents. They are low voltage and low current-rated and operate one time and must be replaced.

High dielectric cable: Cable that provides high voltage (HV) insulation between conductors, between conductors and the shield, and between the shield and the earth.

High voltage (HV) disconnect jack: A device that is used to disconnect cable pairs for testing purposes. They are used to help safeguard personnel from remote ground potentials.

High voltage (HV) isolating relay: A device that provides for the repeating of direct current (DC) on/off signals while maintaining longitudinal isolation. HV isolating relays may be used in conjunction with isolating transformers or may be used as stand-alone devices for DC tripping or DC telemetering.

Horn gaps: Metal electrode air gap devices, usually used outdoors on open-wire lines that are exposed to high voltage (HV) power lines and lightning strikes. They are normally used in conjunction with isolating or drainage transformers. They are sometimes used along open-wire pairs.

Isolating transformers: Transformers that provide longitudinal isolation of the telecommunication facilities. They can be designed for use in a combined isolating drainage transformer configuration.

Isolating transformers with high voltage (HV) isolating relays: An assembly that provides protection for standard telephone service and consists basically of an isolating transformer and an HV isolating relay. The transformer provides a path for voice and ringing frequencies while the relay provides a means for repeating DC signals around the transformer. A locally supplied battery or DC power supply is required for operation of the telephone and relay.

Lightning characteristics (typical):

- Voltage = millions (dielectric strength of air is approximately 100 kV/ft)
- Current = 15–65 kA (most are 15–25 kA)
- Rise time to peak voltage = 2–4 μs
- Impulse duration = 25–50 μs

Lightning protection: Bottom line is to provide a short low impedance current path to ground. High resistance paths for lightning energy can cause excessive heating and damage property and cause high GPR for safety concerns.

Longitudinal induction: Wire-line telecommunication facilities entering electric supply locations are frequently routed close to power lines. Such facilities are then subject to the interfering induction effects of the power lines under both normal and fault conditions. Satisfactory electrical coordination between the two systems should be achieved under both normal and fault conditions on the power system.

Neutralizing transformers and reactors: Devices that introduce a voltage into a circuit pair that opposes an unwanted voltage. These devices neutralize extraneous longitudinal voltages resulting from ground rise potential (GPR), longitudinal induction, or both while simultaneously allowing alternating current (AC) and direct current (DC) metallic signals to communicate. These transformers or reactors are primarily used to protect telecommunication or control circuits at power stations or along routes exposed to power line induction or both.

Open-wire protectors (sometimes called hotline protectors): Combined isolating and drainage transformer protectors that are used in conjunction with horn gap protectors and grounding relays on open-wire lines to provide protection against lightning, power contacts, or high values of induced voltage.

Optic coupling devices: An isolation device that uses optical communication links to provide isolation. Circuitry on both sides of the optical connection is used to convert the electrical signals into optical signals for transmission through the optical link.

Short circuit relays (sometimes called **grounding relays):** Circuit grounding relays that are used to ground an exposed telecommunications or telephone pair, usually on open-wire joint-use facilities during periods of severe power system disturbances.

Solid-state protectors: A protective device that employs solid-state circuit elements. They provide both a high speed voltage-limiting function and current sensing. Avalanche diodes are used as current limiters and crowbar devices (similar to silicon controlled rectifiers [SCRs]) to reduce current in the telecommunications circuit within nanoseconds. They are usually integrated into the terminal apparatus.

Spark gaps: Two electrodes having an air dielectric spacing are used to protect telecommunication circuits from damage due to voltage stress in excess of their dielectric capabilities.

Ventricular fibrillation: The quivering of the heart muscles.

Wireless services provider (WSP): A company that provides wireless telecommunication service to customers, for example, cellular service providers, radio common carriers, and paging companies.

Appendix: Service Request Form

This appendix provides a simple work sheet to collect required information to calculate a ground potential rise (GPR) and zone of influence (ZOI) that is available from the Annex of IEEE Std. 1590™. The service request form (see Fig. A) can be used by wireless and telecommunications service providers. Most of the data are provided by the electric utility, which establishes the environment and whether Levels I, II, or III protection is required, as well as the safety implications. It is then a matter of need, preference, policy, and/or urgency who calculates the resulting GPR and ZOI and who uses the results.

Location and Contact Information

1. ***Name.*** The name of the power company or wireless service provider (WSP).
2. ***Authorized Agent.*** The name and telephone number of the individual(s) placing the request for service.
3. ***Location.*** The location of the electric supply location (either electric power station or wireless site) where service is to be provided.
4. ***Signatures.*** The power company-licensed engineer who provides the technical data. Further, the names, titles, and telephone numbers of the technical contact representatives should be provided for future reference.

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Power Company/WSP	Authorized Agent	Telephone:
Telephone Company	Authorized Agent	Telephone:
Order Date:	Order Number:	Service Date:

Circuit Number	SPO	TYPE	Circuit Description

Power Station:		Address:	
Grid Area (square feet):		Earth Return current:	
Fault Current (rms)	Grid DC Resistance or Impedance at 60 Hz (Ω)	X/R	Ground Potential Rise (GPR) rms: peak:
Pole/Tower:		Address/Number:	
Grid Area (square feet):		Earth Return current:	
Fault Current (rms)	Grid DC Resistance or Impedance at 60 Hz (Ω)	X/R	Ground Potential Rise (GPR) rms: peak:

Power Company Engineer			
Name: Title:	Telephone:	Date:	Signature:
WSP Company Engineer			
Name: Title:	Telephone:	Date:	Signature:
Telephone Company Engineer			
Name: Title:	Telephone:	Date:	Signature:

Figure A Service request form.

Circuit Information

1. ***Circuit Description.*** Number and type of circuits desired. A projected circuit forecast may be helpful.
2. ***Service Performance Classification.*** The service performance objective (Class A, B, or C) and the service type (i.e., four-wire analog data, plain old telephone service) and a circuit description.
3. ***Service Date.*** The customer's desired in service date.

Technical Data

1. ***Grid Area.*** The dimensions of the ground mat or grid area.
2. ***Grid DC Resistance or Impedance at 60 Hz.*** The resistance in ohms (Ω) to remote earth of the ground mat.
3. ***Expected Fault Current.*** The expected total fault current (line-to-ground) at the site must be provided. Fault current is the total current produced by the fault.
4. ***X/R Ratio.*** The ratio of inductive reactance to resistance of the power system at the fault location.
5. ***Expected GPR.*** The calculated GPR information is provided as both V_{rms} and V_{peak}.
6. ***Earth Return Current.*** This is the portion of the fault current (usually expressed in percentage or actual fault current magnitude) that returns to the source locations.

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