GROUNDING

Proper grounding strongly affects personnel safety as well as the safety of equipment, power distribution systems, computers, solid-state devices, lightning, and static protection systems. Improperly grounded installations can result in fatalities, electric shock, equipment damage, and improper operation, especially of solid-state equipment. Improper grounding can even affect cows, resulting in reduced milk production.

Grounding or earthing is applied to electrical systems and to the associated electrical equipment. Electrical systems are grounded, that is, connected to earth, to provide a degree of safety for humans and animals, to limit voltages due to lightning and line surges, to stabilize the system voltages during normal operations, and to limit the voltage when the electrical system comes into contact with a higher-voltage system. Equipment associated with electrical systems is connected to the electrical system and to earth to provide a low-impedance path for a fault current to flow back to the source. This low-impedance path is important in that it allows sufficient current to flow to operate the protective device(s) when a fault to the electrical equipment enclosure or to earth/ground occurs.

Unless noted otherwise, this article will refer to low-voltage systems, defined as those under 600 V.

Abbreviations

AFCI	arc-fault circuit interrupters
ANSI	American National Standards Institute
AWG	American Wire Gauge
CENELEC	European Union Standards Organization
CSA	Canadian Standards Association
GFCI	ground fault circuit interrupter
GFP	ground fault protection
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
ISO	International Standards Organization
NIST	National Institute of Standards and Technology
NFPA	National Fire Protection Association
NEC	National Electrical Code
NESC	National Electrical Safety Code
OSHA	Occupational Safety and Health Administration

Definitions

The definitions are predominately those used in the United States unless otherwise noted.

Bonding. "The permanent joining of metallic parts to form an electrically conductive path that will ensure electrical continuity and the capacity to conduct safely any current likely to be imposed. Bonding is the electrical interconnection of conductive parts, designed to maintain a common electrical potentia." (1)

Circuit. Dictionary definition: "A path or route, the complete traversal of, which without local change of direction, requires returning to the starting point. b. The act of following such a path or route. 3. *Electronics* a. A closed path, followed or capable of being followed by an electric current."

Earth. A conducting body of arbitrary resistance, used in place of a conductor. (The term is used interchangeably with "ground" in the US.)

Electrode. A conductor through which an electric current enters or leaves a medium, such as the earth.

Equipment Bonding Conductors. Jumpers of short conductors used to bridge loose or flexible sections of raceway, ducts, or conduits, or, in the US, to connect service entrance parts.

Equipment Grounding. The interconnection of all the non-current-carrying metal parts of equipment, such as receptacles, motors, electrical equipment housings, metallic raceways, and other metallic enclosures, to the ground electrode and/or the system grounded conductor

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

at the service entrance equipment or at the source of a separately derived ground.

Equipment-Grounding Conductor. A conductor that must be continuous from the source to the enclosure containing the load.

Ground. A conducting connection, whether intentional or accidental, by which an electric circuit or equipment is connected to the earth or to some conducting body of large extent that serves in place of the earth (2). (See also "Grounding" in this subsection.)

Ground Current. Current that flows on the ground, earth, equipment ground conductors, and related equipment. The ground current resulting from any phase-conductor-to-earth fault should be brief, lasting only until the protective device or devices opens. This flow of current is normal. The ground current resulting from a neutral-to-ground fault, which is continuous, is objectionable and the fault should be removed, corrected, or repaired as soon as possible. If the circuit is protected by a GFCI, the flow will be brief, as the device operates between 4 and 6 mA.

Ground Electrode. A conductor buried in the earth and used for collecting ground current from or dissipating ground current into the earth.

Ground Fault. See the sub-subsection on "Short circuit versus ground fault" under "Design fundamentals."

Ground Fault Current. The ground current resulting from any phase-conductor-to-earth fault. The flow of ground fault current should be brief, lasting only until the protective device opens. This flow of current is considered normal.

Ground Grid. A grid, used in large substations where large fault currents can flow over the earth, to equalize and reduce the voltage gradient when a fault current flows. See the subsections on "Step voltage" and "Touch voltage" under "Personnel safety protection." "A system of horizontal ground electrodes that consist of a number of interconnected, bare conductors buried in the earth, providing a common ground for electrical devices or metallic structures, usually in one specific location (2)." The object of installing a ground grid is to reduce the step voltage, provide a ground plane for connection of computer grounds, and make a low-resistance connection to earth.

Ground Mat. "A solid metallic plate or a system of closely spaced bare conductors that are connected to and often placed in shallow depths above a ground grid or elsewhere at the earth surface, in order to obtain an extra protective measure minimizing the danger of the exposure to high step or touch voltages in a critical operating area or places that are frequently used by people. Grounded metal gratings placed on or above the soil surface or wire mesh placed directly under the crushed rock, are common forms of a ground mat (2)." Ground mats are placed where a person would stand to operate a high voltage switch. See also the subsection "Grounding grids" under "Connecting to earth."

Ground Return Circuit. "A circuit in which the earth or an equivalent conducting body is utilized to complete the circuit and allow the current circulation from or to its current source (2)." Connected to earth or to some extended conducting body that serves instead of the earth, whether the connection is intentional or accidental (3).

Grounded Conductor. A conductor that is intentionally grounded. This can be the neutral or an identified conductor or one of the phase conductors, as in corner-of-the-delta grounding. This conductor is part of the electrical power distribution system.

Grounded, Effectively. Grounded through a sufficiently low impedance that for all system conditions the ratio of zero-sequence reactance to positive sequence reactance is positive and less than 3, and the ratio of zero-sequence resistance to positive-sequence reactance (R_0/X_1) is positive and less than 1 (3). The NEC definition is: "Intentionally connected to earth through a ground connection or connections of sufficiently low impedance and having sufficient current-carrying capacity to prevent the buildup of voltages that may result in undue hazards to connected equipment or to persons."

Grounded, Solidly. Connected directly through an adequate ground connection in which no impedance has been intentionally inserted (3).

Grounding. "A permanent and continuous conductive path to the earth with sufficient ampacity to carry any fault current liable to be imposed on it, and of a sufficiently low impedance to limit the voltage rise above ground and to facilitate the operation of the protective devices in the circuit (1)."

Grounding Conductor. A conductor used to connect electrical equipment or the grounded circuit of a wiring system to a grounding electrode or electrodes. Part of the equipment grounding system.

Grounding Electrode. A buried metal water-piping system, or other metal object or device, buried in or driven into the ground so as to make intimate contact. The grounding conductor is connected to the grounding electrode.

Grounding Electrode Conductor. The NEC defines the grounding electrode conductor as "The conductor used to connect the grounding electrode to the equipment grounding conductor, to the grounded conductor, or to both, of the circuit at the service equipment or at the source of a separately derived system." Green or bare copper is used for identification.

Grounding Grid. A system of bare conductors, usually copper, buried in the earth to form an interconnecting grid forming a ground electrode. See "Ground grid" in this subsection.

Noiseless Terminal to Earth (TE). A supplemental electrode for equipment grounding. IEC terminology, under debate in the IEC. A terminal for connection to an external, noiseless earth, isolated, conductor. In the US the PE and TE terminals must be electrical and mechanical continuous. Not recommended for use unless connected together. See the section "Grounding of computer systems."

Protective External Conductor (PE). IEC terminology. See the section "Equipment grounding." Terminals for the protective conductor may be identified by the bicolor combination green and yellow.

System, Electrical. The portion of the electrical conductors between transformers, and extending from the last transformer.

History

Early on, Edison connected one side of his two-wire direct current electrical system to earth. The uncontrolled current returning over the earth resulted in the electrical shocking of horses and Edison's employees as they installed underground electrical equipment. This prompted Edison to devise the three-wire distribution system with all the current contained within insulated conductors. This system allowed him to know where the current was at all times.

However, in the 1890s it became clear that on connecting one side of a two-wire circuit, or the middle, neutral wire of a three-wire circuit, to earth, the maximum potential would be that of the source, even if the circuit was to come into contact with one of higher voltage. The Telsa–Westinghouse alternating current (ac) system was connected to earth, according to this principle.

Major debate raged on whether to ground or not to ground an electrical system. It was not until 1913 that it became legally mandatory to ground one wire of any system of 150 V or more to earth.

Even so, when more than one connection to earth exists on the same system, current can flow uncontrolled over the earth, ground path, equipment, etc., resulting in problems even today in the protection of personnel safety, images on computer screens, etc.

Grounding Concepts

Unfortunately, the terms *ground* and *grounding* have been corrupted in the United States. The term *ground* means several different things. It is interchangeable with the terms *earthing* and *bonding*. The rest of the world uses the term *earthing* to mean the connection to earth or a path connecting to earth.

To understand grounding one must understand several facts. The first is that the earth is not a sponge that absorbs electricity. The second is that the earth is a conductor. The third is that every grounding system, be it used for power distribution, radio, lightning, or static, consists of a circuit. Understanding the route the ground current takes to complete its circuit is critical to understand grounding and grounding systems. Completing the ground circuit will resolve most grounding problems.

Example. A lightning strike is not absorbed in the earth, but completes the circuit begun by the movement of electrons from the rain cloud and deposited on the earth by the raindrops. The bottom of the cloud becomes negatively charged and the top of the cloud positively charged as the electrons are wiped away. The negatively charged bottom of the cloud repels the negative charges on the earth, resulting in a positive charge seeking the highest point below the cloud. The lightning strike allows charges to flow back to the cloud, completing the circuit and neutralizing the charges.

Electrical drawings often show only the power circuit, either all three phases or, for simplicity, only one phase, representing the three. However, the electrical grounding system has also become complex. Today it is common for a drawing to show the grounding system as well—its conductors, connections, etc. It is recommended that this always be done. This will allow proper installation and can provide help in determining the source of and the solution to grounding problems.

Table 1. Reasons for Grounding

Reason for Grounding	Protection Required			
	Humans	Equipment	Structures	Power Systems
Lightning	×	×	×	×
Static	×	×		
Computers	×	×		
Communications	×	×		
Equipment	×	×		
Power systems	×	×		×
Swimming pools	×			

Design Fundamentals

The reasons and methods for grounding of electrical equipment may not be the same as for grounding electrical power systems, or for grounding buildings to divert lightning safely. When one speaks of grounding without setting defining limits, confusion can result.

Table 1 lists the reasons why grounding is used and what is affected by grounding and/or bonding.

Short Circuit versus Ground Fault. One should be exact in describing circuits. Figure 1 details a typical circuit showing the secondary side of a transformer. The transformer has a center tap, providing a neutral connection. No voltage is shown, as it is not relevant for the discussion.

Common types of faults are the following:

Phase-to-Phase Short Circuit. When line 1 at point A is connected accidentally or purposely to line 2 at point B, a *phase-to-phase,* or *line-to-line,* short circuit occurs.

Phase-to-Neutral Short Circuit. Should either line 1 at ponit A or line 2 at point B contact the neutral conductor at point C, a *phase-to-neutral* short circuit exists.

Phase-to-Ground Fault. Should either line 1 at point A or line 2 at point B contact the earth/ground, a *phase-to-ground fault* exists. The protective device (circuit breaker or fuse) may open, depending on the circuit impedance. The circuit impedance of the earth is dependent on the resistivity of the soil. If point G is a metal surface and the metal has low resistance (impedance) and is bonded back to the ground electrode, then, provided enough current flows, the protective device should open.

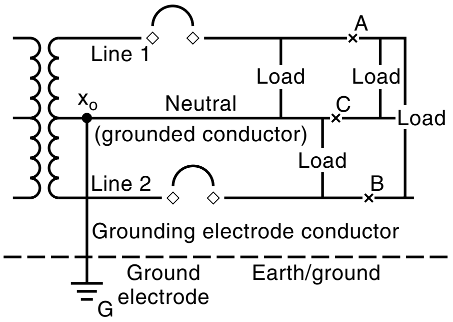

Figure 1. Short circuit versus ground fault.

Neutral-to-Ground Fault. When the neutral conductor contacts the earth/ground, a *neutral-to-ground fault* exists. This fault condition usually is undetected, as there may be no protective devices to detect it. One study of two 42-pole lighting panels supplying fluorescent fixtures found 20% of the circuits had the neutral faulted to the equipment ground. Currents, flowing uncontrolled over the earth, as high as 60 A have been measured on a 1,500 kVA, 120/208 V electrical system.

The continuous flow of current over the equipment ground, water pipes, metal enclosures, and earth can result in conditions hazardous to human safety. Uncontrolled current flow has been reported to cause electric shocks in swimming pools, showers, and other wet environments. Cows are very sensitive to voltage due to their step distance. (See the subsections "Step voltage" and "Touch voltage" under "Personnel safety protection.") The voltage resulting from stray uncontrolled current is one cause of cows not giving milk. Current flow over water pipes has been reported to cause video terminals to flutter as a result of the current producing stray magnetic fields.

For additional discussion see "Neutral-to-ground fault current" under "Low-voltage circuits" under "Uncontrolled flow of current over the earth" in the section "Personnel safety protection."

See also the subsection "Ground fault circuit interrupters" under "Personnel safety protection."

INSTALLATION PRACTICES

Installation practices vary from country to country. Politics dictate many decisions made concerning electrical and building codes. Whether to ground an electrical system or not and how to ground are debatable. The United States uses a solidly grounded electrical distribution system, while some European and Latin American countries may ground the distribution system at only the power source (the transformer), eliminating stray uncontrolled ground currents. Japan uses resistance grounding.

The controlling factors are the codes in each country.

Codes

Canadian Codes

Canada Standards Association. The Canada Standards Association (CSA) is the organization responsible for standards in Canada. CSA coordinated not only the development of the installation standard, but the requirements for testing and manufacturing. The Canadian Electrical Code reports to the CSA.

Canadian Electrical Code. The CSA is the governing body for the Canadian Electrical Code (CEC). "The preliminary work in preparing the CEC was begun in 1920 when a special committee, appointed by the main committee of the Canadian Engineering Standards Association, recommended that action be taken with regards to this undertaking. . . . the revised draft . . . was formally approved and a resolution was made that it be printed as Part 1 of the Canadian Electrical Code." The present CSA consists of members from inspection authorities, industries, utilities and allied interests. "The Subcommittee meets twice a year and deals with reports that have been submitted by the 39 Sections Subcommittees that work under the jurisdiction of the main Committee."

European Codes. Prior to the adoption of the European Common Market, each country had its own codes. With the advent of the European Common Market, each country has modified its codes to come into close compliance with Cenelec. Not all the differences between countries have been eliminated. All the standards-developing organizations are trying to make compromises to bring their standards into harmony.

Cenelec. The European Common Market directed that there be one standard for the Common Market. Cenelec is the result of the Commission of the European Communities in the 1970s requiring harmonization of all standards. The resulting standards are similar to the IEC standards and are being followed by all of the Western European countries.

International Electrotechnical Commission. The major worldwide standard-developing organization is the International Electrotechnical Commission (IEC). It was founded in 1906 at the World's Fair in St. Louis. There are now over 40 member countries headquartered in Geneva, Switzerland. The IEC is responsible for the electrical standards.

International Standards Organization. The International Standards Organization (ISO) was founded in 1947 and is responsible for mechanical standards. With the advent of the computer technology explosion, the ISO and the IEC have joined together to develop computer standards.

Mexico. Mexico has adopted the National Fire Protection Association's National Electrical Code.

United States Codes

American National Standards Institute. The American National Standards Institute (ANSI) accredits and coordinates several hundred United States organizations and committees that develop standards for approval as American National Standards, based in part on evidence of due process and consensus. ANSI provides the criteria and procedures for achieving due process and determining consensus as well as other requirements for the development, approval, maintenance, and coordination of American National Standards. These ANSI criteria and requirements are accepted by each accredited standards developer as a condition of accreditation. ANSI itself does not generate any standards.

Factory Mutual Research Corporation. The Factory Mutual Research Corporation (FM) develops standards for use in assuring building and factories are acceptable risks for insurance. Although there are many testing organizations recognized by OSHA, the major two are FM and UL (Underwriters Laboratories, Inc.).

National Electrical Code. The National Fire Protection Association (NFPA) has been the sponsor of the National Electrical Code (NEC) since 1911. The NEC was developed in 1897 as the results of losses suffered by insurance companies. Combining with the insurance companies were the electrical installers, manufacturers, and architectural and other allied interests. "The purpose of this *Code* is the practical safeguarding of persons and property from the hazards arising from the use of electricity." The NEC governs the installation of electrical equipment. It is considered the "law of the land," as it has been adopted by the majority of all levels of governing bodies in the United States.

National Electrical Safety Code. The Institute of Electrical and Electronics Engineers is the secretariat for the National Electrical Safety code (NESC). The "standard covers basic provisions for safeguarding of persons from hazards arising from the installation, operation, or maintenance of 1) conductors and equipment in electrical supply stations, and 2) overhead lines and underground electric supply and communication lines. It also includes work rules for the construction, maintenance, and operation of electric supply and communication lines and equipment." The standard is for the utilities and for industrial facilities that have similar installations.

Occupational Safety and Health Administration. The Occupational Safety and Health Administration (OSHA) was formed by an act of the United States Congress in 1971. The act requires OSHA to oversee the practices of industry with respect to safeguarding the health of employees. OSHA adopted the 1971 NEC. In addition, OSHA has propagated many supplemental rules and regulations.

Underwriters Laboratories, Inc. The Underwriters Laboratories (UL) have developed standards to assure the safety of persons and the prevention of fire. The standards define the construction and performance of appliances, tools, and other products. These standards are then used for testing the devices.

PERSONNEL SAFETY PROTECTION

Voltage alone does not kill. The voltage is the driving force that determines how much current will flow through the resistance of the body. Current is the important factor. In a human, of the five layers of skin, almost all of the resistance is in the first layer of dead, dry skin. It takes a pressure of over 35 V to penetrate this first layer. Table 2 shows resistance values for parts of the human body.

Effects of Current on the Human Body

The physiological effects of current are described in Table 3. When an electrical shock happens, the current is the most important factor. Current flow through the chest cavity should be avoided, as the current can affect the heart. Five milliamperes has been accepted as the upper limit of safe current. The muscular reaction to the electrical shock can be hazardous, as one may be knocked from a ladder, fall, hit one's head, etc.

Electrocution. The act of electrocuting a person in the electric chair can be considered the ultimate application of current and voltage. Three electrodes are used. Conductive jelly is applied before the electrodes are placed on the shaved head and both ankles. To arrest the heart, 2,000 V is sufficient. However, an additional 400 V is added for hefty persons and 240 V to compensate for the voltage drop. Thus, 2,640 V and 5 A are used. The body will burn if more than 6 A is applied.

Table 2. Typical Resistance for Human Body

Path	Resistance (Ω)
Dry skin	100,000–600,000
Wet skin	1,000
Hand to foot (internal)	400–600
Ear to ear (internal)	100

Table 3. Effects of Current on the Human Body

60 Hz Current (mA)	Effect
≤1	Threshold of sensation—not felt.
1–8	Shock, not painful. Can let go; muscular control maintained.
	Unsafe Current Values
8–15	Painful. Can let go; muscular control maintained.
15–20	Painful shock. Cannot let go; muscular control of adjacent muscles lost.
20–50	Painful. Breathing difficult. Severe muscle contractions.
100–500	Ventricular fibrillation—heat valves do not operate correctly. They flutter; thus no blood is pumped. Death results.
≥200	Severe muscular contractions—chest muscles clamp the heart and stop it as long as the current is applied. Severe burns, especially if over 5 A.

Two one-minute jolts are applied. After the first jolt, the adrenal activity keeps the heart in action. The second jolt is applied after a 10 second delay. Within 4.16 ms consciousness is lost. Approximately $0.35 worth of electricity is used. Fred A. Leutcher Associates, Inc., of Boston, Massachusetts are considered experts in the field.

Ground Fault Circuit Interrupters

Ground fault circuit interrupters (GFCIs) are devices that measure the current flowing on a supply line and compare it with the current on the return line. If there is a difference between 4 and 6 mA, the circuit protective device opens. UL, a US testing company, classifies such a device as a Class A device. GFCIs are required on certain types of circuits in the United States, Canada, and other countries to offer protection for humans. In some European countries, the mains services have similar devices. See the following subsection "Equipment ground fault protection."

GFCI devices usually incorporated in 15 to 30 A circuit breakers. They are also built into receptacles and extension cords.

If the device is set to operate at a difference of about 20 mA, the UL classifies it as a Class B device. The application of such devices in the US is to swimming pool lighting installed before 1965.

Equipment Ground Fault Protection

Equipment ground fault protection (GFP) devices also measure the current flowing on the supply line and compare it with the current on the return line. If there is a sufficient difference between the two, the protective device opens the circuit. These devices are for the protection of equipment. The common settings are 30 to 50 mA. Other values are available. One of the uses for GFP devices is the protection of electric heat tracing lines and devices. The low value of trip current for a GFCI would result in nuisance tripping if applied to heat tracing circuits. Such circuits can have leakage currents greater than 5 mA.

GFPs are also available for three-wire, single-phase circuits. They mesure the flow of current on the two-phase conductors and the neutral. If the sum of the currents does not equal zero, and the difference exceeds the trip rating, the GFP opens the circuit.

GFP devices are usually found in circuit breakers. There are heat tracing controllers that have GFPs built into them.

Ground Fault Sensing

The application of ground fault sensing is to power distribution systems to protect against equipment-damaging, continuous, low-current, low-voltage arcing. Solidly grounded wye electrical systems, where the phase voltage to ground exceeds 150 V, can develop an arcing fault with insufficient fault current to operate the protective device. The NEC requires any service disconnect rated 1000 A or more to have ground fault protection of equipment.

Ground fault sensing using induction disk or solid-state relays can detect phase unbalance. Ground fault sensing can be accomplished in three ways, using relays.

A ground fault relay can be inserted in the neutral conductor of the wye transformer—the conductor going from the transformer's neutral tap to the grounding electrode. This relay will detect any current flow returning from the earth to the transformer. Tripping of the protective device can then be set at a safe value.

Another method is to use a zero-sequence or toroidal transformer enclosing the phase and neutral conductors. If the sum of the currents on the conductors does not equal zero within the transformer, then a current is produced by the zero-sequence or toroidal transformer. The tripping value can then be set.

The third method is to insert a ground fault relay in the phase overcurrent relay circuit that will measure the differential current by the summation of the phase currents.

Arc Fault Circuit Interrupters

The arc fault circuit interrupter (AFCI) is a solid-state circuit breaker with software built into the breaker, to detect arcing within the load wiring. The arcing current is usually inadequate to generate sufficient current flow to operate the protective device. The AFCI will detect the arcing of a damaged extension cord, or of a cable within the wall that has been damaged by the accidental driving of a nail through the conductors.

At the time of writing (August 1997), an AFCI must clear a 5 A arc in no more than 1 s and clear a 30 A arc in no more than 0.11 s. The device must trip in four full cycles. Should the extension cord be cut, the device may have to open with a 100 A fault in eight half cycles. Because of the arcing, testing may be based on half cycles.

Step Voltage

The technical definition of step voltage is "the difference in surface potential experienced by a person bridging a distance of 1 m with his feet without contacting any other grounded object" (2). The soil has resistance. When a high fault current flows through the earth due to a conductor coming into contact with the earth, a voltage is developed across the earth as long as the current flows.

The flow of large fault currents over the resistance of the earth develops a potential between different points on the surface of the earth. The installation of a ground grid reduces the potential to acceptable limits.

Touch Voltage

The touch voltage is "the potential difference between the ground potential rise and the surface potential at the point where a person is standing, while at the same time having his hands in contact with a grounded structure" (2). This is like the step voltage, except the person is standing on the ground and at the same time touches a grounded metal object. The potential difference between the point on the earth where the person is standing and the point where he touches the metal object is called the touch voltage, or touch potential. See the subsection "Grounding grid" under "Connecting to earth."

For example, the installation of ground mats under operating handles of high-voltage switches, and bonded to the metal switch parts, reduces the potential between the earth where the feet are and the switch handle where the hands are touching.

Uncontrolled Flow of Current over the Earth

It is an unsafe practice to allow current to flow over the earth continuously, uncontrolled. All continuously flowing current must be contained within insulated electrical conductors. During the time a phase conductor faults to and contacts earth, it is normal to have the current flow over the earth until the protective device(s) operate to clear the circuit and stop the current flow. The time should be seconds or less.

Neutral-to-earth faults allow the current to flow uncontrolled over the earth continuously. This uncontrolled flow of current over the earth can result in electrical shocks to humans and animals, cause computer screens to flutter, damage electrical equipment, cause fires, and generate magnetic fields.

Low-Voltage Circuits. In some countries the neutral of a low-voltage system (<600 V) is connected to earth at the transformer and again just inside the building being served by the utility. In Fig. 2 the neutral is grounded at T to TG (transformer ground), and inside the building at B to BG. For the time being, ignore the fault at **X**. Continuous current can flow over the earth from point BG to TG. Current returning from the load on the neutral will enter point B. According to Kirchhoff's and Ohm's laws, the current will divide in inverse

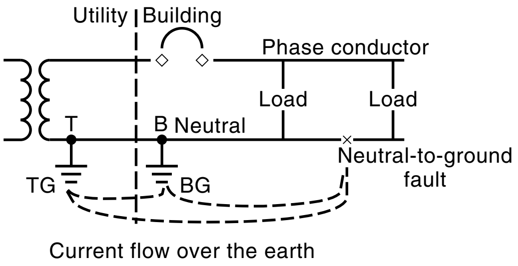

Figure 2. Current flow over the earth from a neutral-to-ground fault.

ratio to the resistance, and the sum of the currents flowing into and out of the node will be zero.

Example. With a resistance from point B to T of 0.1 Ω and a resistance from point BG to TG of 25 Ω through the earth, and with a neutral return current of 100 A, a current of 0.398 A will be flowing over the earth continuously. See the subsection "Effects of current on the human body." With only 2 A of return current, 0.00786 A would flow over the earth.

Neutral-to-Ground Fault Currents. Figure 2 shows a single-phase circuit. When a fault occurs on the phase conductor, the fault current flows through the earth, equipment ground conductors, grounded water piping, etc., back to the earth connection at either BG or TG, completing the circuit. If the path has low impedance, sufficient current will flow, resulting in the protective device(s) opening, stopping the current flow.

When the neutral conductor contacts earth, say point **X**, the current can flow from point **X** to either ground electrode at point BG or point TG, in addition to the flow over the neutral from point **X** to the neutral connection of the transformer. Since the load is in the circuit, the resultant current flow will be controlled by the impedance of the load. The protective device will have normal current flow and the protective device will not operate. However, the current flow over the earth will be uncontrolled. The current can flow anywhere over water piping, building steel, etc.

If the single transformer serves several buildings or residences, the normal distribution practice in the US, there will be two insulated phase conductors, and a bare conductor serving three functions: the supporting messenger, the neutral, and the ground. Each building will have its incoming service connected to earth at the entrance of the building and through the metallic water piping. Should the supporting combination messenger, neutral, and ground conductor corrode and thus develop a high resistance, preventing full neutral current from returning over the conductor, the neutral current will flow back to the transformer over the earth and metallic water piping to the next house and all the other houses, and through the earth to the transformer. The current flow will be uncontrolled. It will be a function of the combined impedances.

As an example, currents of 30 A have been reported flowing over water pipes from an unknown source, not in the house containing the water pipe. This current flow over the water pipe results in electric and magnetic fields. The magnetic fields interfere with video display computer terminals located near the water pipes.

Current flows have been reported to cause voltage differences between the floor drain and the water control valve in showers. Electric shocks occurred when standing in the shower and touching the water temperature control valve. It was not feasible to eliminate this voltage difference by bonding. The current's origin was unknown, somewhere in the electrical distribution system.

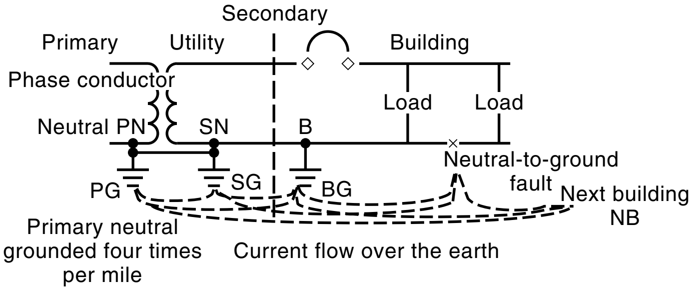

Figure 3. Current flow over the earth from secondary and primary connections.

Distribution Circuits. In distribution circuits (>600 V), it is the practice in some countries to connect the primary neutral to the secondary neutral, as in Fig. 3. The object is to protect the secondary from primary-voltage excursions. Also, in the United States there is a requirement that the primary neutral conductor be connected to earth four times per mile. In addition, some utilities depend on the earth to carry part of the return current. It is common to have only 40% to 60% of the return current carried by the neutral conductors of the primary distribution system and the rest returned over the earth. This flow of primary return current over the earth is uncontrolled and unrestrained, and has caused serious problems. Current flow through swimming pools has shocked swimmers, especially if they have cuts or have fillings in their teeth and open their mouths. Persons taking showers feel tingles when they touch the water control valve.

Some would claim that bonding will eliminate such problems. In one case, however, the swimming pool was properly bonded, but the current flowed through the pool as part of a return path to the source transformer. In other cases, it was not practical to install bonding between the water piping and the drain piping. The responsibility for the uncontrolled current flow remains with the suppliers of the faulty circuit.

The solutions are to (1) have all conductors insulated from earth except at one location, (2) install isolation transformers, and (3) install a device that will block the connection between the primary and the secondary neutral (a *neutral blocker*). The neutral blocker devices allow fault current to flow but block any normal current flow.

Hospital and Operating Rooms

See the subsection "Isolated power systems or supplies" under "Types of low-voltage power system grounding."

EQUIPMENT GROUNDING

The object of grounding the electrical equipment is to:

1. Reduce the potential for electric shock hazards to personnel.
2. Provide a low impedance return path for phase-to-equipment fault current necessary to operate the protective device(s).
3. Provide a path with sufficient current-carrying capacity, in both magnitude and duration, to carry the fault current, as allowed by the protective devices, for their operation.

Personnel Safety—Electrocution

Grounding electrical equipment can provide a fault current with a lower-impedance path than the path through a person. Ohm's law states that the magnitudeof the current will be inversely proportional to the resistance.

Example. Assume the copper equipment-grounding conductor has a impedance of 2 Ω. A person, standing on the earth with a normal resistance of 25 Ω, would have a body resistance from dead, dry skin of hand to foot of 350,000 Ω. With a 120 V circuit, a parallel path exists. One path, through the series of the body and the earth, is 350,025 Ω, while the equipment grounding conductor path is only 2 Ω. The voltage, 120 V, divided by the resistance, 0.500002857 Ω, allows 60.000343 A to flow. With the equipment grounding conductor carrying 60.0 A, the current through the body is only 0.00034 A.

Conductors

Were one to rely on metallic conduit, locknuts, bushings, etc. as the equipment grounding path, the probability of preserving a low-impedance path after exposure to the weather, corrosive atmospheres, or shoddy workmanship would be low. To ensure safety, an equipment grounding conductor should be contained within the equipment raceway. There exists a report that purports to show the reliability of metallic conduit. However, this university-generated report, paid for by a party with an interest in the outcome, has not undergone peer review.

The importance of an equipment ground conductor is to offer a low-impedance return fault current path back to the connection to the ground or the transformer neutral terminal. This path will permit sufficient current to flow, allowing the protective device to operate. The equipment grounding conductor must be contained within the raceway for all types of circuits, as this will lead to the lowest circuit impedance. That includes power circuits, motor and motor control circuits, lighting and receptacle circuits, and appliance circuits.

Thermal Capacity. The ground circuit conductors must be capable of carrying all fault current imposed upon them. The fault current will last until the protective device(s) clear the phase conductors. The fault carrying capacity includes the ability to limit the temperature of the grounding circuit conductors to their thermal rating. When designing the grounding circuit, the temperature rise during the time the fault current is flowing must be considered. Component parts in the circuit, such as locknut connections and the thickness of the metal enclosure, must also be considered.

In addition, the impedance of the grounding circuit must be less than that of any other possible parallel ground circuit. Fault current flow through other, higher-impedance paths may result in arcs, sparks, and fire, especially where loose connections occur between sheet metal enclosures, the connectors, and locknuts or conduit couplings.

Conduit and Connectors

If one is to rely on the conduit, terminals, connectors, locknuts, etc. as the equipment grounding conductor for the return ground current path, good workmanship is a prerequisite. The metallic path must be continuous and have low impedance. With iron conduit serving as the ground return path, if a fault occurs, there will be a large increase in both the resistance and the reactance of the ground return path circuit. In addition, depending on the amount of fault current flowing, the resistance and reactance will vary over a large range, depending on the amount of fault current flow.

In a typical industrial facility, constructed of steel, there will be many parallel ground return paths. Because of the reactance of the circuit, the return fault current will mainly flow in the path nearest to the outgoing current path. Given the "choice" of returning over the equipment ground conductor contained within the conduit containing the phase conductor supplying the fault current, or a parallel path adjacent to the conduit, only approximately 10% of the return fault current will flow over the adjacent path, and 90% will flow over the conduit, provided the conduit is continuous and has low impedance. When a single phase-to-ground fault current flows in a conductor within a conduit, the size of the conductor has very little effect on the impedance of the circuit.

To assure a reliable, continuous, low-impedance ground fault return circuit, an equipment ground conductor should be installed within the conduit supplying all circuits. This includes not only power circuits, but those for lighting, receptacles, appliances, etc.

Buildings. Buildings with reinforcing steel bars in the foundation and piers for the steel columns with bolts have been found to be inherently grounded. One out of four column bolts are usually in contact with the reinforcing bar in the footer steel reinforcing bar cage. (See the subsection "Concrete-encased electrodes—Ufer ground" under "Connecting to earth." Although the steel has a primer coat of paint, small projecting points on the surface of the steel puncture the coating and bond to adjacent steel surfaces. The multitude of parallel electrical paths within a steel building reduces the resistance to a low value.

When the steel columns are less than 7.6 m (25 ft), apart they form a *Faraday cage.* A lightning strike to the steel will travel down the perimeter of the building steel and will be dissipated into the earth, provided the building is effectively grounded. The columns inside the structure will be devoid of current.

Instrumentation

See the section on "Grounding of Computer Systems," especially the subsection "Grounding of Instrumentation Shields."

Grounding of Power Conductor Shields

All cables at voltages 5 kV and higher should be constructed with a shield. It is not uncommon to install 5 kV cables without any shielding. Utilities, with their rigid safety work rules, have managed to avoid problems. However, this practice should be avoided by all others, as there are reports of fatal electrical accidents due to touching an unshielded 5 kV cable.

The construction of cable for 5 kV and over begins with a conductor of copper or aluminum. In order to achieve a smooth surface a semiconducting material is extruded over the conductor. A layer of high-voltage insulation is applied, and over it another layer of semiconducting material, followed by a thin metallic copper cover sheet, which is overlapped to assure that all the semiconducting surface is covered. A final outer layer of insulation is then applied.

It is necessary to have the high-voltage insulation under equal electrical stress. This is achieved by having, smooth semiconducting material on both sides of the high-voltage insulation, and equal distance maintained between the two semiconducting surfaces. The metallic shield is connected to earth. This produces an equal and constant voltage stress between the first layer of semiconducting material at the potential of the conductor and the second layer of semiconducting material at earth potential.

The shield must be continuous, extending over splices. The shield should be connected to earth wherever possible. This is to allow fault current to enter the earth and follow a parallel path back to the source. The shield should be selected to be able to handle any fault current applied to it, and to conduct the fault current to the nearest connection to earth, where the resistance (impedance) should be less than the shield impedance.

The shield ampacity must be adequate to carry the fault current. Should the shield burn open in several places and leave sections of the shield ungrounded, damage can occur to the high-voltage insulation and the whole cable may have to be replaced.

Lighting Fixtures

In buildings of all types, lighting fixtures are installed. The inexpensive method of connecting the lighting fixture to earth/ground is to rely on the raceway—the rigid intermediate conduit or electrical metallic tubing (EMT)—as the ground return fault path. It is not unusual to find poor workmanship with the installation of the raceway. EMT pulls apart easily, breaking the ground path. Loose locknuts result in poor connections.

All raceways should have a separate equipment grounding/earthing conductor installed with the phase and neutral conductors. This will assure a reliable fault return path of low impedance that will operate the protective device(s).

Motors

The inexpensive method of connecting the motor frame to earth/ground is to rely on the raceway (the rigid or intermediate conduit or EMT) as the ground return fault path. It is not unusual to find poor workmanship with the installation of the raceway. EMT pulls apart easily, breaking the ground path. Loose locknuts result in poor connections.

The practice of using cable-tray cable, with the earthing/grounding conductor within the tray cable, should be carried over to the raceway installation. All raceways should have separate equipment grounding/earthing conductor installed with the phase conductors. This will assure a reliable fault return path of low impedance that will operate the protective device(s).

Most motor manufacturers have installed an equipment grounding screw within the motor cable termination box. The use of this screw to earth the motor frame has proven successful. There are those, however, who feel the need to be able to see the connection to earth and insist on running an earthing cable on the outside of the conduit and connecting it to the exterior of the motor frame. The fault return path must be a path that is in very close proximity to the outgoing phase-fault-supplying conductor. An external ground conductor does not meet these criteria and will have higher impedance.

It may be necessary to connect the motor frame to nearby ungrounded metallic enclosures, bonding the two together. This will prevent touch voltage hazards.

Substations

There are substations for utilities, industrial facilities, and commercial sites. Utility substation earthing/grounding involves soil resistivity measurements, step/touch potentials, ground grid installations, equipment grounding, and so on. It is a complex subject. For detailed information consult Ref. 2.

Commercial and Industrial Substations. A commercial or industrial substation is defined as one where the utility supplies power to one or more step-down transformers and a high-voltage switchyard is lacking. There may be a high-voltage switch or two. The secondary voltage may be as high as 35 kV. The substation may be either outdoors or within an enclosed building housing the switchgear and the transformers, which can be either inside or outside.

Ideally, the concrete transformer pads and the foundation for the building, should there be one, would serve as the earth connection, using the reinforcing bars. A less effective method of connecting to earth is the use of a ground loop encircling the area and connected to ground wells. The ground loop can be used to connect the various pieces of electrical equipment together. Each major piece of electrical equipment should be connected to the ground loop from at least two different locations. A line-up of switchgear would have each end connected to the grounding loop.

Step and touch potentials should be considered. It may be necessary to install a ground grid and ground mats under the operating handles of high-voltage switches. The fence needs to be connected to earth and the ground grid.

Distribution and Transmission Lines

Where lightning could result in damage and interruptions, protection of the distribution and transmission lines should be installed. A static wire will divert the majority of lightning strikes harmlessly to earth. A static wire is a conductor installed over the phase conductors and connected to earth approximately every 400 m (1,300 ft). In addition to the static wire, lightning arresters should be installed periodically.

The major cause of disruptions is tree limbs. They need to be kept trimmed.

TYPES OF LOW-VOLTAGE POWER SYSTEM GROUNDING

Various voltages, phases, wires, frequencies, and earthing requirements for low-voltage (<600 V) are found in various countries. In the United States, one will hear of different voltages, such as 110 or 120 V. This confuses many people. The standard voltages in different parts of various systems are shown in Table 4.

Before 1965, the transformer for an industrial installation was usually located in the parking lot. There was a voltage drop between the transformer and the main distribution panel just inside the building, and another voltage drop from the panel to (say) the starter and motor out in the factory. Before 1965, if one was speaking correctly and mentioned 115 V, one was referring to the main distribution panel. If one mentioned 110 V, one was referring to the motor.

In the early 1960s, transformers were moved indoors, closer to the loads. The motor control was located in a motor control center next to the main distribution panel. The previ-

Table 4. Standard Voltage Terminology

	Voltage (V)			
Era	System (nominal)	Transformer	Distribution	Utilization
Before 1965	120	120	115	110
	208/120	208/120	200/115	190/110
	240	240	230	220
	480	480	460	440
After 1965	120	120	115	115
	208/120	208/120	200/115	200/115
	240	240	230	230
	480	480	460	460

ous voltage drops were eliminated, reducing utility costs. It was then discovered that the voltage being applied to the motors had increased. Thus, a new standard was developed in 1965. Unfortunately, some still refer to the voltage at fixtures as 110 V, instead of the correct 115 V.

Purpose of Electrical System Grounding

The purpose of connecting an electrical system to ground is to protect personnel from serious injuries or fatalities, to improve the system reliability, and for continuity of service. The object is to control the voltage to ground, or earth, within predictable limits. Grounding of the electrical system will limit voltage stress on cable and equipment. Proper installation will facilitate the protective device operation, removing hazardous voltages from the ground. Each electrical system grounding method has its advantages and disadvantages.

The characteristic features one must evaluate are (4):

1. Suitability for serving the load
2. Grounding equipment requirements for the method of system grounding selected
3. First costs
4. Continuity of service
5. Fault current for a bolted line-to-ground fault
6. Probable level of sustained single-phase line-to-line arcing fault level
7. Shock hazard
    a. No ground fault
    b. Ground fault on phase conductor
8. Advantages
9. Disadvantages
10. Area of applications

A summary of the various grounding systems for low-voltage installations is given in Table 5.

Personnel Safety—Flash Burns

When a (1) phase-to-phase, a (2) phase-to-neutral short circuit, or a (3) phase-to-ground fault on a solidly grounded electrical system occurs, large fault currents can flow, depending on the electrical system grounding method. Severe burns can occur up to approximately 3 m (10 ft) from the arc, depending on the available fault current and the duration of flow. An electrical arc is hotter than the surface of the sun. The amount of burning is a function of the available fault current, the distance from the arc, and the time of exposure. In evaluating the selection of an electrical system grounding method, consideration should be given to flash hazard to personnel from accidental line-to-ground faults.

Ralph H. Lee's paper on electric arc burns contains a formula and a chart for calculating the degree of a burn (5). M. Capelli-Schellpfeffer and R. C. Lee's paper on "Advances in the evaluation and treatment of electrical and thermal injury emergencies" lists the necessary actions one must take after someone has been subjected to electric shock (6). The critical responses are:

1. The injured person should be strapped to a board, as the shock and the reaction can damage the spine.
2. The person should be transported to a burn center.
3. Someone should immediately record the characteristics of the area, the time and weather conditions, how the accident occurred, etc., and send the information to the hospital as soon as possible.

The following listing will clarify and assist in selecting the proper electrical earthing/grounding system for the application.

Ungrounded Systems

Neither the phase nor the neutral conductors in an ungrounded electrical system are directly connected to earth. They are connected to earth by the distributed phase-to-ground capacitance of the phase conductors, motor windings, etc. The cited advantages are (1) freedom from power interruption on the first phase-to-earth failure and (2) lower initial costs.

With a single-phase fault to earth, a small charging current will flow and the protective devices will not operate. As long as none of the other phases contact earth, operation can continue. However, when one of the other phases contacts earth, a phase-to-phase short circuit occurs. The resulting fault current, flowing into the phase-to-phase fault, can result in severe damage to equipment, flash hazard to personnel, and the cessation of operation.

In order to ensure the operation will continue without interruption, a ground detection system should be installed. Most installations make the error of placing lamps across the phases to the ground. As long as all phases are isolated from earth, the lamps will burn at equal and less than full brightness. When a single phase faults to earth occurs, the lamp on that phase will dim and the other two will burn brighter, at full voltage. The problem with such lamps is that an incipient fault will not be detected. Voltmeters should always be used, as they are much more sensitive than trying to determine the relative brightness of any lamp.

When the voltmeters indicate a difference in voltage between the phases, the weak, high-impedance phase-to-ground fault or incipient fault should be located. If the phase-to-ground fault is not remedied as soon as possible, a phase-to-phase fault may develop, resulting in a hazardous condition.

An arcing fault can raise the system voltage to levels where motor windings and cable can be stressed beyond their limits. If the motor control circuits are at full voltage without

Table 5. System Grounding Features

Type of System	Suitable for Serving Load Circuits	Grounding Equipment Required	First Costs versus Solidly Grounded	Suitable for Voltages (V)	Fault Current[a] (%)	Arc Voltage (V)	Restrike Voltage (V)	Flash Hazard, Phase to Ground	Shock Hazard[b,c]	Difficulty Locating First Phase-to-Ground Fault	Recommended
Ungrounded	two-wire, one-phase three-wire, three-phase	Yes	Same if no equipment added	120				(*d*)	Phase to ground of higher potential	Hard	Never
				208	2	275	275				
				240							
				380							
				480	74	275	375				
				600	85	275	375				
Solidly grounded neutral	two-wire, one-phase two-wire, one-phase, ground a side three-wire, three-phase four-wire, three-phase	None	Referred to this system[e]	208	2	275	275	Severe	Limited to low-voltage L-to-N	Easy	For lighting receptacles, small appliance loads
				380							
				480	74	275	375				
				600	85	275	375				
High-resistance grounded neutral	two-wire, one-phase three-wire, three-phase[f]	Yes[g]	Higher	208[h]	2	275	275	Practically none unless phase-to-phase	None	Can be hard without pulse-tracing system	Highly for continuous loads
				240		275	275				
				380							
				480	74	275	375				
				600	85	275	375				
Corner of the delta	two-wire, one-phase, ground one side three-wire, three-phase	None	Same	120				Severe	Limited to secondary L-to-L	Easy	Not for new installations; O.K. for retrofit
				208	2	275	275				
				240		275	275				
				380							
				480	74	275	375				
				600	83	275	375				
Delta transformer with one side midpoint grounded	two-wire, one-phase two-wire, one-phase, ground one side three-wire, one-phase, midphase grounded three-wire, three-phase	None[i]	Same	240		275	275	Serious	Limited	Easy	(*j*)
				480	74	275	375				
				600	85	275	375				

[a] Where no value appears, no tests were conducted.

[b] L-to-N: line to neutral. L-to-L: line to line.

[c] Phase-to-ground shock hazard when fault includes a higher voltage. The phase-to-ground voltage is as listed in columns.

[d] No flash with one phase grounded. When one of the other two phases go to ground, flash hazard exists.

[e] Ground fault relaying may be required and will add to the price.

[f] Not suitable for single-phase loads from a four-wire, three-phase center-tapped transformer. For lighting loads a separate transformer is required: 480 V delta primary, 208/120 V wye secondary.

[g] Neutral resistor for wye systems. Delta systems require grounding transformer. An alarm is recommended. A fault tracing/pulsing system is strongly suggested. Installation of two sets of inexpensive ammeters on feeders recommended to (1) measure load current, (2) indicate ground fault when pulsing system is installed and operated.

[h] Not normally used, as the neutral is not available. Good for only three-wire, three-phase.

[i] The phase opposite the midpoint ground (the phase with the higher voltage to ground) must be identified throughout the electrical system.

[j] Recommended for areas where the loads are predominately single-phase three-wire 240/120 V and some three-phase 240 V loads. Also can be used where the existing transformer is single-phase 240/120 V; three-wire and additional three-phase load is then required.

the benefit of a control transformer, the extended circuit conductors increase the likelihood of an arcing fault.

Where continuous operation is a requirement, a high-resistance grounded system should be used.

For information on how to detect and find phase-to-ground faults see the subsection "Resistance-grounded neutral systems," especially the sub-subsection "Phase-to-ground faults: detection and location methods." For detailed information see Ref. 4.

Isolated Power Systems or Supplies

Isolated power systems or supplies are used in hospital operating rooms using certain anesthetizing chemicals, wet locations, and life support equipment that must continue to operate when one phase-to-ground fault exists, such as intensive care areas, coronary care areas, and open-heart surgery operating rooms. Isolated power systems consist of a motor–generator set, an isolation transformer or batteries, and a line isolation monitor, monitoring ungrounded conductors. For the last thirty years, the components of the isolated power system have been packaged together in one assembly referred to as an isolated power package. The package is less costly than assembling the components.

All of the wiring in the system is monitored for leakage current and voltage differential. The maximum safe current leakage limits range from 10 μA for catheter electrodes inside the heart to 500 μA for appliances, lamps, etc. The maximum safe voltge differential is 20 mV.

The advantages, disadvantages, and limitations are different for health care facilities than for normal electrical system grounding. For detailed information see Ref. 7.

Generating a System Neutral

There are times when it is desirable to have a system neutral to connect to earth, but none is available. This may occur where the secondary system connection is a delta, either because an old distribution system is to be upgraded or because a delta secondary is less expensive than a wye-connected transformer.

A neutral can be generated by the use of a zigzag, T-connected, or wye–delta transformer. Usually these transformers are rated to carry current for a limited time, typically 10 s or 1 min. The sizing in kilovolt-amperes is the line-to-neutral voltage in kilovolts times the neutral current in amperes. These transformers are much smaller in size than a fully rated transformer.

The transformer should be connected directly to the bus. When that is done, the possibility of its being disconnected is remote. The transformer has to be considered as part of the bus protection.

Solid Grounded Neutral System

All electrical systems should be grounded by some means. Numerous advantages result, such as greater personnel safety, the elimination of excessive system overvoltages, and easier detection and location of phase-to-ground faults.

A solidly grounded neutral system has the transformer neutral point directly connected to earth through an adequate and solid ground connection. The connection between the transformer and the earth has no intentionally inserted impedance or resistance. The neutral should be connected to earth at only one place, preferably at the transformer. This will reduce uncontrolled circulating currents. (See the section "Grounding of computer systems.")

The solidly grounded neutral system is the most widely used in the US, not only for residential, but also for commercial and industrial service. The solidly grounded neutral system is the most effective for three-phase four-wire low-voltage distribution systems.

The solidly grounded neutral system is effective in controlling overvoltage conditions and in immediately opening the protective device when the first phase-to-neutral fault occurs. Low-voltage arcing faults do not permit sufficient current to flow to open the protective device(s). The resulting continuous arcing can destroy the electrical equipment. Low-level arcing ground faults can, however, be detected and the protective device(s) opened. See the subsection "Ground fault sensing" under "Personnel safety protection."

The low cost of the solidly grounded neutral system, combined with the features of immediate isolation of the fault, overvoltage control, and protection against arcing fault burndown, account for the use of this system. The benefits of protection of faulty equipment and circuits and the ability to locate the fault are other reasons for its use. To gain the benefit of protection against arcing fault burndown, one has to add additional equipment at a cost.

One disadvantage of the solidly grounded neutral system is that the first phase-to-ground fault opens the protective device(s), shutting off the power, lights, control, etc. In an operating room or a continuous process, the sudden loss of electrical power can be catastrophic. Severe flash hazard exists with a phase-to-ground fault. Severe damage can occur to electrical equipment because of the high possible fault current.

The immediate removal of the electrical power with the first phase-to-ground fault is considered by some as a major detriment, especially when a critical process or service is involved. To avoid disorderly and abrupt shutdowns when the first phase-to-neutral fault happens, one should consider a high-resistance grounded system, which has the advantages of a solidly grounded neutral system and none of the disadvantages. For additional details, see Ref. 4.

Corner-of-the-Delta Grounded System

The corner of-the-delta grounded system is one in which one corner of the delta, a phase conductor, is intentionally connected through a solid connection to earth. The connection has no intentionally inserted impedance. The grounded phase should be identified and marked throughout the system. In the US, the grounded phase conductor must be located at the center of any three-phase device such as a switch or meter socket.

The ungrounded delta system was used in some manufacturing facilities to allow for continuous operation. When such a system is encountered and it has been decided to convert it to a solidly grounded system, the corner of-the-delta system can be and usually has been selected.

All motor control overload relays and instrumentation must be connected to the hot phases. The motor control may have only two overload relays in the motor circuit. These two relays must be installed on the two ungrounded phases to assure proper registration or operation.

A ground fault on the grounded phase can go undetected, resulting in a flow of uncontrolled current over the equipment ground conductors, the earth, metallic piping, etc.

Insulation. With the corner of the delta grounded, the other two phases will have 73% higher insulation stress. Since these systems are predominately used on system voltages of 600 V or less and 600 V insulation rating is used for the conductors, no problem exists. If the system voltage is 380 V, then 300 V insulation can be used, as the two phases see a stress of 277 V. When 480 V and 120/208 V systems are installed in the same building, it is usual for conductor with 600 V rated insulation to be used. However, where costs are to be strictly controlled, two different conductor insulations can be used, 600 V and 300 V. In that case, unless there are strict safeguards to prevent intermingling of the two kinds of insulation, severe problems may develop over time. The mixing of insulation on the same project is not recommended.

For detailed information see Ref. 4.

Midphase-Grounded (Neutral) System

The midphase-grounded (neutral) system is one where the three-phase delta transformer has one side tapped in the middle and this tap, the so-called neutral, connected to earth. This connection came into expanded use in the mid 1940s in residential neighborhoods where only small corner stores existed. The typical service was from a large single-phase, three-wire, 240/120 V transformer.

With the advent of air conditioning, the local stores needed three-phase power. It was simple to add a single-phase transformer with a secondary of 240 V connected to one end of the large single phase, three-wire, 240/120 V transformer in an open delta configuration. This resulted in single-phase, 240/120 V, three-wire service from the single-phase large transformer, and three-phase, 240 V, three-wire service from the two transformers. The open delta was limited to 58% of the 240 V single-phase transformer rating. By closing the delta with a third single-phase, 240 V transformer, full rating of the two single-phase, 240 V transformers could be supplied.

The midpoint on the one phase is often called a *neutral.* However, since the point is not in the middle of the electrical system as a true neutral would be, others refer to the midpoint on one side of a delta transformer as the *identified conductor.* It will be called a neutral here for simplicity.

The phase leg opposite the midpoint neutral will have an elevated voltage with respect to earth or neutral. If the three-phase voltage is 240 V, then the voltage from either phase on either side of the midpoint will be 120 V. The voltage from the phase leg opposite the midpoint to the neutral or earth, since the midpoint is grounded, will be 208 V. Because of this voltage, the phase opposite the midpoint is referred to as the high leg, red leg, or bastard leg. See Fig. 4. This “hottest” high leg must be positively identified throughout the electrical system when carried with the neutral conductor. It should be the center leg in any switch, motor control, or three-phase panelboard. It is usually identified by red tape.

For detailed information see Ref. 4.

Resistance-Grounded Neutral Systems

Resistance-grounded neutral systems offer many advantages over solidly grounded systems. Destructive transient voltages are controlled. As with all electrical systems, destruction results when a phase-to-phase fault occurs. The resistance-grounded system does, however, limit the amount of fault current that can flow when a phase-to-earth fault occurs. Other advantages are:

1. Arc blast or flash hazard to personnel is reduced when a phase-to-ground fault occurs and personnel are in the area of the fault.
2. Stray continuous phase-to-ground fault currents are reduced and limited.
3. The destructive burning of phase-to-ground fault currents is eliminated, reducing the destruction of electrical equipment.
4. Stress is reduced in electrical equipment when a phase-to-ground fault happens.
5. There is no voltage dip such as happens when the protective device clears a phase-to-ground fault current in a solidly grounded system.
6. The system allows continuous process operation after the first phase-to-ground fault. (A phase-to-phase fault will develop if either of the other two phases contacts earth. The fault current from the first phase-to-ground fault will flow through the earth to the point of the second phase-to-ground fault.)

There are two methods to ground an electrical system using resistance grounding. See Fig. 5.

High-Resistance Grounded Neutral System. When a phase-to-ground fault occurs, little if any damage occurs when the electrical system is grounded using high-resistance grounded neutral methods.

A high-resistance grounded system has a resistor installed between the transformer neutral terminal and the earth connection. No phase-to-neutral loads are permitted on any resistance grounded systems. A separate transformer is used to generate neutral loads. For instance, on a 480/277 V system a separate transformer with a 480 V delta primary and a 480/277 V wye secondary would be used for the 277 V lighting and other loads.

The resistor in the neutral-to-earth connection prevents excess fault current from flowing. The value of the resistor is selected to limit the fault current to approximately 5 A. Because of the capacitance between the earth and the phase conductors connected to the loads, a capacitance charging current will flow. The trip value of the detection relay has to allow for the charging current. The charging current can be measured by methods described in Ref. 8.

It is important to find the phase-to-ground fault as soon as possible. Should either of the two other phases contact earth, a phase-to-phase fault would occur. This would result in the operation of the protective device(s) and the cessation of operation. When a phase-to-earth fault occurs, the potential to earth on the other two phases rises to the phase-to-phase potential. Depending on the conductor insulation, this may cause a problem. See the subsubsection “Phase-to-ground faults: detection and location methods.”

The high-resistance grounded system has been tried on high-voltage systems (15 kV) with less than satisfactory results. The system has been used at 5 kV without any adverse results. For additional details see Refs. 4 and 8.

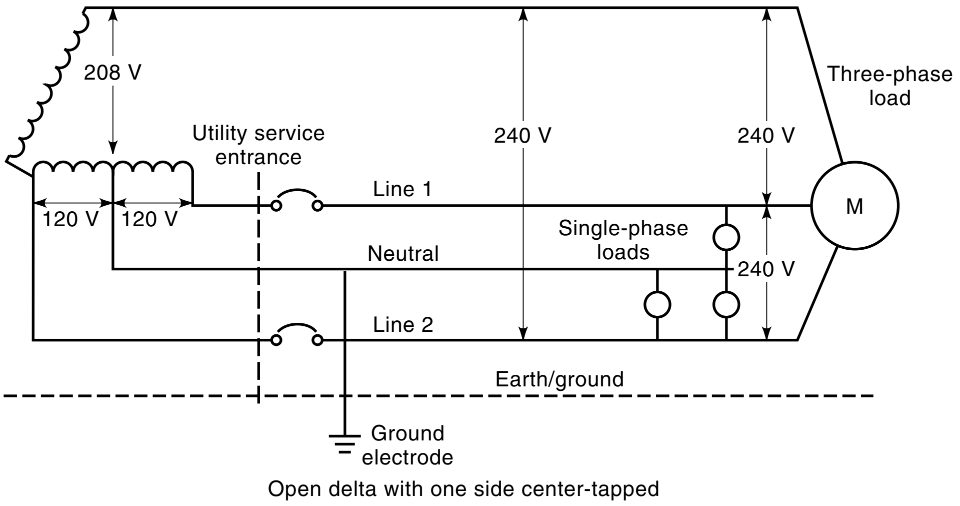

Figure 4. Open delta one-side midphase-grounded (neutral) system.

Insulation. This section applies to all ungrounded and resistance grounded systems, particularly to high-voltage cables. When a phase-to-earth fault occurs, the potential to earth on the other two phases rises to the phase-to-phase potential. Depending on the conductor insulation level and on the time that the fault remains, this may cause a problem.

Cables are rated as 100%, 133%, and 173% voltage insulation level. The guidelines for fault duration are:

100% Cable Insulation Level. If the phase-to-ground fault is detected and removed within 1 min, 100% insulation cable can be used.

133% Cable Insulation Level. If the phase-to-ground fault is expected to remain on the system for a period not exceeding 1 h, 133% cable insulation level should be used.

173% Cable Insulation Level. If the phase-to-ground fault will remain on the system for an indefinite time before the fault is deenergized, 173% cable insulation level should be used. Cable with 173 percent insulation level is recommended to be used on resonant grounded systems in any case.

Phase-to-Ground Faults: Detection and Location Methods. It is imperative that a phase-to-ground fault on electrical systems, other than solidly grounded systems, be detected and found and repaired as soon as possible. There are several methods available.

Ungrounded systems can have relays installed that respond to changes in voltage between phases and ground. Commercial equipment is available that will place a high-frequency signal on the system. This signal can be used to trace the fault.

Resistance-grounded systems lend themselves to either of two detection methods. A current relay can be installed around the conductor connected to the transformer neutral terminal and run through the resistance/impedance device to the earth connection. Any flow of current returning to the transformer neutral over the ground will be an indication of a phase-to-ground fault, and the relay will operate. See Fig. 6.

Because of patents on the current-transformer method, another method using the principle of voltage differential was developed. When phase-to-ground fault current flows through the grounding resistor, a voltage will be developed across the resistor. A voltage-sensing relay can detect this fault current flow and operate the alarm system.

High-resistance grounded systems can be provided with a square-wave pulsing system. Figure 6 illustrates this. A timer operating at a rate of about 20 to 30 equal pulses per minute shorts out part of the high-resistance grounding resistor. With part of the resistance removed from the circuit, the flow of phase-to-ground fault current will increase. This increase in fault current will generate a square wave.

To find the fault, a large-opening clamp-on ammeter is used. The phase-to-ground fault current will be flowing on the phase that is faulted. If the ammeter is placed on the outgoing raceways, then if the fault current is flowing within the raceway being checked, the ammeter will pulse. The other raceways, without any fault current flowing, will not deflect the ammeter.

Tracing the fault current to the exact point of the phase-to-ground fault is an art, not a scientific method. A person must observe the extent of deflection of the ammeter and recognize the possibility of parallel ground fault return paths.

Low-Resistance-Grounded Neutral System. The low-resistance-grounded neutral system has a low-value resistor inten-

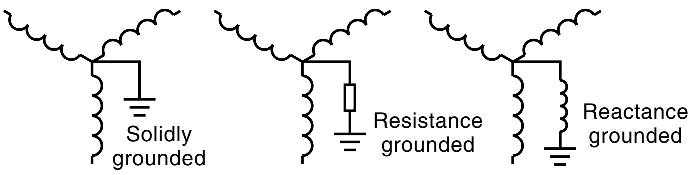

Figure 5. Neutral earthing methods.

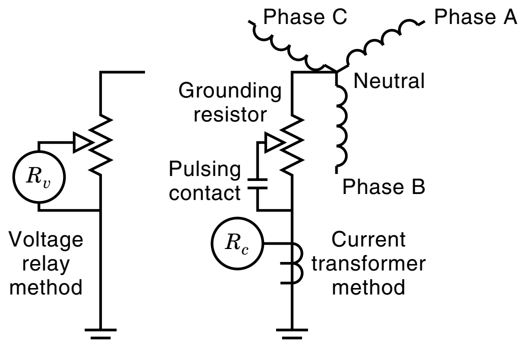

Figure 6. Ground fault detection methods.

tionally inserted between the transformer neutral terminal and the grounding electrode. This resistor limits the fault current to a value in the range of 25 to 1000 A, a level that significantly reduces the fault point damage. It still allows sufficient current to flow to operate the protective device(s). The fault can be isolated by fault ground detection devices. This grounding method is usually used on industrial systems of 5 to 25 kV.

Initially this system was hampered by the lack of sensitive, low-cost ground fault protective devices for application on downstream circuits. By now, its application in industrial facilities for the powering of large motors and for the distribution of power in the 5 to 25 kV range has become commonplace. The low-resistance grounded system with sensitive ground fault sensing allows the application of 100% level conductor insulation.

For additional details see Ref. 4.

Low-Reactance-Grounded Neutral System

The low-reactance-grounded neutral system is one where a low-value reactor is inserted between the transformer neutral terminal and the ground electrode. The reactor limits the fault current to a value not less than 25% to 100% of the three-phase bolted faulted current. This system is not used very often.

The low-reactance-grounded neutral system effectively controls to a safe level the overvoltages generated in the power system by resonant capacitive induced circuits, restriking of ground faults, and static charges. The system cannot control overvoltages from contact with a higher-voltage system.

This method of grounding is used where the capabilities of the mechanical or electrical equipment require reducing the ground fault current. Its main applications have been to generators below 600 V, to limit the ground fault contribution of the generator to a value no greater than the three-phase bolted fault current.

This type of grounding system is not practical on systems requiring phase-to-neutral loads, as there may not be sufficient fault current to operate the protective device(s).

For additional details, see Ref. 4.

Separately Derived Systems

The NEC defines a separately derived system as "a premises wiring system whose power is derived from a battery, a solar photovoltaic system, or from a generator, transformer, or converter windings, and that has no direct electrical connection, including solidly connected grounded circuit conductor, to supply conductors originating in another system." The major application of a separately derived system is the installation of a transformer to supply lighting and appliance loads.

An example is where the electric service to the building or facility is 380/220 V, three-phase, and four-wire and a supply at 120 V is needed, perhaps to supply a computer system or other special loads. A transformer with a primary of 380 V (single-phase connected) and a secondary of 240/120 V (single phase, three-wire) is supplied. The 240/120 V system has no connection back to the primary. For safety and code reasons, this separately derived electrical system will need to be grounded. The most common method is the solidly grounded neutral system.

The key to a proper installation is to connect *only* the transformer's neutral terminal to the grounding electrode. The grounding electrode should be in the same area as the transformer and as near as practical. In order of preference the connection should be made to (1) the nearest effectively grounded building steel, (2) the nearest available effectively grounded metallic water pipe, (3) other electrodes that are not isolated from the main electrical system. (See the section "Grounding of Computer systems.") If necessary, the grounding conductor should be connected back to the system ground for the building.

Resonant Grounding (Ground Fault Neutralizer)

The resonant grounding (ground fault neutralizer) system is used primarily on systems above 15 kV used for distribution and or transmission lines. It consists of a reactor connected between the transformer neutral terminal and the grounding electrode, earth. The reactor has high reactance and is tuned to the system's capacitive charging current. The result is that the ground fault current is a low resistive current. Being resistive, it is in phase with the line-to-neutral voltage, so that the current zero and the voltage zero occur at the same time.

A built-in feature of this method of grounding is that with transmission line insulators experiencing a flashover, the flashover may be self-extinguishing.

For additional details, see Ref. 9.

Grounding of Uninterruptible Power Supplies

An uninterruptible power supply (UPS) is considered a separately derived electrical system. Its separately derived neutral will need to be connected to earth. The grounding electrode should be in the same area as the UPS and as near to it as practical. In order of preference the connection should be made to (1) the nearest effectively grounded building steel, (2) the nearest available effectively grounded metallic water pipe, (3) other electrodes that are not isolated from the main electrical system. (See the section "Grounding of computer systems.") If necessary, the grounding conductor can be connected back to the system ground for the building. Figure 7 illustrates the grounding of a separately derived UPS system.

Most UPSs have the incoming power supplying a rectifier, which converts the ac into dc, which in turn charges batteries and supplies the inverter converting the dc back into ac. The inverter generates a separate and "new" neutral that is not connected back to the building neutral. In addition, there is usually an alternative power source for the UPS. The UPS can switch from the inverter to the alternative power source should the inverter fail. This assumes the neutral is not connected to the UPS load through the alternative power source to the building earthing connection.

If the UPS load neutral is solidly connected to the alternative power supply's neutral, without any switching, then no connection of the UPS derived neutral should be made to earth.

The alternative power supply may have a transformer on the line side of the UPS alternative supply. The UPS neutral may be solidly connected to the UPS load-side neutral and the alternative transformer's neutral. For ease of access and checking, the UPS neutral's connection to earth should be made within the terminal compartment of the UPS, even if

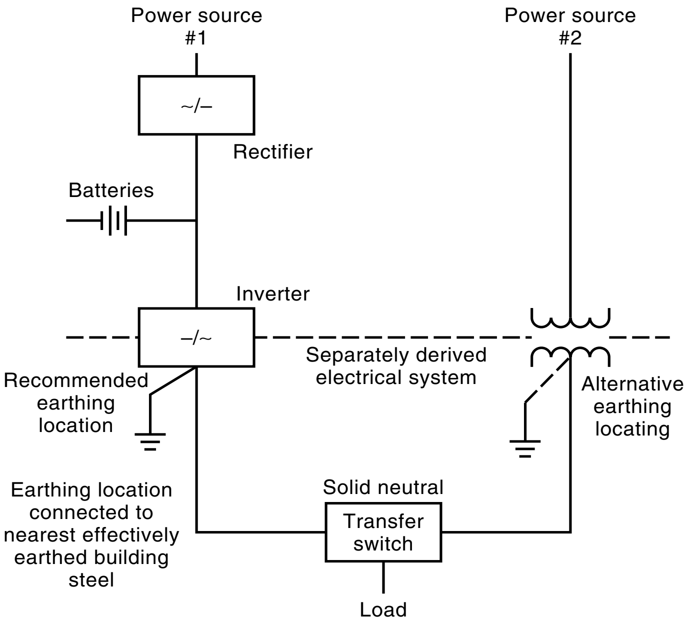

Figure 7. Grounding of a separately derived UPS system.

transformers are associated with the UPS. Only one connection of the neutral to earth should be made.

Autotransformers

Autotransformers have the line-side neutral connected solidly to the load-side neutral. Since the line-side neutral should have been connected to earth within the originating transformer's terminal block, no additional connection to the neutral should be made. Any second connection to the neutral—for instance, at the secondary neutral terminal of the autotransformer—will afford a parallel path through the earth for uncontrolled current. On any power system with a neutral, only one connection to earth should be made.

Grounding of Wye–Wye Transformers

A wye–wye transformer is one with the primary transformer winding connected in a four-wire wye configuration and the secondary winding also connected in a wye arrangement, with the primary and secondary neutrals connected together. This connection is not recommended for commercial or industrial installations, as currents can circulate between the primary and secondary circuits, especially if three single transformers are used. When the wye–wye connection is used, the transformer needs to be constructed with five windings to reduce the ferroresonance. This is an additional cost.

Utility distribution systems that are solidly grounded, requiring the primary supply switches to be opened one phase at a time, will generate ferroresonance. In addition, to minimize the neutral-to-earth potential throughout the length of the distribution system, the utilities ground the primary neutral point. The connection of the neutral to transformer case and ground minimizes the secondary-neutral-to-ground voltage during a fault between primary and transformer case.

Typically, the utilities have used bare concentric neutral cables in underground primary distribution circuits. See the sub-subsection "Distribution circuits" under "Uncontrolled flow of current over the earth" in the section "Personnel safety protection."

In order to supply zero-sequence current, with secondary neutral connected to earth, the primary neutral of the wye–wye transformer will be required to be connected to the primary neutral of the primary source. The wye–wye transformer will be required to be connected to the primary neutral of the primary source. The wye–wye transformer is not a source of zero-sequence current, unlike a delta–wye connection. On the other hand, if a delta tertiary winding is added to a wye–wye transformer, it will supply the zero-sequence current.

Special Applications

Both ac and dc separately derived power supplies should have one side connected to earth. Should the object containing the power supply be a car, a plane, space vehicle, computer, etc., the "earth" can be the metallic enclosure, the metallic base plate, or the equipment ground conductor contained in the cord supplying power to the device. In no case should the neutral, which is connected to earth back at the supplying power transformer, be used for the connection to earth.

Instrumentation. A dc or ac separately derived power supply needs to have one side connected to earth. The instrumentation shielding is discussed in the subsection "Grounding of instrumentation shields" under "Grounding of computer systems."

Motor Control Circuits. All motor control circuits should be powered by either a common circuit or a separate, individual control power transformer in each motor circuit. The latter is the preferred method, as failures on the common circuit will jeopardize all the motors. A motor control circuit using one phase of the motor circuit will unnecessarily increase the power circuit's vulnerability to conductor failure. Should the system be ungrounded, any arcing on the control circuit can raise the floating midpoint of the ungrounded system to voltage levels twice the base voltage or more. This high-voltage excursion, because of arcing combined with the capacitance of the conductors to earth, can damage equipment insulation, especially in motors. In Fig. 8 motor control transformer grounding is shown.

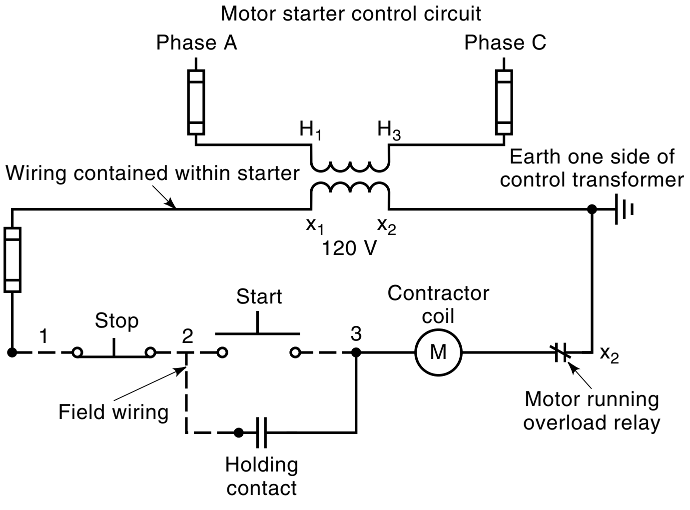

Figure 8. Motor control transformer grounding.

One side of the control transformer should be connected to the grounded equipment enclosure. There have been many debates on the advantages and disadvantages of which side the pushbuttons should be located on. The agreed-upon standard is that the ungrounded side of the control power transformer should be protected by either a fuse or circuit breaker, and should supply the operating devices in the circuit, such as pushbuttons. The motor running the overload relays should go on the grounded side of the control power transformer. The other side of that motor should be connected to the operating coil of the motor contactor.

ELECTRICAL PROPERTIES OF THE EARTH

The earth consists of many different materials, each with its own resistivity. Some materials, rich in loam and containing moisture, will have a low resistivity, whereas dry sandy material will have a high resistivity. In general, the earth is considered and classified as a conductor. The earth is not a sponge, and it cannot absorb electrons, but acts like any conductor carrying current.

Resistivity of Soils

The resistivity of the soil is a function of:

1. Type of material
2. Depth from the surface
3. Moisture content
4. Type of soluble chemicals in the soil
5. Concentration of soluble chemicals in the soil
6. Temperature of the soil

Standing water is not an indication of low resistance. The soil itself has to be investigated and the resistivity calculated.

Resistance to Earth

The most common method of connecting to earth is the use of a grounding electrode, the ground rod. Visualize a series of nested cylinders of increasing dimensions surrounding the rod, capped at the bottom by hemispheres (Fig. 9). As the current flows outwards from the rod, it encounters the resistance of these shells. As we progress outward from the rod, the area of each shell increases and the resistance decreases inversely.

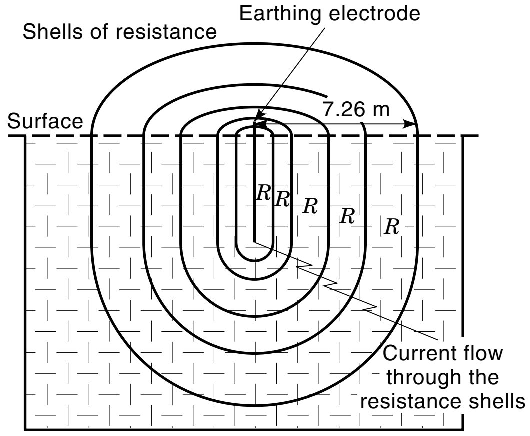

Figure 9. Earth resistance shells.

Calculations show that 25% of the resistance occurs in the first 0.03 m (0.1 ft) from the rod's surface. Thus, the region next to the rod is the most important in determining the resistance to earth. At 8 m (25 ft), essentially all of the resistance is accounted for.

Ideally, to reduce the resistance to earth using a second rod, one would drive this second rod 16 m (50 ft) away. The outer cylinders about the two rods, with 8 m radius, would just touch. The depth of the rod determines the total area. For maximum efficiency and cost effectiveness the distance between rods should be

$$\text{Total distance between electrodes} = \text{depth of first electrode} + \text{depth of second electrode}$$

Measuring Ground Resistance

In order to calculate the spacing necessary for the installation of a utility substation earth grid, the resistivity of the soil is needed. Portable instruments are available that will measure the resistivity of the soil. Four test rods are driven in the area to be measured and connected to the instrument. A push of a button (for battery-operated instruments) or the turn of a crank will result in the value being displayed. The resistivity of the soil can then be used to calculate the number of conductors or electrodes necessary.

After the earthing electrode system is installed, it should be tested and the values of the resistance of the electrodes recorded. Ideally, the measurement of each electrode should be made during construction. For instance, if there is any doubt, for first-time users of the Ufer electrode, about the resistance of individual footers, the measurements should be made before any interconnection between footers is made.

There are commercially available instruments that measure ground–electrode resistance. These instruments are specially designed to measure the low resistances that may be present, and they will reject spurious voltages found in the earth. The usual ohmmeter cannot be used to measure either the resistance of the earth or that between earth and electrodes. There are three methods used for measuring the resistance of earth electrodes.

1. The *fall-of-potential* method (Fig. 10) uses two auxiliary electrodes and an alternating current. For a single electrode to be tested, one auxiliary electrode is set approximately 30 m (100 ft) away, and the current conductor is connected to it. Current is passed through the earth from the auxiliary electrode to the electrode under test. The region between the two electrodes must be free of conductive objects such as metallic underground pipes and bare wires. The third electrode is placed at the 60% distance, 18 m (60 ft), from the first auxiliary electrode, and the potential is measured. The instrument uses Ohm's law to calculate the resistance of the electrode. This principle is based on a flat knee in the curve generated by taking multiple measurements between the electrode under test, the current electrode, and the more distant electrode. This kness occurs at the 62% point. The auxiliary electrodes need to be only 0.3 m (1 ft) long, and can just be pushed into the earth, as their

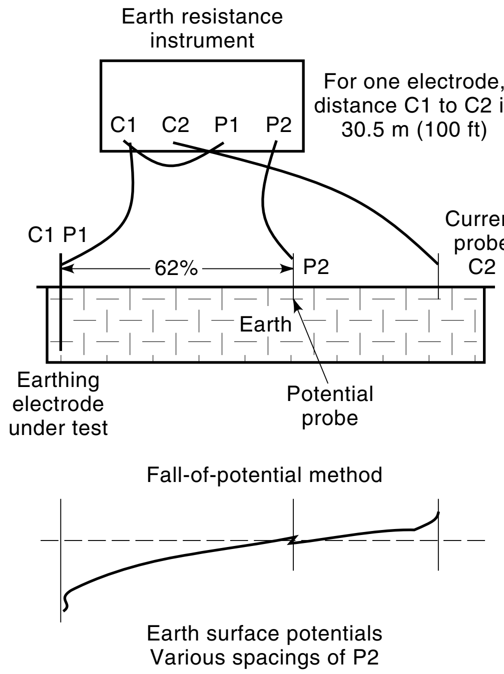

Figure 10. Measuring earthing electrode resistance by the fall-of-potential method.

resistance is canceled. When testing two or more electrodes connected together, as the diagonal distance increases, the distance of the current probe must extend to greater and greater distance. At 3 m (10 ft) diagonal the current probe must be out at a distance of 49 m (160 ft), with the potential probe at 30 m (100 ft). With a 61 m (200 ft) diagonal electrode system, the current probe must be out at 216 m (710 ft) and the potential probe at 134 m (440 ft).

2. The *direct method* is the easiest way to perform a resistance test. The main requirement is there must be an extensive ground electrode system whose characteristics are known. The electrode under test is connected to the test instrument, and the other lead is connected to the known electrode. There are limitations with this method: (1) the known electrode must have negligible resistance, and (2) the electrode under test must not be influenced by underground water or gas piping, bare conductors, etc.
3. Large electrode systems can be measured by the *intersecting curves method.* This complex method is described in the publication *Getting Down to Earth,* available from Biddle Instruments, Blue Bell, PA, USA.

Calculating the Resistance to Earth of Electrodes

To calculate the resistance to earth of an electrode, the type of soil must be determined. Each type of soil will have an average resistivity. Moisture will have an effect on the resistivity of the soil, as will temperature. The soil resistivity will vary directly with the moisture content and inversely with the temperature.

The symbol for resistivity, measured in ohm-centimeters, is ρ.

For each configuration of earthing electrode, there will be a formula. The formulas can be found in Ref. 3.

CONNECTION TO EARTH—GROUNDING ELECTRODE SYSTEMS

Connections to earth are designed to minimize the voltage differences between conductive metallic objects and ground. Various methods are used for this purpose.

Grounding or earthing electrodes can be divided into two groups. One group consists of electrodes specifically designed for and used only for the electrical connection to earth. The other group consists of objects primarily used for functions other than earthing electrodes, such as underground metallic water piping, well casings, concrete-encased reinforcing bar, and steel piling.

The type of earthing electrode selected will depend on the soil resistivity, type of soil or rock, available soil depth, moisture content, corrosiveness, etc. When multiple earthing electrodes are installed (Fig. 11), for maximum effectiveness they should be installed according to the formula

$$\begin{aligned}&\text{Total distance between electrodes}\\&\qquad = \text{depth of first electrode} + \text{depth of second electrode}\end{aligned}$$

For example, if the first electrode is driven 3 m deep and the second electrode 2 m deep, the distance between the two electrodes should be 5 m.

Concrete-Encased Electrodes—Ufer Ground

H. G. Ufer discovered that concrete-encased reinforcing bar made an excellent connection to earth. Starting in 1942, he studied 24 buildings in Tucson and Flagstaff, Arizona, with reinforcing rods in the foundations. Arizona is normally dry, with less than 0.3 m (1.0 ft) of rain per year. He checked the resistance reading to earth, once every two months, for over 16 years. The maximum reading was 4.8 Ω, the minimum was 2.1 Ω, and the average for the 24 buildings was 3.6 Ω. He presented his findings in 1961, at an IEEE conference. A technical paper presented in 1970 by Fagen and Lee (10) also proved the validity of the method. The NEC adopted the Ufer grounding method, thus assuring general acceptance.

Concrete above the earth acts as an insulator, whereas concrete below the earth can be treated as a conducting medium. The resistance to the earth of the concrete-encased electrode is less than that of an electrode in the average loam

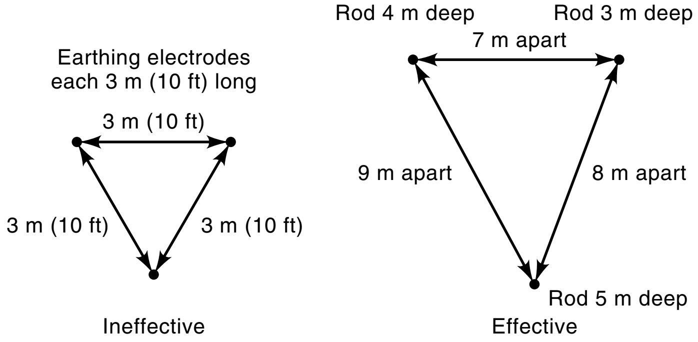

Figure 11. Spacing of multiple earth electrodes.

type soil, which has a resistivity of approximately 3000 $\Omega \cdot \text{cm}$. It has been shown that a footing or foundation has a lower resistance than a single driven rod of the same depth. With the large number of footings on the long length of a foundation, the total resistive connection to ground is lower than that provided by any other nonchemical electrode. In tests made at Las Vegas, NV, the most efficient method of connecting to earth, excluding the chemical earthing electrodes, was the concrete-encased electrode for all types of locations (11).

The key to an efficient connection to earth is to have either the reinforcing rod, or a length of bare copper conductor in place of the reinforcing rod, at the bottom of the concrete. The minimum length of rod or conductor needed is 6.1 m (20 ft), and it must be placed within or near the bottom of the concrete. The conductor should be surrounded by at least 51 mm (2.0 in.) of concrete. The reinforcing bar should be at least 12 mm (0.5 in.) in diameter. If bare copper conductor is used, it should be larger than 20 mm^2 (#4 AWG).

The reinforcing rod or bare copper conductor should be placed within the bottom of the foundation, column or spread footing, or pad. It has been shown that it is not necessary to have the pressure and depth of a foundation or footing to be effective. A concrete pad poured for a transformer is just as efficient. Figure 12 shows details of reinforcing rod grounds.

It is necessary to make an electrical connection to the reinforcing rod and bring the connection out to the ground bus bar, electrical equipment, or steel column. One method is to connect a copper conductor to the reinforcing rod, overlapping the reinforcing rod with approximately 0.5 m (18 in.) of bare copper conductor. The overlapped bare copper conductor can be fastened to the reinforcing rod with the same iron wire ties used to fasten the reinforcing rod together, or with plastic tie wraps. To eliminate the corrosive action of the copper conductor exiting from the concrete, an insulated conductor can be used, provided the overlapping section is bare, or a nonferrous conduit sleeve. The copper earthing conductor can be connected to the necessary electrical equipment earthing terminals.

The other method of connecting the reinforcing rod to the outside is by overlapping the rods with one of the bolts that will hold the steel column. Again, the wire ties used to secure the reinforcing rods or plastic wire ties can be used. The top of the bolt should be marked by painting or some other means so that the grounding bolt can be identified later.

Only foundations or footings at the perimeter of the structure are effective. Interior grounding electrodes are ineffective.

There have been reports of failures of the reinforcing rod method of earthing. This may stem from the IEEE Power Engineering Standards on transmission tower foundations and the standard on transmission tower construction. Prior to 1996, neither standard contained any information on grounding of the reinforcing rods, insertion of copper conductors in the concrete, the connection of the steel towers to the reinforcing rods, or any earthing method for the towers. This oversight may be the source of reports of problems with lightning and the cracking of the transmission tower foundations. Steel structures used in the chemical industry have been reported to withstand direct lightning strikes without any visible signs of damage to the foundations.

Ground Rods

Ground rods can consist of driven pipe, conduit, iron, or stainless steel. The outer covering should be galvanized or given some other protective surface. The normal ground rod is a copper-clad steel rod 2.44 m (8 ft) or 3.05 m (10 ft) long. When multiple earthing electrodes are installed, they are usually installed incorrectly. Three rods are usually specified to be

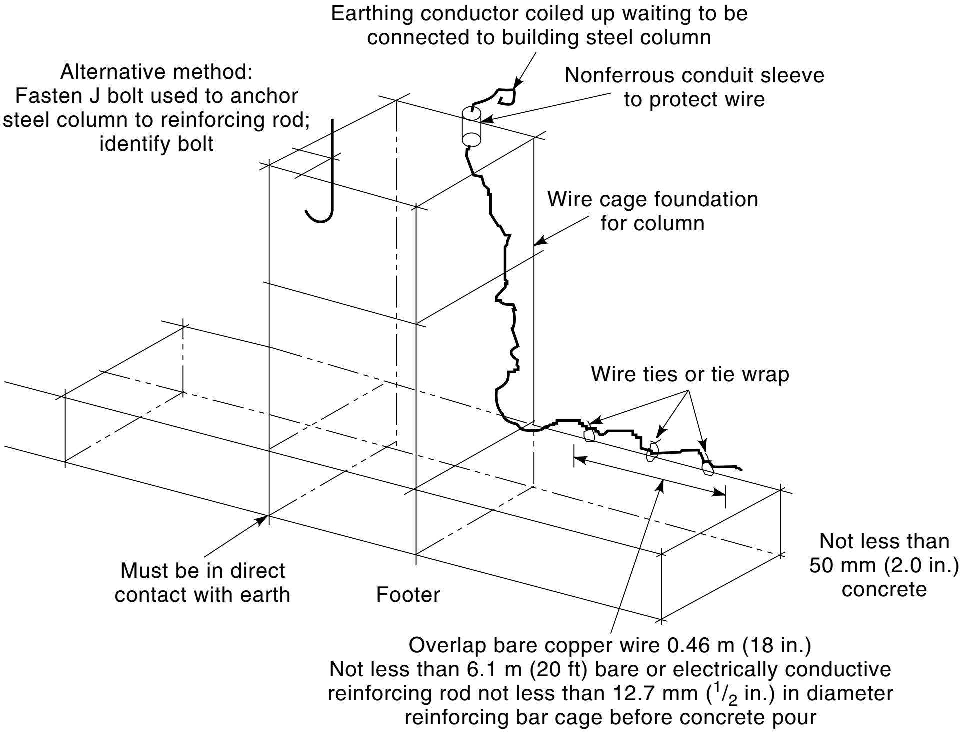

Figure 12. Reinforcing rod earthing details.

spaced in a triangle 3.05 m apart and driven 3.05 m deep. The cones of influence overlap instead of just touching. (See the section "Electrical properties of the earth.") The third rod becomes ineffective. For maximum effectiveness they should be installed according to the formula

Total distance between electrodes
= depth of first electrode + depth of second electrode

It is not unusual to find the resistance of a single ground rod varying, depending on the resistivity of the soil, from the unlikely value of 25 Ω to 10 times as much.

Unfortunately, most individual houses lack reinforcing rod in the foundations that could serve as the earth electrode. One could have installed a length of bare copper conductor in the footer for the walls to act as the earthing electrode, but this is rarely done. A ground rod is often installed right next to the foundation, where the soil has been backfilled and is lightly compacted, providing poor contact with the earth. Any rods should be driven, the depth of the rod away from the foundation, in virgin soil for maximum effectiveness.

Water Pipe Systems

Before the use of plastics, metallic water piping was installed. With the water piping in intimate contact with the earth, it was natural to make use of it as a grounding electrode. In older houses, the soil piping was cast iron with lead joints forming a path to earth. A person in a bathtub, lacking any dead, dry skin, could easily be electrocuted when any current-carrying conductor was touched or fell into the tub. By connecting one of the two power conductors to the water pipe, the chances of an accident occurring were reduced by 50%. In addition, the metallic water pipe was an excellent conductor and could serve as a low-resistance (low-impedance) path to allow the flow of sufficient fault current to operate the protective device.

Problems developed with the use of the water pipe as an earthing electrode. Where houses were in close proximity to each other, connected by underground metallic water piping, stray current could flow from one house to another. With single-phase, three-wire service, the neutral conductor also serves as the messenger and as the grounding conductor. Should the messenger–neutral–grounding conductor become corroded and develop a high resistance, the return current would seek a lower resistance path. The current could flow over the water piping to the adjacent housing, with the neutral return current flowing back to the transformer over the neighbor's messenger–neutral–ground conductor. Overloading of conductors resulted. Electric water heaters sometimes burned out. Persons taking showers could experience electric shocks. In addition, water meter personnel removing the water meter for inspection and repairs could place themselves in the ground current circuit and experience electric shocks.

The advent of plastic piping and the installation of GFCIs has reduced the problems. However, all metallic water and fire piping within a building should still be connected to the electrical grounding system.

Building Steel

For the purposes of this discussion, building steel is a structure consisting of a steel skeleton, with the steel columns bolted to the foundation piers, and the foundations having steel reinforcing rods. It has been found that in such construction, the steel columns are inherently connected to earth through the column bolts in the footers contacting the steel reinforcing rods. At least one of the four bolts holding the steel in place will accidentally make contact with the reinforcing rods, either by being wire-tied to the reinforcing rods, or by being placed next to them.

Although the steel has a primer coat of paint, the small points on the surface of the steel puncture the coating and bond to adjacent steel surfaces. The multitude of parallel electrical paths within a steel building reduces the resistance to a low value (12).

Grounding Grids

See the section "Personnel safety protection."

Mats

See the section "Personnel safety protection."

Counterpoise

A counterpoise is a system of conductors, usually arranged beneath the earth and under transmission lines. The counterpoise is connected to the transmission towers to dissipate any lightning strike. A counterpoise conductor system can be located above the ground and placed above buildings, especially buildings storing explosives, to intercept any lightning strikes.

Pole Butt Grounds

One of the methods the utilities use to ground their systems is a (pole) butt ground. Bare copper wire is wound in a spiral fashion and stapled around the bottom of a utility pole. With the weight of the pole pressing down on the bare copper wire on the bottom of the pole, the copper wire is placed in intimate contact with the earth. Tests conducted by the Southern Nevada Chapter, International Association of Electrical Inspectors, Las Vegas, indicated that this method of connecting to earth was the least effective (11).

INSTALLATION RECOMMENDATIONS AND PRACTICES

Electrical Power System

The requirement that all continuous flowing electrical power must be contained in conductors is paramount. The method used to earth electrical equipment should be a separate conductor, either a bare copper or a green-insulated equipment earthing/grounding conductor. The earthing/grounding conductor connecting electrical equipment enclosures to earth must be contained within the raceway with the phase conductors. The raceway or external conductor should not be used to bond equipment.

Bonding

Bonding is the connecting together of two electrical conducting metallic parts to minimize the voltage difference (see the official definition in the introduction). At the point of bonding the potential difference drops to zero. For proper bonding the conductor cross-section area, the magnitude of the ground fault current, the impedance of the bonding path, and the spacing to the phase conductors must be taken into consideration.

The connecting together, or bonding, of the motor frame to the supporting building steel is made so that both metal parts will be at the same potential. Bonding is critical when dealing with static. When the flow of materials crosses a glass section, it is important to bond around the glass piping, as static charges can build up on the metallic piping where it changes to glass.

The most common error made in the installation of bonding and grounding conductors is placing them inside of ferrous conduit. The function of the bonding or grounding conductor can then be negated, especially if the conductor is insulated. The insulated bonding or grounding conductor is a single conductor that under fault conditions can carry large fault currents. It will have a magnetic field around it when carrying fault current. If it is placed inside the ferrous conduit, the combination will act as a single-turn transformer, introducing impedance into the circuit and restricting the flow of fault current. Both ends of the conductor must be bonded (connected) to the end of the conduit so that the conduit carries the fault current in parallel with the conductor.

Shielding

See the subsections "Grounding of power conductor shields" under "Equipment grounding" and "Grounding of instrumentation shields" under "Grounding of computer systems."

LIGHTNING PROTECTION GROUNDING

Adequate earthing is the key to lightning protection, as the earthing electrodes must conduct (some would say "dissipate") currents as high as 300,000 A in 1 to 1,000 μs. The lightning path begins with the air terminal. Several differently designed air terminals are manufactured. One design has multiple spikes closely spaced, mounted on an umbrella or shaped like barbed wire.

The air terminal is connected to down conductors. The high frequency of the lightning stroke forces the current to flow on the outside of the down conductor. Thus a braided, hollow copper conductor should be considered. Because the lightning stroke will not make sharp turns, but tends to flow in a straight path, all bends must be made with a sweeping turn.

If the structure has electrically continuous paths from the top to the bottom and is effectively connected to the earth through the reinforcing bars, the steel columns can serve as the down conductor. When the steel columns are less than 7.62 m (25 ft) apart they form a Faraday cage. A lightning strike to the steel will travel down the perimeter of the building steel. The columns inside the structure will be devoid of current.

In order to reduce any potential between the air terminals and the earth, a multiplicity of earthing electrodes must be installed over a large area. It has been shown that earthing terminals 1.0 m (40 in.) deep are effective when a multitude are installed over a large area. An earthing electrode should not be placed next to the foundation, as it will then be only half as effective as one that is placed the depth of the rod away from the foundation. The soil next to the foundation is usually loose and would be in relatively poor contact. Ideally, each down conductor should be connected to two or more earthing electrodes.

New information appears to validate the dissipation array lightning protection system. A charged space cloud evidently forms above the dissipation array and intercepts any lightning stroke leader. A massive earthling system is installed to earth the dissipations array system.

For additional information consult Refs. 3 and 13.

STATIC-PROTECTION GROUNDING

Static is considered a mystery by many. The key to protection against static is the completion of the circuit. Static charges are developed when electrons are moved from one location to another without an adequate conductive return path back to the source. Charges that are insulated from other conducting paths back to the source are the problem. Harm can develop if the charges are allowed to concentrate, build up sufficient potential, and break down the insulation properties of air, resulting in a sparkover.

Bonding between the location losing charges and the location gaining charges will permit the charges to recombine, preventing any buildup of harmful voltages. The earth (ground) may be a path allowing the charges to neutralize. Thus, many times earthing is looked on as the remedy for static. There are various methods to generating the necessary path.

Earthing and bonding are the first line of defense. Naturally, if the insulating medium is between the charge area and earth, the connection to earth of the charged area will allow recombining of the charges. Otherwise, installation of a bonding conductor between the charged area and the charge-deficient area will allow recombining of the charges.

An example is a rubber-lined pipe, connected to a metallic pipe, connected to a glass section, connected to another metallic pipe flowing into a glass lined tank. Both metallic pipe sections are insulated from earth. With sufficient flow of a material that was capable of carrying charges, charges can be wiped from the first metallic pipe section and deposited on the second.

There are two solutions. One would be just to connect (bond) the two metallic sections together. This would allow the charges to recombine. The other solution would be to connect both the first and the second metallic section to earth. The return path would use the earth. This solution would also eliminate any touch-potential problems.

Moisture is another solution to static problems. Moisture-laden air will conduct charges. If the air is in contact with both charged areas, the charges can return through it. Many times steam is injected into the air to provide moisture. Explosive-powder-producing plants rely on this method. [In addition, since man-made clothing (nylon, rayon, etc.), when rubbed, can generate static charges, such plants require all employees to wear cotton clothing or other natural materials.]

Static charges can build up on computer personnel walking across a floor while wearing nylon clothing. The soles of the shoes insulate their bodies from the conductive floor. Sufficient charges sometimes built up to jump to a mainframe computer, damaging the sensitive computer chips. When working on computers, the human body should be bonded to the computer frame through a wrist-bonding strap. Conductive floors and conductive shoes are other methods that can be used to solve the problem. This method is especially useful in computer rooms and in explosive-powder-producing factories. Ionization—the generating of free-floating ions—will also allow the recombining of charges.

Fast-moving belts will wipe charges from one rotating metallic roller to another. The charge can be collected by spirally wound tinsel or wire set near the moving belt and connected to earth. The earth conducts the charges back to the source to be recombined.

Any flowing material, either dry or liquid, can generate static charges. The grain industries are particularly susceptible. For additional information see the NFPA standards.

GROUNDING OF COMPUTER SYSTEMS

A major problem is the earthing of sensitive electronic equipment such as computers, process control equipment, programmable logic controllers (PLCs), instrumentation distributed (process) control systems (DCSs), and similar sensitive electronic equipment. These items will be lumped together under the term *computers* for ease of reference. The proper installation of earthing is critical in order to achieve satisfactory operation of such sensitive electronic equipment. The low voltages that computers operate at makes them extremely sensitive to interference from other low voltages, voltages that are not perceptible to humans. Such voltages do not affect electrical power equipment. Thus, when computers came on the scene, new techniques had to be developed, new logic applied, and new methods used to connect these sensitive electronic pieces of equipment effectively to earth.

History of Computer Grounding

It was unfortunate that the electronic technicians, who became the leaders in this new field of computers, were mostly not schooled either in power distribution grounding or in radio and antenna construction techniques. One electronic–computer leader of a large project to automate the manufacturing of explosive blasting caps insisted on using 120 V to power a 50-hp motor because 120 V was safer than higher voltages. (Even 120 V can harm humans; see the section "Personnel safety protection.") Exemplifying the maxim that a little learning is a dangerous thing, there were many who knew the neutral was connected to earth. Therefore, when a connection to earth was needed in a computer circuit, the neutral was employed and was usually connected to the metal cabinet of the device under construction, especially where no equipment ground conductor was present. Isolation of the electrical conduit from the computer equipment frame became prevalent. Plastic couplings were required to be installed in the power-supply conduit to the computer to isolate the computer frame from the building electrical equipment ground system. Yet, the computer water piping was connected to the computer by persons who were not aware of the fact that the metallic water piping was connected to the system neutral, the equipment ground system, and earth also. To add to this, there were those who viewed the earth as a collection of insulated sponges that were capable of absorbing electrons. All of these misconceptions led to mass confusion and erroneous grounding methods that were applied to computer grounding, not only by leading computer manufacturers, but also by the new class of engineers known as (electronic) instrumentation engineers.

Because of the interconnection of neutral conductors and other early wiring mistakes, uncontrolled current flowed over the computer circuits, resulting in damage to the computers. The popularity of isolated earth connections for computers grew. It became necessary, in order to meet the requirements of the computer companies and the instrumentation engineers, to run the computer grounding connection out to the parking lot's pink petunia bed and drive a rod for the computer earthing system. Common sense was lacking, though all one had to do for a solution was look to the heavens, to the circling satellites with several computers on board. If it were really necessary, for the operation of a computer, to be connected to earth through a rod in the parking lot, the use of computers in satellites would be difficult indeed.

The science of computer earthing has progressed to where the majority of the misconceptions have been dispelled. Correct principles are now in place and are being used. First and foremost is the principle that there must be only one connection to earth and that connection is by way of the electrical power system's equipment ground conductor.

Types of Computer Grounding Systems

Because of the various earthing functions thought necessary for computers, several types of computer earthing systems came into being. Personnel safety required the frame of the computer equipment to be connected to the electrical system equipment grounding conductor. This grounding connection became known as the "safety ground bus." It was also called, naturally, the "equipment ground bus." This was normally the green wire emanating from the electrical power system earthing connection.

The shield wires from the remote instrumentation signals needed to be connected to earth. All the signal shields were gathered together, and at one time they were connected to a separate, isolated earth connection. The connection became known as the "signal ground."

The computer had its own power supplies. These ac and dc power supplies needed to have one side connected to "earth." Since the object was to keep voltage excursions to a minimum, it would have been sufficient to connect one side of the power supply to the equipment metallic enclosure. Nevertheless, a separate isolated earth connection was provided for the "dc power supply reference ground bus."

For each application where an earth connection was required, an isolated earth connection was listed as needed. There were many different names for these connections to earth, such as computer reference ground, earth common, dc master ground point, ac safety ground, dc signal common, dc ground bus, and power supply common ground point or bus. There were no standards for computer grounding systems, and each computer company had its own terminology. There were usually at least three separate ground buses in each computer system.

Computer Grounding Methods

In a properly designed system, there is only one connection to earth and that connection is by way of the electrical power system's equipment ground conductor. How the various ear-

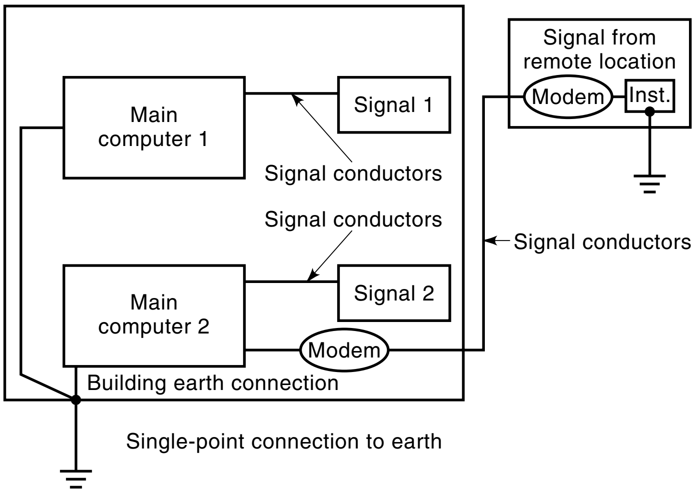

Figure 13. Single-point computer earthing.

thing buses are routed or connected depends on the detailed design. It is necessary to distinguish between the electrical power system equipment (safety) ground and all the other “ground” buses. The earthing conductor is always insulated. The insulation is colored green or green and yellow.

Single-Point Grounding Systems. It is necessary to keep stray uncontrolled current from entering the computer system, its signal conductors, its power supplies, etc. (See the subsection “Uncontrolled flow of current over the earth” under “Personnel safety protection.”) The method used to accomplish the control of stray currents is to connect the computer ground buses to the equipment ground system at only one point. It is desirable to keep the grounding systems of different computers isolated from each other except at one point where they are connected together. (See Fig. 13.)

Remote computer locations pose a problem. When the communication cables extend beyond the computer room and remote inputs exist, voltage potentials can develop if the remote locations are earthed locally. This is especially true when thunderclouds are in the vicinity. See Figure 14.

Central Radial Grounding Systems. The computer parts that need to be connected to earth can be connected in a radial or star type earthing connection. Again, this type of connection achieves a single-point connection to earth. The main object is to prevent the computer grounding conductor from carrying continuous current. The exception to this is the equipment ground conductor, as it is connected unintentionally at many places through the equipment sitting on earth.

Fiber Optics. The problems of ground currents flowing over shields and being injected into the signal conductors is eliminated with the use of fiber optic cable connections between remote locations. Fiber optic cable can be used within the control building and will eliminate interference from adjacent current carrying conductors. Fiber optic cables are offered with a ground conductor or shield and/or current-carrying conductors. Remember that a shield can carry unwanted and interfering current from one place to another.

Grounding of Instrumentation Shields

Instrumentation cable should have a shield, consisting of either solid metal foil or expanded braided wire, over the signal conductors to eliminate interference from being inducted into the signal carrying conductors. To be effective the shield must be grounded. The best method of connecting the shields to earth depends on the voltage difference at the ends, the frequency of the interference signal, and the need to protect against lightning and large current flows.

If one can be assured that the only interference will be from either low frequency or high frequency, then a single shield will be adequate. However, if frequencies below 1 MHz and also above 1 MHz are to be encountered, then a single shield will be insufficient. For interference below 1 MHz the shield needs to be grounded at one end only, to prevent circulating currents from inducing interference. Above 1 MHz, the shield needs to be grounded, not only at both ends, but perhaps even at points in between, in order to attenuate the high-frequency interference.

The earthing leads need to be short, as they develop impedance proportional to their length as well as to the fre-

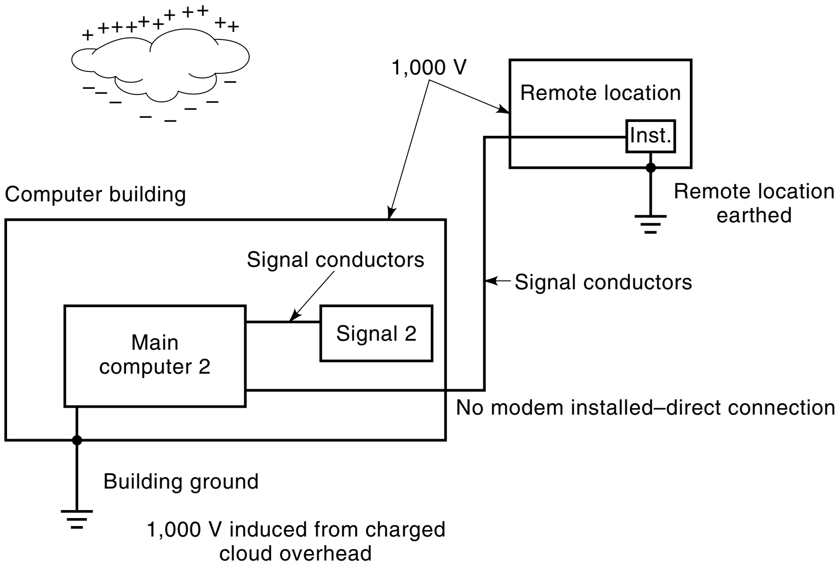

Figure 14. Dangerous and damaging potentials.

quency of the interference. A lead longer than $\frac{1}{20}$ of the wavelength can produce a resonating circuit. As the wave travels down the conductor, if the length is the same as the wavelength and the peak is reflected back, a new pulse will occur at the same time, effectively doubling the pulse. Peaks will occur at $\frac{1}{4}$-wavelength intervals. Since the speed of an electromagnetic wave in a vacuum is about 300,000 km (186,000 miles) per second, the wavelength in meters is 300 divided by the frequency in megahertz.

Example. A 10 MHz pulse in a conductor will travel approximately 30 m (98 ft) in free space during one cycle (0.1 μs). In a conductor, the speed is lower. The pulse might travel 26.82 m (88 ft) in 0.1 μs. The peak will occur $\frac{1}{4}$ wavelength, or 6.7 m (22 ft). Thus, the connection cannot be longer than 6.7 m if the voltage is to be equalized between the ends.

If current were to flow over the inner shield, the current could induce unwanted voltages into the signal conductors. In order to eliminate this possibility, the shield is connected to earth at only one end, usually at the control end. (The exception is thermocouples, where the shield is connected at the thermocouple.) If the shield were connected at both ends, capacitive current could flow over the shield.

Before the advent of cable-tray installations, instrumentation cables were installed within rigid ferrous-metal conduit. This overall shield was connected to ground at support points, approximately every 3 m. It acted as an outer shield and, being grounded at multiple points, attenuated high-frequency interference and the large magnetic fields from nearby lightning strikes.

The advent of cable tray eliminated the rigid conduit and the protection it afforded against high-frequency interference and lightning strikes. Computer-controlled instrumentation has inputs of 3 V to 5 V today. At this low voltage, interference is easily injected into the instrumentation control cables. A nearby lightning strike can induce sufficient voltage to destroy the sensitive control circuits and equipment.

Instrumentation cables are manufactured with an inner shield over the signal conductors, and sometimes also with an overall outer shield. However, this overall shield lacks sufficient ferrous cross section to overcome the effects of large current flows through the earth or air or of strong magnetic fields; also, it usually has insufficient current-carrying capacity. Therefore, for maximum protection against interference from large current flow through the earth, the magnetic fields associated with lightning, and other strong electric and magnetic fields from adjacent current-carrying conductors, all sensitive electronic circuits extending outside the control room should be installed within ferrous conduit or fiber optic cable. In particular, ferrous conduit should be used underground, as PVC conduit offers no protection against magnetic interference.

GENERATOR GROUNDING

Generators have characteristics considerably different from other electrical devices, such as transformers and other sources of power. The construction of a generator lacks the ability to withstand the mechanical effects of short-circuit currents, as well as heating effects. The reactances of the generator are not equal, as a transformer's are. A generator can develop third-harmonic voltages. Space limitations restrict the amount of insulation that can be installed. Internal faults to the generator ground can result in extremely high current flow that can damage the laminations. Generators are often operated in parallel, producing additional problems.

Depending on the voltage, generators should be grounded by one of the methods already discussed. For additional information on industrial generation grounding see Ref. 3, and for utility generators see the IEEE Power Engineering Society Standards.

TESTING THE GROUNDING AND BONDING SYSTEMS

Finding neutral-to-ground faults is difficult and can be time-consuming. Determining that they exist is very easy. A preliminary test involves placing a clamp-on ammeter on the conductor between the transformer's neutral X_0 connection and the earth connection (see Fig. 2, terminals T and TG). Any current flow will indicate neutral-to-ground faults exist.

To verify that there are such faults, the power to the panel is disconnected or the circuit breakers are all opened (turned off). The incoming neutral conductor is lifted from the panel terminals. One lead of an ohmmeter is placed on the neutral bus bar, and the other lead is placed on earth or ground. The reading should be infinity. If the reading of the resistance is zero, there are solid connections from neutral to ground.

The neutral-to-ground faults can be isolated by lifting all the neutral connections from the neutral bus bar and replacing them one at a time, checking the resistance each time a conductor is replaced.

Bonding and grounding connections can be tested using the *direct method;* see the subsection “Measuring ground resistance” under “Electrical properties of the earth.”

For a description of Ground-fault detectors see the “White Book” (7).

BIBLIOGRAPHY

1. *IEEE standard dictionary of electrical and electronic terms,* 6th ed., ANSI/IEEE Std. 100, New York: IEEE, 1997.
2. IEEE guide for safety in substation grounding, ANSI/IEEE Std. 80.
3. IEEE recommended practice for grounding of industrial and commercial power systems, ANSI/IEEE Std. 142.
4. F. J. Shields, System grounding for low-voltage power systems, 12345GET-3548B, 12-76. General Electric Company, Industrial Power Systems Engineering Operations, Schenectady, NY.
5. R. H. Lee, The other electrical hazard: Electric arc blast burns, *IEEE Trans. Ind. Appl.,* **IA-18**: 246–251, 1982.
6. M. Capelli-Schellpfeffer and R. C. Lee, Advances in the evaluation and treatment of electrical and thermal injury emergencies, *IEEE Trans. Ind. Appl.,* **31**: 1147–1152, 1995.
7. IEEE recommended practice for electric systems in health care facilities, ANSI/IEEE Std. 602.
8. B. Bridger, Jr., High resistance grounding, *IEEE Trans. Ind. Appl.* **19**: 15–21, 1983.
9. AIEE Committee Report, Application of ground fault neutralizers, *Electrical Eng.,* **72**: 606, July 1953.
10. E. J. Fagan and R. H. Lee, The use of concrete enclosed reinforcing rods as grounding electrodes, *IEEE Trans. Ind. Appl.,* **IGA-6**: 337–348, 1970.

11. T. Lindsey, Grounding/Earthing electrode studies, 1 of 2, IAEI/SNC Grounding Committee, Clark County Building Department, Las Vegas, NV 89101, May 1997.
12. R. B. West, Impedance testing equipment grounding conductors, *IEEE Trans. Ind. Appl.,* **IA-25**: 124–136, 1981.
13. Lightning protection code, ANSI–NFPA Std. 780.

Reading List

American National Standard for electrical power systems and equipment—voltage ratings (60 Hz), ANSI C84.1, 1984.

National Fire Protection Association's National Electrical Code, ANSI/NFPA 70, 1996.

National Fire Protection Association's Lightning Protection Code, ANSI/NFPA 780, 1998.

Canadian Electrical Code Part I, Canadian Standards Association, Rexdale, Ontario, Canada M9W 1R3, 1997.

Grounding for process control computers and distributed control systems: The National Electrical Code and present grounding practices, *IEEE Trans. Ind. Appl.,* **IA-23** (3): 417–423, 1987.

Guideline on electrical power for ADP (Automatic Data Processing) installations, Federal Information Processing Standards Publication 94 (FIPS 94), National Technical Information Service, 1983.

Recommended practice for powering and grounding sensitive electronic equipment (Emerald Books), IEEE Std 1100, 1992.

H. R. Kaufmann, Some fundamentals of equipment grounding circuit design, *IEEE Trans. Ind. Gen. Appl.,* **IGA73**: part 2, November 1954.

R. H. Lee, Grounding of computers and other sensitive equipment, *IEEE Trans. Ind. Appl.,* **IA-23**: 408–411, 1987.

R. B. West, Grounding for emergency and standby power systems, *IEEE Trans. Ind. Appl.,* **IA-15**: 124–136, 1979.

R. B. West, Equipment grounding for reliable ground-fault protection in electrical systems below 600 V, *IEEE Trans. Ind. Appl.,* **IA-10**: 175–189, 1974.

D. W. Zipse, Multiple neutral to ground connections, in *IEEE 1972 I&CPS Technical Conference,* 72CH0600-7-1A, pp. 60–64.

D. W. Zipse, Lightning protection systems: Advantages and disadvantages, *IEEE Trans. Ind. Appl.,* **IA-30**: 1351–1361, 1994.

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