

IEEE Guide for Safety in AC Substation Grounding

Sponsor

Substations Committee
of the
IEEE Power Engineering Society

Approved 30 January 2000

IEEE-SA Standards Board

Abstract: Outdoor ac substations, either conventional or gas-insulated, are covered in this guide. Distribution, transmission, and generating plant substations are also included. With proper caution, the methods described herein are also applicable to indoor portions of such substations, or to substations that are wholly indoors. No attempt is made to cover the grounding problems peculiar to dc substations. A quantitative analysis of the effects of lightning surges is also beyond the scope of this guide.

Keywords: ground grids, grounding, substation design, substation grounding

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Introduction

(This introduction is not part of IEEE Std 80-2000, IEEE Guide for Safety in AC Substation Grounding.)

This fourth edition represents the second major revision of this guide since its first issue in 1961. Major modifications include the further extension of the equations for calculating touch and step voltages to include L-shaped and T-shaped grids; the introduction of curves to help determine current division; modifications to the derating factor curves for surface material; changes in the criteria for selection of conductors and connections; additional information on resistivity measurement interpretation; and the discussion of multilayer soils. Other changes and additions were made in the areas of gas-insulated substations, the equations for the calculation of grid resistance, and the annexes. The fourth edition continues to build on the foundations laid by three earlier working groups: AIEE Working Group 56.1 and IEEE Working Groups 69.1 and 78.1.

The work of preparing this standard was done by Working Group D7 of the Distribution Substation Subcommittee and was sponsored by the Substation Committee of the IEEE Power Engineering Society. At the time this guide was completed, the Substation Grounding Safety Working Group, D7, had the following membership:

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This fourth edition of IEEE Std 80 is dedicated to the memory of J. G. Sverak, who, through his technical knowledge and expertise, developed the touch and step voltage equations and the grid resistance equations used in the 1986 edition of this guide. His leadership, humor, and perseverance as Chair of Working Group 78.1 led to the expansion of substation grounding knowledge in IEEE Std 80-1986.

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IEEE Guide for Safety in AC Substation Grounding

1. Overview

1.1 Scope

This guide is primarily concerned with outdoor ac substations, either conventional or gas-insulated. Distribution, transmission, and generating plant substations are included. With proper caution, the methods described herein are also applicable to indoor portions of such substations, or to substations that are wholly indoors.¹

No attempt is made to cover the grounding problems peculiar to dc substations. A quantitative analysis of the effects of lightning surges is also beyond the scope of this guide.

1.2 Purpose

The intent of this guide is to provide guidance and information pertinent to safe grounding practices in ac substation design.

The specific purposes of this guide are to

- a) Establish, as a basis for design, the safe limits of potential differences that can exist in a substation under fault conditions between points that can be contacted by the human body.
- b) Review substation grounding practices with special reference to safety, and develop criteria for a safe design.
- c) Provide a procedure for the design of practical grounding systems, based on these criteria.
- d) Develop analytical methods as an aid in the understanding and solution of typical gradient problems.

¹Obviously, the same ground gradient problems that exist in a substation yard should not be present within a building. This will be true provided the floor surface either assures an effective insulation from earth potentials, or else is effectively equivalent to a conductive plate or close mesh grid that is always at substation ground potential, including the building structure and fixtures.

Therefore, even in a wholly indoor substation it may be essential to consider some of the possible hazards from perimeter gradients (at building entrances) and from transferred potentials described in Clause 8. Furthermore, in the case of indoor gas-insulated facilities, the effect of circulating enclosure currents may be of concern, as discussed in Clause 10.

The concept and use of safety criteria are described in Clause 1 through Clause 8, practical aspects of designing a grounding system are covered in Clause 9 through Clause 13, and procedures and evaluation techniques for the grounding system assessment (in terms of safety criteria) are described in Clause 14 through Clause 20. Supporting material is organized in Annex A through Annex G.

This guide is primarily concerned with safe grounding practices for power frequencies in the range of 50–60 Hz. The problems peculiar to dc substations and the effects of lightning surges are beyond the scope of this guide. A grounding system designed as described herein will, nonetheless, provide some degree of protection against steep wave front surges entering the substation and passing to earth through its ground electrodes.² Other references should be consulted for more information about these subjects.

1.3 Relation to other standards

The following standards provide information on specific aspects of grounding:

- IEEE Std 81-1983³ and IEEE Std 81.2-1991 provide procedures for measuring the earth resistivity, the resistance of the installed grounding system, the surface gradients, and the continuity of the grid conductors.
- IEEE Std 142-1991, also known as the IEEE Green Book, covers some of the practical aspects of grounding, such as equipment grounding, cable routing to avoid induced ground currents, cable sheath grounding, static and lightning protection, indoor installations, etc.
- IEEE Std 367-1996 provides a detailed explanation of the asymmetrical current phenomenon and of the fault current division, which to a large degree parallels that given herein. Of course, the reader should be aware that the ground potential rise calculated for the purpose of telecommunication protection and relaying applications is based on a somewhat different set of assumptions concerning the maximum grid current, in comparison with those used for the purposes of this guide.
- IEEE Std 665-1995 provides a detailed explanation of generating station grounding practices.
- IEEE Std 837-1989 provides tests and criteria to select connections to be used in the grounding system that will meet the concerns described in Clause 11.

2. References

This guide should be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply.

Accredited Standards Committee C2-1997, National Electrical Safety Code® (NESC®).⁴

IEEE Std 81-1983, IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System (Part 1).⁵

IEEE Std 81.2-1992, IEEE Guide for Measurement of Impedance and Safety Characteristics of Large, Extended or Interconnected Grounding Systems (Part 2).

²The greater impedance offered to steep front surges will somewhat increase the voltage drop in ground leads to the grid system, and decrease the effectiveness of the more distant parts of the grid. Offsetting this in large degree is the fact that the human body apparently can tolerate far greater current magnitudes in the case of lightning surges than in the case of 50 Hz or 60 Hz currents.

³Information on references can be found in Clause 2.

⁴The NESC is available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://standards.ieee.org/>).

⁵IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://standards.ieee.org/>).

IEEE Std 142-1991, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems (IEEE Green Book).

IEEE Std 367-1996, IEEE Recommended Practice for Determining the Electric Power Substation Ground Potential Rise and Induced Voltage from a Power Fault.

IEEE Std 487-1992, IEEE Recommended Practice for the Protection of Wire-Line and Communication Facilities Serving Electric Power Stations.

IEEE Std 525-1992 (Reaff 1999), IEEE Guide for the Design and Installation of Cable Systems in Substations.

IEEE Std 665-1995, IEEE Guide for Generating Station Grounding.

IEEE Std 837-1989 (Reaff 1996), IEEE Standard for Qualifying Permanent Connections Used in Substation Grounding.

IEEE Std 1100-1999, IEEE Recommended Practice for Powering and Grounding Electronic Equipment (IEEE Emerald Book).

IEEE Std C37.122-1993, IEEE Standard for Gas-Insulated Substations.

IEEE Std C37.122.1-1993, IEEE Guide for Gas-Insulated Substations.

3. Definitions

Most of the definitions given herein pertain solely to the application of this guide. No further references will be made to any of the definitions stated below, unless necessary for clarity. All other definitions are placed within the text of individual clauses. For additional definitions refer to *The IEEE Standard Dictionary of Electrical and Electronics Terms* [B86].⁶

3.1 auxiliary ground electrode: A ground electrode with certain design or operating constraints. Its primary function may be other than conducting the ground fault current into the earth.

3.2 continuous enclosure: A bus enclosure in which the consecutive sections of the housing along the same phase conductor are bonded together to provide an electrically continuous current path throughout the entire enclosure length. Cross-bondings, connecting the other phase enclosures, are made only at the extremities of the installation and at a few selected intermediate points.

3.3 dc offset: Difference between the symmetrical current wave and the actual current wave during a power system transient condition. Mathematically, the actual fault current can be broken into two parts, a symmetrical alternating component and a unidirectional (dc) component. The unidirectional component can be of either polarity, but will not change polarity, and will decrease at some predetermined rate.

3.4 decrement factor: An adjustment factor used in conjunction with the symmetrical ground fault current parameter in safety-oriented grounding calculations. It determines the rms equivalent of the asymmetrical current wave for a given fault duration, t_f , accounting for the effect of initial dc offset and its attenuation during the fault.

⁶The numbers in brackets correspond to those of the bibliography in Annex A.

3.5 effective asymmetrical fault current: The rms value of asymmetrical current wave, integrated over the interval of fault duration (see Figure 1).

$$I_F = D_f \times I_f \quad (1)$$

where

I_F is the effective asymmetrical fault current in A
 I_f is the rms symmetrical ground fault current in A
 D_f is the decrement factor

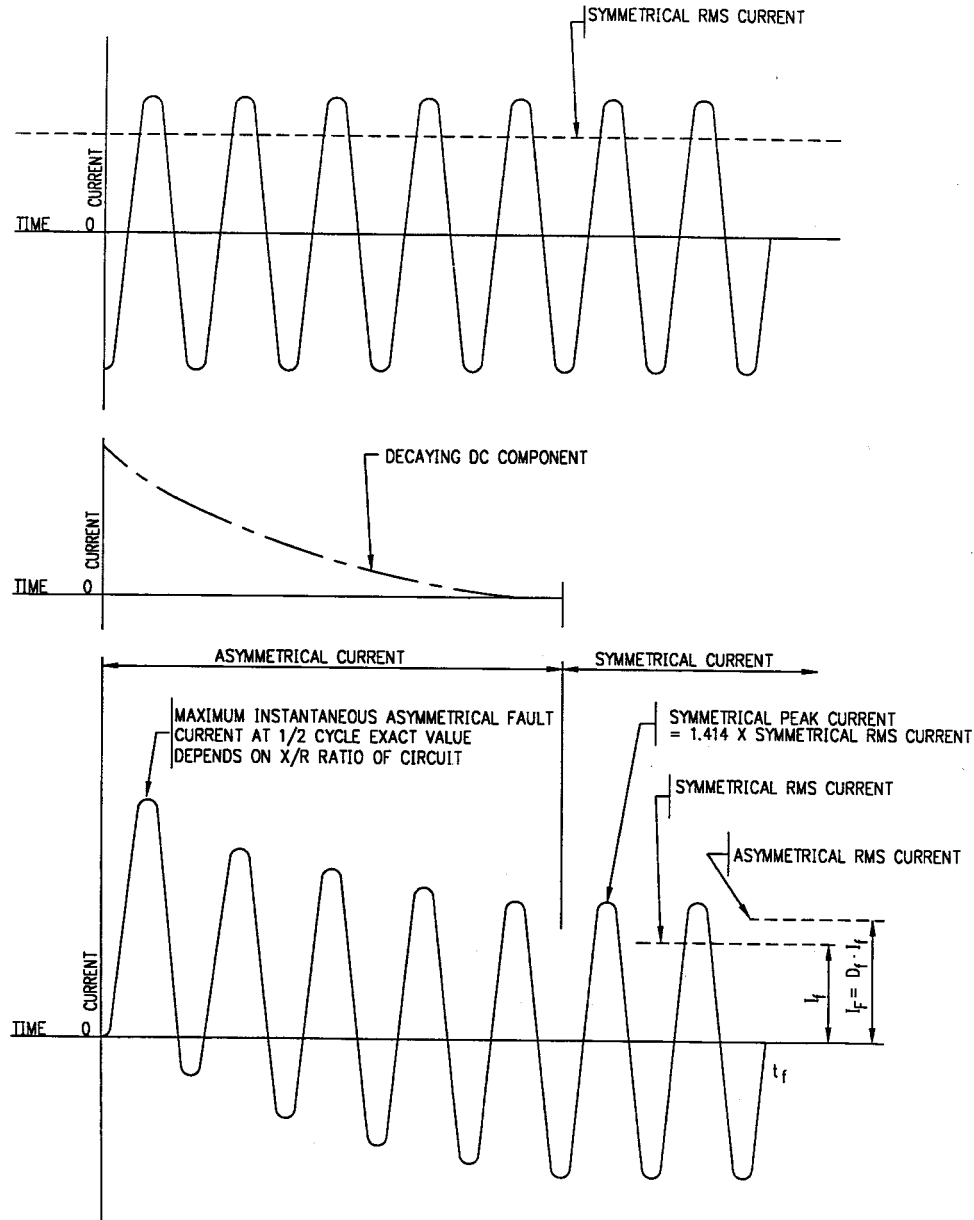


Figure 1—Relationship between actual values of fault current and values of I_F , I_f , and D_f for fault duration t_f

3.6 enclosure currents: Currents that result from the voltages induced in the metallic enclosure by the current(s) flowing in the enclosed conductor(s).

3.7 fault current division factor: A factor representing the inverse of a ratio of the symmetrical fault current to that portion of the current that flows between the grounding grid and surrounding earth.

$$S_f = \frac{I_g}{3I_0} \quad (2)$$

where

S_f is the fault current division factor
 I_g is the rms symmetrical grid current in A
 I_0 is the zero-sequence fault current in A

NOTE—In reality, the current division factor would change during the fault duration, based on the varying decay rates of the fault contributions and the sequence of interrupting device operations. However, for the purposes of calculating the design value of maximum grid current and symmetrical grid current per definitions of symmetrical grid current and maximum grid current, the ratio is assumed constant during the entire duration of a given fault.

3.8 gas-insulated substation: A compact, multicomponent assembly, enclosed in a grounded metallic housing in which the primary insulating medium is a gas, and that normally consists of buses, switchgear, and associated equipment (subassemblies).

3.9 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 relatively large extent that serves in place of the earth.

3.10 grounded: A system, circuit, or apparatus provided with a ground(s) for the purposes of establishing a ground return circuit and for maintaining its potential at approximately the potential of earth.

3.11 ground current: A current flowing into or out of the earth or its equivalent serving as a ground.

3.12 ground electrode: A conductor imbedded in the earth and used for collecting ground current from or dissipating ground current into the earth.

3.13 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's 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 surface material, are common forms of a ground mat.

3.14 ground potential rise (GPR): The maximum electrical potential that a substation grounding grid may attain relative to a distant grounding point assumed to be at the potential of remote earth. This voltage, GPR, is equal to the maximum grid current times the grid resistance.

NOTE—Under normal conditions, the grounded electrical equipment operates at near zero ground potential. That is, the potential of a grounded neutral conductor is nearly identical to the potential of remote earth. During a ground fault the portion of fault current that is conducted by a substation grounding grid into the earth causes the rise of the grid potential with respect to remote earth.

3.15 ground return circuit: A circuit in which the earth or an equivalent conducting body is utilized to complete the circuit and allow current circulation from or to its current source.

3.16 grounding grid: A system of horizontal ground electrodes that consists 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.

NOTE—Grids buried horizontally near the earth's surface are also effective in controlling the surface potential gradients. A typical grid usually is supplemented by a number of ground rods and may be further connected to auxiliary ground electrodes to lower its resistance with respect to remote earth.

3.17 grounding system: Comprises all interconnected grounding facilities in a specific area.

3.18 main ground bus: A conductor or system of conductors provided for connecting all designated metallic components of the gas-insulation substation (GIS) to a substation grounding system.

3.19 maximum grid current: A design value of the maximum grid current, defined as follows:

$$I_G = D_f \times I_g \quad (3)$$

where

I_G is the maximum grid current in A
 D_f is the decrement factor for the entire duration of fault t_f , given in s
 I_g is the rms symmetrical grid current in A

3.20 mesh voltage: The maximum touch voltage within a mesh of a ground grid.

3.21 metal-to-metal touch voltage: The difference in potential between metallic objects or structures within the substation site that may be bridged by direct hand-to-hand or hand-to-feet contact.

NOTE—The metal-to-metal touch voltage between metallic objects or structures bonded to the ground grid is assumed to be negligible in conventional substations. However, the metal-to-metal touch voltage between metallic objects or structures bonded to the ground grid and metallic objects internal to the substation site, such as an isolated fence, but not bonded to the ground grid may be substantial. In the case of a gas-insulated substation (GIS), the metal-to-metal touch voltage between metallic objects or structures bonded to the ground grid may be substantial because of internal faults or induced currents in the enclosures.

In a conventional substation, the worst touch voltage is usually found to be the potential difference between a hand and the feet at a point of maximum reach distance. However, in the case of a metal-to-metal contact from hand-to-hand or from hand-to-feet, both situations should be investigated for the possible worst reach conditions. Figure 12 and Figure 13 illustrate these situations for air-insulated substations, and Figure 14 illustrates these situations in GIS.

3.22 noncontinuous enclosure: A bus enclosure with the consecutive sections of the housing of the same phase conductor electrically isolated (or insulated from each other), so that no current can flow beyond each enclosure section.

3.23 primary ground electrode: A ground electrode specifically designed or adapted for discharging the ground fault current into the ground, often in a specific discharge pattern, as required (or implicitly called for) by the grounding system design.

3.24 step voltage: The difference in surface potential experienced by a person bridging a distance of 1 m with the feet without contacting any grounded object.

3.25 subtransient reactance: Reactance of a generator at the initiation of a fault. This reactance is used in calculations of the initial symmetrical fault current. The current continuously decreases, but it is assumed to be steady at this value as a first step, lasting approximately 0.05 s after an applied fault.

3.26 surface material: A material installed over the soil consisting of, but not limited to, rock or crushed stone, asphalt, or man-made materials. The surfacing material, depending on the resistivity of the material, may significantly impact the body current for touch and step voltages involving the person's feet.

3.27 symmetrical grid current: That portion of the symmetrical ground fault current that flows between the grounding grid and surrounding earth. It may be expressed as

$$I_g = S_f \times I_f \quad (4)$$

where

I_g is the rms symmetrical grid current in A
 I_f is the rms symmetrical ground fault current in A
 S_f is the fault current division factor

3.28 symmetrical ground fault current: The maximum rms value of symmetrical fault current after the instant of a ground fault initiation. As such, it represents the rms value of the symmetrical component in the first half-cycle of a current wave that develops after the instant of fault at time zero. For phase-to-ground faults

$$I_{f(0+)} = 3I_0'' \quad (5)$$

where

$I_{f(0+)}$ is the initial rms symmetrical ground fault current
 I_0'' is the rms value of zero-sequence symmetrical current that develops immediately after the instant of fault initiation, reflecting the subtransient reactances of rotating machines contributing to the fault

This rms symmetrical fault current is shown in an abbreviated notation as I_f , or is referred to only as $3I_0$. The underlying reason for the latter notation is that, for purposes of this guide, the initial symmetrical fault current is assumed to remain constant for the entire duration of the fault.

3.29 touch voltage: The potential difference between the ground potential rise (GPR) and the surface potential at the point where a person is standing while at the same time having a hand in contact with a grounded structure.

3.30 transferred voltage: A special case of the touch voltage where a voltage is transferred into or out of the substation from or to a remote point external to the substation site.

3.31 transient enclosure voltage (TEV): Very fast transient phenomena, which are found on the grounded enclosure of GIS systems. Typically, ground leads are too long (inductive) at the frequencies of interest to effectively prevent the occurrence of TEV. The phenomenon is also known as transient ground rise (TGR) or transient ground potential rise (TGPR).

3.32 very fast transient (VFT): A class of transients generated internally within a gas-insulated substation (GIS) characterized by short duration and very high frequency. VFT is generated by the rapid collapse of voltage during breakdown of the insulating gas, either across the contacts of a switching device or line-to-ground during a fault. These transients can have rise times in the order of nanoseconds implying a frequency content extending to about 100 MHz. However, dominant oscillation frequencies, which are related to physical lengths of GIS bus, are usually in the 20–40 MHz range.

3.33 very fast transients overvoltage (VFTO): System overvoltages that result from generation of VFT. While VFT is one of the main constituents of VFTO, some lower frequency (≈ 1 MHz) component may be present as a result of the discharge of lumped capacitance (voltage transformers). Typically, VFTO will not exceed 2.0 per unit, though higher magnitudes are possible in specific instances.

3.34 X/R ratio: Ratio of the system reactance to resistance. It is indicative of the rate of decay of any dc offset. A large X/R ratio corresponds to a large time constant and a slow rate of decay.

4. Safety in grounding

4.1 Basic problem

In principle, a safe grounding design has the following two objectives:

- To provide means to carry electric currents into the earth under normal and fault conditions without exceeding any operating and equipment limits or adversely affecting continuity of service.
- To assure that a person in the vicinity of grounded facilities is not exposed to the danger of critical electric shock.

A practical approach to safe grounding thus concerns and strives for controlling the interaction of two grounding systems, as follows:

- The intentional ground, consisting of ground electrodes buried at some depth below the earth's surface.
- The accidental ground, temporarily established by a person exposed to a potential gradient in the vicinity of a grounded facility.

People often assume that any grounded object can be safely touched. A low substation ground resistance is not, in itself, a guarantee of safety. There is no simple relation between the resistance of the ground system as a whole and the maximum shock current to which a person might be exposed. Therefore, a substation of relatively low ground resistance may be dangerous, while another substation with very high resistance may be safe or can be made safe by careful design. For instance, if a substation is supplied from an overhead line with no shield or neutral wire, a low grid resistance is important. Most or all of the total ground fault current enters the earth causing an often steep rise of the local ground potential [see Figure 2(a)]. If a shield wire, neutral wire, gas-insulated bus, or underground cable feeder, etc., is used, a part of the fault current returns through this metallic path directly to the source. Since this metallic link provides a low impedance parallel path to the return circuit, the rise of local ground potential is ultimately of lesser magnitude [see Figure 2(b)]. In either case, the effect of that portion of fault current that enters the earth within the substation area should be further analyzed. If the geometry, location of ground electrodes, local soil characteristics, and other factors contribute to an excessive potential gradient at the earth's surface, the grounding system may be inadequate despite its capacity to carry the fault current in magnitudes and durations permitted by protective relays.

Clause 5 through Clause 8 detail those principal assumptions and criteria that enable the evaluation of all necessary factors in protecting human life, the most precious element of the accidental circuit.

4.2 Conditions of danger

During typical ground fault conditions, the flow of current to earth will produce potential gradients within and around a substation. Figure 3 shows this effect for a substation with a simple rectangular grounding grid in homogeneous soil.

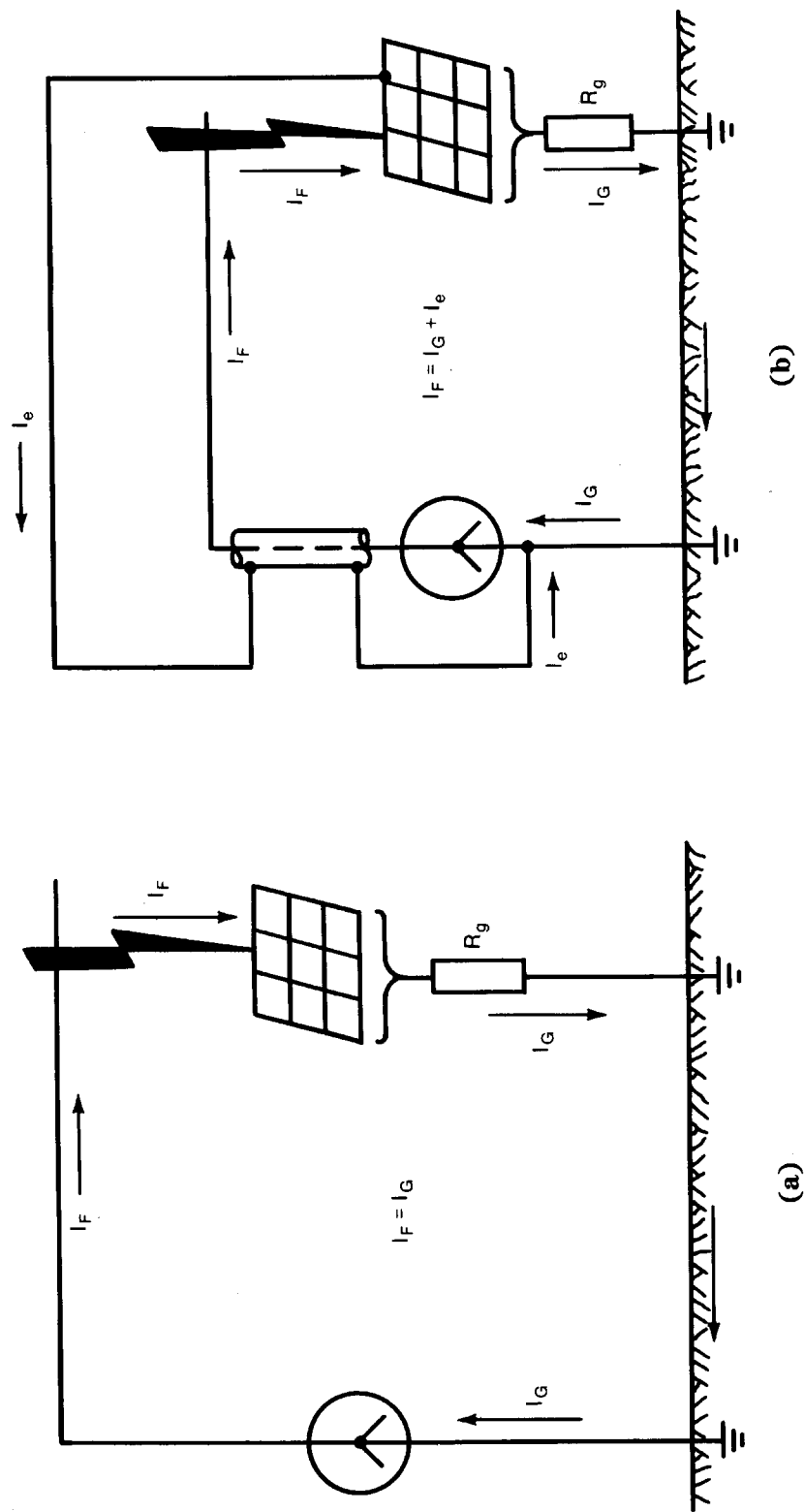


Figure 2—Equipotential contours of a typical grounding grid with and without ground rods

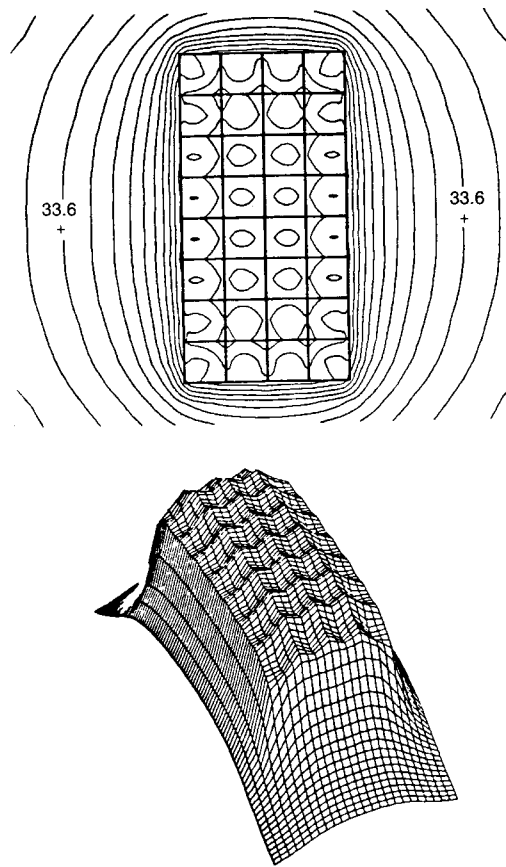


Figure 3—Equipotential contours if a typical grounding grid with and without ground rods

Unless proper precautions are taken in design, the maximum potential gradients along the earth's surface may be of sufficient magnitude during ground fault conditions to endanger a person in the area. Moreover, dangerous voltages may develop between grounded structures or equipment frames and the nearby earth.

The circumstances that make electric shock accidents possible are as follows:

- a) Relatively high fault current to ground in relation to the area of ground system and its resistance to remote earth.
- b) Soil resistivity and distribution of ground currents such that high potential gradients may occur at points at the earth's surface.
- c) Presence of an individual at such a point, time, and position that the body is bridging two points of high potential difference.
- d) Absence of sufficient contact resistance or other series resistance to limit current through the body to a safe value under circumstances a) through c).
- e) Duration of the fault and body contact, and hence, of the flow of current through a human body for a sufficient time to cause harm at the given current intensity.

The relative infrequency of accidents is due largely to the low probability of coincidence of all the unfavorable conditions listed above.

5. Range of tolerable current

Effects of an electric current passing through the vital parts of a human body depend on the duration, magnitude, and frequency of this current. The most dangerous consequence of such an exposure is a heart condition known as ventricular fibrillation, resulting in immediate arrest of blood circulation.

5.1 Effect of frequency

Humans are very vulnerable to the effects of electric current at frequencies of 50 Hz or 60 Hz. Currents of approximately 0.1 A can be lethal. Research indicates that the human body can tolerate a slightly higher 25 Hz current and approximately five times higher direct current. At frequencies of 3000–10 000 Hz, even higher currents can be tolerated (Dalziel and Mansfield [B33]; Dalziel, Ogden, and Abbott [B36]). In some cases the human body is able to tolerate very high currents due to lightning surges. The International Electrotechnical Commission provides curves for the tolerable body current as a function of frequency and for capacitive discharge currents [IEC 60479-2 (1987-03) [B83]]. Other studies of the effects of both direct and oscillatory impulse currents are reported in Dalziel [B25][B27].

Information regarding special problems of dc grounding is contained in the 1957 report of the AIEE Substations Committee [B21]. The hazards of an electric shock produced by the electrostatic effects of overhead transmission lines are reviewed in Part 1 of the 1972 report of the General Systems Subcommittee [B88]. Additional information on the electrostatic effects of overhead transmission lines can be found in Chapter 8 of the *EPRI Transmission Line Reference Book 345 kV and Above* [B57].

5.2 Effect of magnitude and duration

The most common physiological effects of electric current on the body, stated in order of increasing current magnitude, are threshold perception, muscular contraction, unconsciousness, fibrillation of the heart, respiratory nerve blockage, and burning (Geddes and Baker [B74]; IEC 60479-1 (1994-09) [B82]).

Current of 1 mA is generally recognized as the threshold of perception; that is, the current magnitude at which a person is just able to detect a slight tingling sensation in his hands or fingertips caused by the passing current (Dalziel [B27]).

Currents of 1–6 mA, often termed let-go currents, though unpleasant to sustain, generally do not impair the ability of a person holding an energized object to control his muscles and release it. Dalziel's classic experiment with 28 women and 134 men provides data indicating an average let-go current of 10.5 mA for women and 16 mA for men, and 6 mA and 9 mA as the respective threshold values (Dalziel and Massogilia [B34]).

In the 9–25 mA range, currents may be painful and can make it difficult or impossible to release energized objects grasped by the hand. For still higher currents muscular contractions could make breathing difficult. These effects are not permanent and disappear when the current is interrupted, unless the contraction is very severe and breathing is stopped for minutes rather than seconds. Yet even such cases often respond to resuscitation (Dalziel [B29]).

It is not until current magnitudes in the range of 60–100 mA are reached that ventricular fibrillation, stoppage of the heart, or inhibition of respiration might occur and cause injury or death. A person trained in cardiopulmonary resuscitation (CPR) should administer CPR until the victim can be treated at a medical facility (Dalziel [B30]; Dalziel and Lee [B31]).

Hence, this guide emphasizes the importance of the fibrillation threshold. If shock currents can be kept below this value by a carefully designed grounding system, injury or death may be avoided.

As shown by Dalziel and others (Dalziel, Lagen, and Thurston [B35]; Dalziel and Massogilia [B34]), the nonfibrillating current of magnitude I_B at durations ranging from 0.03–3.0 s is related to the energy absorbed by the body as described by the following equation:

$$S_B = (I_B)^2 \times t_s \quad (6)$$

where

- I_B is the rms magnitude of the current through the body in A
- t_s is the duration of the current exposure in s
- S_B is the empirical constant related to the electric shock energy tolerated by a certain percent of a given population

A more detailed discussion of Equation (6) is provided in Clause 6.

5.3 Importance of high-speed fault clearing

Considering the significance of fault duration both in terms of Equation (6) and implicitly as an accident-exposure factor, high-speed clearing of ground faults is advantageous for two reasons

- a) The probability of exposure to electric shock is greatly reduced by fast fault clearing time, in contrast to situations in which fault currents could persist for several minutes or possibly hours.
- b) Tests and experience show that the chance of severe injury or death is greatly reduced if the duration of a current flow through the body is very brief.

The allowed current value may, therefore, be based on the clearing time of primary protective devices, or that of the backup protection. A good case could be made for using the primary clearing time because of the low combined probability that relay malfunctions will coincide with all other adverse factors necessary for an accident, as described in Clause 4. It is more conservative to choose the backup relay clearing times in Equation (6), because they assure greater safety margin.

An additional incentive to use switching times less than 0.5 s results from the research done by Biegelmeier and Lee [B9]. Their research provides evidence that a human heart becomes increasingly susceptible to ventricular fibrillation when the time of exposure to current is approaching the heartbeat period, but that the danger is much smaller if the time of exposure to current is in the region of 0.06–0.3 s.

In reality, high ground gradients from faults are usually infrequent, and shocks from high ground gradients are even more infrequent. Further, both events are often of very short duration. Thus, it would not be practical to design against shocks that are merely painful and do not cause serious injury; that is, for currents below the fibrillation threshold.

6. Tolerable body current limit

The magnitude and duration of the current conducted through a human body at 50 Hz or 60 Hz should be less than the value that can cause ventricular fibrillation of the heart.

6.1 Duration formula

The duration for which a 50 Hz or 60 Hz current can be tolerated by most people is related to its magnitude in accordance with Equation (6). Based on the results of Dalziel's studies (Dalziel [B26]; Dalziel and Lee [B32]), it is assumed that 99.5% of all persons can safely withstand, without ventricular fibrillation, the passage of a current with magnitude and duration determined by the following formula:

$$I_B = \frac{k}{\sqrt{t_s}} \quad (7)$$

where, in addition to the terms previously defined for Equation (6)

$$k = \sqrt{S_B}$$

Dalziel found that the shock energy that can be survived by 99.5% of persons weighing approximately 50 kg (110 lb) results in a value of S_B of 0.0135. Thus, $k_{50} = 0.116$ and the formula for the allowable body current becomes

$$I_B = \frac{0.116}{\sqrt{t_s}} \text{ for 50 kg body weight} \quad (8)$$

Equation (8) results in values of 116 mA for $t_s = 1$ s and 367 mA for $t_s = 0.1$ s.

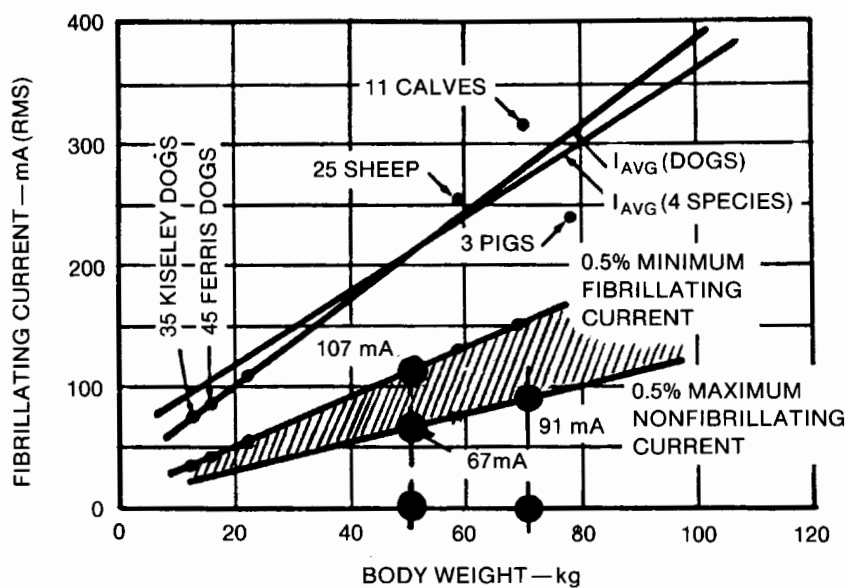
Because Equation (7) is based on tests limited to a range of between 0.03 s and 3.0 s, it obviously is not valid for very short or long durations.

Over the years, other researchers have suggested other values for I_B . In 1936 Ferris et al. [B66] suggested 100 mA as the fibrillation threshold. The value of 100 mA was derived from extensive experiments at Columbia University. In the experiments, animals having body and heart weights comparable to humans were subjected to maximum shock durations of 3 s. Some of the more recent experiments suggest the existence of two distinct thresholds: one where the shock duration is shorter than one heartbeat period and another one for the current duration longer than one heartbeat. For a 50 kg (110 lb) adult, Biegelmeier [B7][B8] proposed the threshold values at 500 mA and 50 mA, respectively. Other studies on this subject were carried out by Lee and Kouwenhoven [B31][B95][B99]. The equation for tolerable body current developed by Dalziel is the basis for the derivation of tolerable voltages used in this guide.

6.2 Alternative assumptions

Fibrillation current is assumed to be a function of individual body weight, as illustrated in Figure 4. The figure shows the relationship between the critical current and body weight for several species of animals (calves, dogs, sheep, and pigs), and a 0.5% common threshold region for mammals.

In the 1961 edition of this guide, constants S_B and k in Equation (6) and Equation (7), were given as 0.0272 and 0.165, respectively, and had been assumed valid for 99.5% of all people weighing approximately 70 kg (155 lb). Further studies by Dalziel [B28][B32], on which Equation (7) is based, lead to the alternate value of $k = 0.157$ and $S_B = 0.0246$ as being applicable to persons weighing 70 kg (155 lb). Thus



VALUE OF CONSTANT k FOR
EFFECTIVE RMS VALUES OF
 I_B ($k = I_B \sqrt{t_s}$):

$$k_{70} = 0.091 \sqrt{3} = 0.157$$

$$k_{50} = 0.067 \sqrt{3} = 0.116$$

$$k_{50} = 0.107 \sqrt{3} = 0.185$$

FIBRILLATION

Figure 4—Fibrillating current versus body weight for various animals based on a three-second duration of the electrical shock

$$I_B = \frac{0.157}{\sqrt{t_s}} \text{ for 70 kg body weight} \quad (9)$$

Users of this guide may select $k = 0.157$ provided that the average population weight can be expected to be at least 70 kg.⁷

Equation (7) indicates that much higher body currents can be allowed where fast-operating protective devices can be relied upon to limit the fault duration. A judgment decision is needed as to whether to use the clearing time of primary high-speed relays, or that of the back-up protection, as the basis for calculation.

6.3 Comparison of Dalziel's equations and Biegelmeier's curve

The comparison of Equation (8), Equation (9), and the Z-shaped curve of body current versus time developed by Biegelmeier that was published by Biegelmeier and Lee [B9] is shown in Figure 5. The Z curve has a 500 mA limit for short times up to 0.2 s, then decreases to 50 mA at 2.0 s and beyond.

⁷Typically, these conditions can be met in places that are not accessible to the public, such as in switchyards protected by fences or walls, etc. Depending on specific circumstances, an assessment should be made if a 50 kg criterion Equation (8) ought to be used for areas outside the fence.

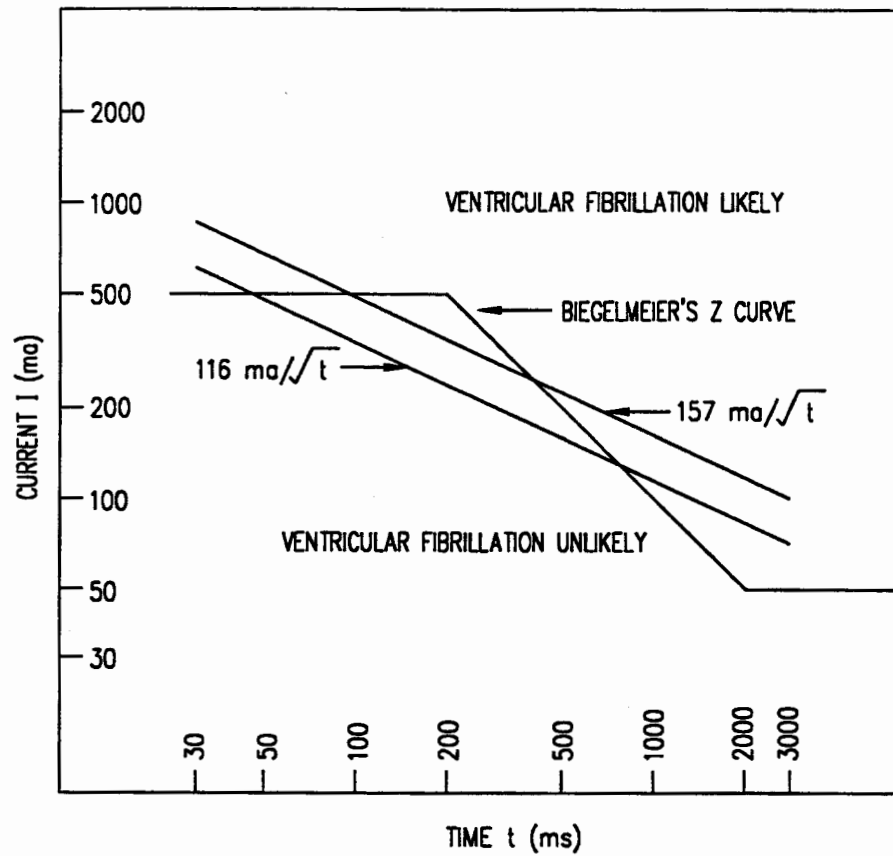


Figure 5—Body current versus time

Using Equation (8), the tolerable body current will be less than Biegelmeier's Z curve for times from 0.06 s to 0.7 s.

6.4 Note on reclosing

Reclosure after a ground fault is common in modern operating practice. In such circumstances, a person might be subjected to the first shock without permanent injury. Next, a single instantaneous automatic reclosure could result in a second shock, initiated within less than 0.33 s from the start of the first. It is this second shock, occurring after a relatively short interval of time before the person has recovered, that might cause a serious accident. With manual reclosure, the possibility of exposure to a second shock is reduced because the reclosing time interval may be substantially greater.

The cumulative effect of two or more closely spaced shocks has not been thoroughly evaluated, but a reasonable allowance can be made by using the sum of individual shock durations as the time of a single exposure.

7. Accidental ground circuit

7.1 Resistance of the human body

For dc and 50 Hz or 60 Hz ac currents, the human body can be approximated by a resistance. The current path typically considered is from one hand to both feet, or from one foot to the other one. The internal resistance of the body is approximately 300 Ω , whereas values of body resistance including skin range from 500 Ω to 3000 Ω , as suggested in Daziel [B26], Geddes and Baker [B74], Gieges [B75], Kiselev [B94], and Osypka [B118]. The human body resistance is decreased by damage or puncture of the skin at the point of contact.

As mentioned in 5.2, Dalziel [B34] conducted extensive tests using saltwater to wet hands and feet to determine safe let-go currents, with hands and feet wet. Values obtained using 60 Hz for men were as follows: the current was 9.0 mA; corresponding voltages were 21.0 V for hand-to-hand and 10.2 V for hand-to-feet. Hence, the ac resistance for a hand-to-hand contact is equal to 21.0/0.009 or 2330 Ω , and the hand-to-feet resistance equals 10.2/0.009 or 1130 Ω , based on this experiment.

Thus, for the purposes of this guide, the following resistances, in series with the body resistance, are assumed as follows:

- a) Hand and foot contact resistances are equal to zero.
- b) Glove and shoe resistances are equal to zero.

A value of 1000 Ω in Equation (10), which represents the resistance of a human body from hand-to-feet and also from hand-to-hand, or from one foot to the other foot, will be used throughout this guide.

$$R_B = 1000 \, \Omega \quad (10)$$

7.2 Current paths through the body

It should be remembered that the choice of a 1000 Ω resistance value relates to paths such as those between the hand and one foot or both feet, where a major part of the current passes through parts of the body containing vital organs, including the heart. It is generally agreed that current flowing from one foot to the other is far less dangerous. Referring to tests done in Germany, Loucks [B100] mentioned that much higher foot-to-foot than hand-to-foot currents had to be used to produce the same current in the heart region. He stated that the ratio is as high as 25:1.

Based on these conclusions, resistance values greater than 1000 Ω could possibly be allowed, where a path from one foot to the other foot is concerned. However, the following factors should be considered:

- a) A voltage between the two feet, painful but not fatal, might result in a fall that could cause a larger current flow through the chest area. The degree of this hazard would further depend on the fault duration and the possibility of another successive shock, perhaps on reclosure.
- b) A person might be working or resting in a prone position when a fault occurs.

It is apparent that the dangers from foot-to-foot contact are far less than from the other type. However, since deaths have occurred from case a) above, it is a danger that should not be ignored (Bodier [B14]; Langer [B96]).

7.3 Accidental circuit equivalents

Using the value of tolerable body current established by either Equation (8) or Equation (9) and the appropriate circuit constants, it is possible to determine the tolerable voltage between any two points of contact.

The following notations are used for the accidental circuit equivalent shown in Figure 6:

- I_b is the body current (body is part of the accidental circuit) in A
- R_A is the total effective resistance of the accidental circuit in Ω
- V_A is the total effective voltage of the accidental circuit (touch or step voltage) in V

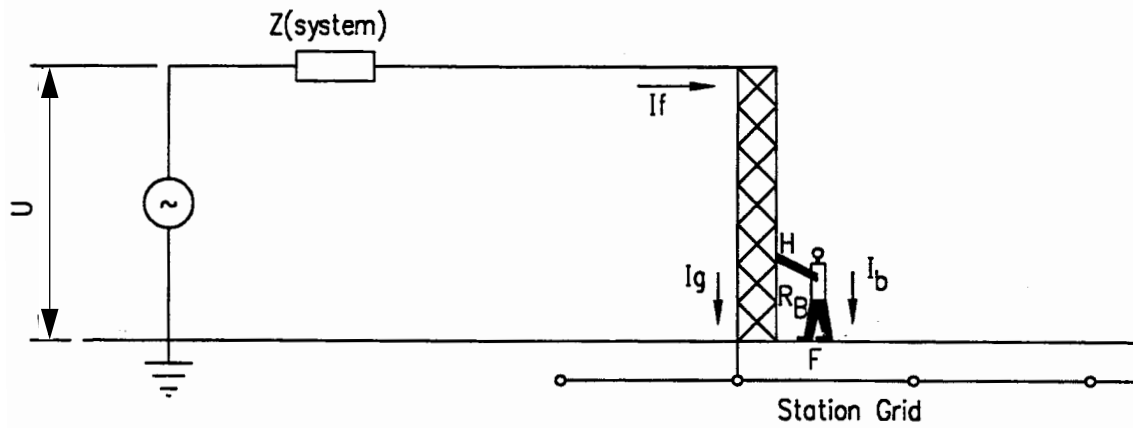


Figure 6—Exposure to touch voltage

The tolerable body current, I_b , defined by Equation (8) or Equation (9), is used to define the tolerable total effective voltage of the accidental circuit (touch or step voltage): the tolerable total effective voltage of the accidental circuit is that voltage that will cause the flow of a body current, I_b , equal to the tolerable body current, I_b .

Figure 6 shows the fault current I_f being discharged to the ground by the grounding system of the substation and a person touching a grounded metallic structure at H. Various impedances in the circuit are shown in Figure 7. Terminal H is a point in the system at the same potential as the grid into which the fault current flows and terminal F is the small area on the surface of the earth that is in contact with the person's two feet. The current, I_b , flows from H through the body of the person to the ground at F. The Thevenin theorem allows us to represent this two terminal (H, F) network of Figure 7 by the circuit shown in Figure 8 (Dawalibi, Southey, and Baishiki [B49]; Dawalibi, Xiong, and Ma [B50]).

The Thevenin voltage V_{Th} is the voltage between terminals H and F when the person is not present. The Thevenin impedance Z_{Th} is the impedance of the system as seen from points H and F with voltage sources of the system short circuited. The current I_b through the body of a person coming in contact with H and F is given by

$$I_b = \frac{V_{Th}}{Z_{Th} + R_B} \quad (11)$$

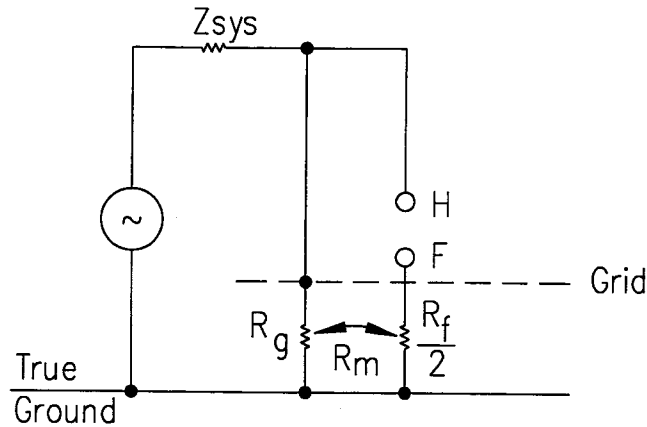


Figure 7—Impedances to touch voltage circuit

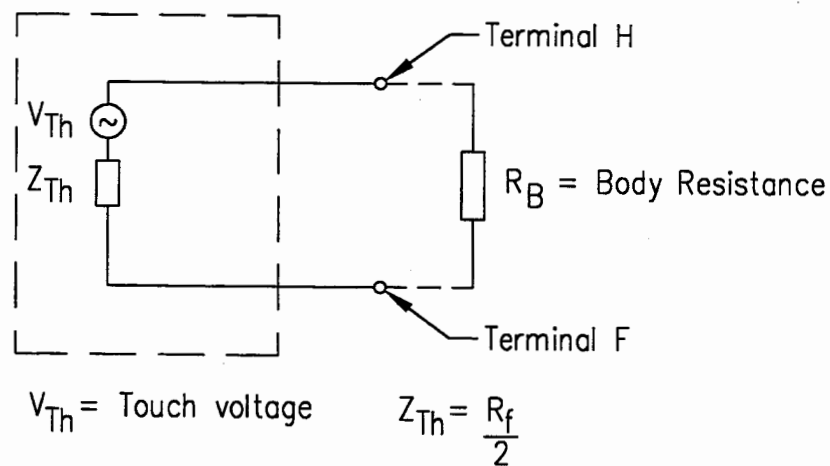


Figure 8—Touch voltage circuit

where

R_B is the resistance of the human body in Ω

Figure 9 shows the fault current I_f being discharged to the ground by the grounding system of the substation. The current, I_b , flows from one foot F_1 through the body of the person to the other foot, F_2 . Terminals F_1 and F_2 are the areas on the surface of the earth that are in contact with the two feet, respectively. The Thevenin theorem allows us to represent this two-terminal (F_1 , F_2) network in Figure 10. The Thevenin voltage V_{Th} is the voltage between terminals F_1 and F_2 when the person is not present. The Thevenin impedance Z_{Th} is the impedance of the system as seen from the terminals F_1 and F_2 with the voltage sources of the system short circuited. The current I_b through the body of a person is given by Equation (11).

The Thevenin equivalent impedance, Z_{Th} , is computable with a number of methods (Dawalibi, Southey, and Baishiki [B49]; Dawalibi, Xiong, and Ma [B50]; ERPI EL-2699 [B60]; Thapar, Gerez, and Kejriwal [B143];

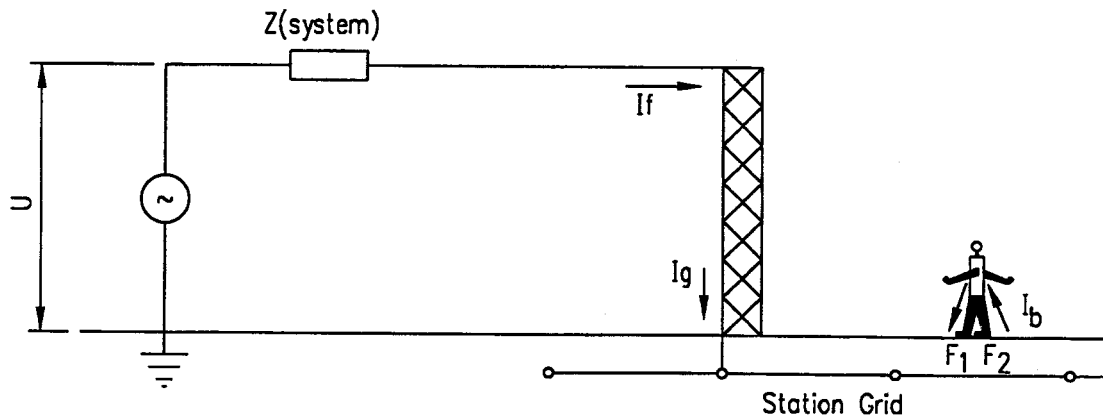


Figure 9—Exposure to step voltage

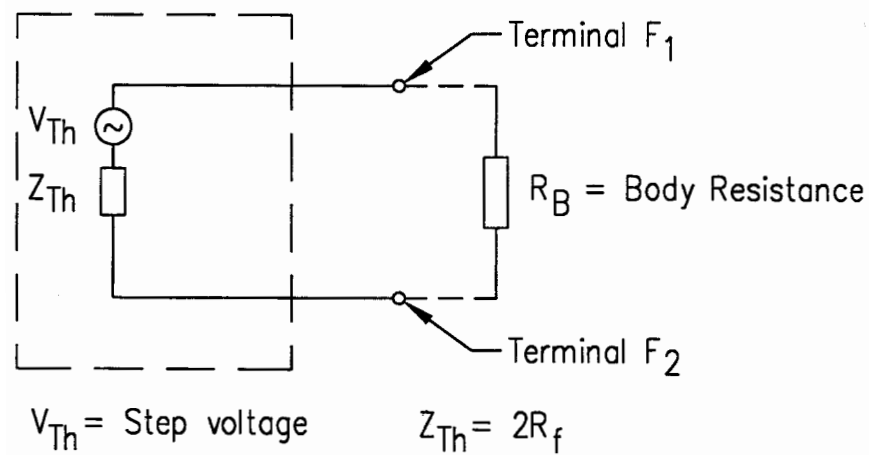


Figure 10—Step voltage circuit

Laurent [B97]). In this guide, the following conservative formulas for the Thevenin equivalent impedance are used.

For touch voltage accidental circuit

$$Z_{Th} = \frac{R_f}{2} \quad (12)$$

And for the step voltage accidental circuit

$$Z_{Th} = 2R_f \quad (13)$$

where

R_f is the ground resistance of one foot (with presence of the substation grounding system ignored) in Ω

For the purpose of circuit analysis, the human foot is usually represented as a conducting metallic disc and the contact resistance of shoes, socks, etc., is neglected. The ground resistance in ohms of a metallic disc of radius b (m) on the surface of a homogeneous earth of resistivity ρ ($\Omega\cdot\text{m}$) is given by Laurent [B97]

$$R_f = \frac{\rho}{4b} \quad (14)$$

Traditionally, the metallic disc representing the foot is taken as a circular plate with a radius of 0.08 m. With only slight approximation, equations for Z_{Th} can be obtained in numerical form and expressed in terms of ρ as follows.

For touch voltage accidental circuit

$$Z_{Th} = 1.5\rho \quad (15)$$

And for step voltage accidental circuit

$$Z_{Th} = 6.0\rho \quad (16)$$

Based on investigation reported in Dawalibi, Xiong, and Ma [B50]; Meliopoulos, Xia, Joy, and Cokkonides [B107]; and Thapar, Gerez, and Kejriwal [B143], Equation (15) and Equation (16) are conservative in the sense that they underestimate the Thevenin equivalent impedance and, therefore, will result in higher body currents.

The permissible total equivalent voltage (i.e., tolerable touch and step voltage), using Equation (15) and Equation (16), is

$$E_{touch} = I_B(R_B + 1.5\rho) \quad (17)$$

and

$$E_{step} = I_B(R_B + 6.0\rho) \quad (18)$$

7.4 Effect of a thin layer of surface material

Equation (14) is based on the assumption of uniform soil resistivity. However, a 0.08–0.15 m (3–6 in) layer of high resistivity material, such as gravel, is often spread on the earth's surface above the ground grid to increase the contact resistance between the soil and the feet of persons in the substation. The relatively shallow depth of the surface material, as compared to the equivalent radius of the foot, precludes the assumption of uniform resistivity in the vertical direction when computing the ground resistance of the feet. However, for a person in the substation area, the surface material can be assumed to be of infinite extent in the lateral direction.

If the underlying soil has a lower resistivity than the surface material, only some grid current will go upward into the thin layer of the surface material, and the surface voltage will be very nearly the same as that without the surface material. The current through the body will be lowered considerably with the addition of the surface material because of the greater contact resistance between the earth and the feet. However, this resistance may be considerably less than that of a surface layer thick enough to assume uniform resistivity in all directions. The reduction depends on the relative values of the soil and the surface material resistivities, and on the thickness of the surface material.

The converse of the derating principle is also true. If the underlying soil has a higher resistivity than the surface material, a substantial portion of the grid current will go upward into the thin layer of surface material. However, unlike the case described in the preceding paragraph, the surface potentials will be altered substantially due to the concentration of current near the surface. Thus, the effective resistivity of the surface material should not be upgraded without taking into account this change in surface potential. This problem can best be solved by using multilayer soil analysis (see Clause 13).

An analytical expression for the ground resistance of the foot on a thin layer of surface material can be obtained with the use of the method of images (Sunde [B130]; Thapar, Gerez, and Emmanuel [B142]; Thapar, Gerez, and Kejriwal [B143]).⁸

Equation (19) through Equation (21) give the ground resistance of the foot on the surface material (Thapar, Gerez, and Kejriwal [B143]).

$$R_f = \left[\frac{\rho_s}{4b} \right] C_s \quad (19)$$

$$C_s = 1 + \frac{16b}{\rho_s} \sum_{n=1}^{\infty} K^n R_{m(2nh_s)} \quad (20)$$

$$K = \frac{\rho - \rho_s}{\rho + \rho_s} \quad (21)$$

where

C_s	is the surface layer derating factor
K	is the reflection factor between different material resistivities
ρ_s	is the surface material resistivity in $\Omega \cdot m$
ρ	is the resistivity of the earth beneath the surface material in $\Omega \cdot m$
h_s	is the thickness of the surface material in m
b	is the radius of the circular metallic disc representing the foot in m
$R_{m(2nh_s)}$	is the mutual ground resistance between the two similar, parallel, coaxial plates, separated by a distance $(2nh_s)$, in an infinite medium of resistivity, ρ_s , in $\Omega \cdot m$

For the determination of $R_{m(2nh_s)}$, consider a thin circular plate, D1, in the x-y plane with the z axis passing through its center. The radius of the plate is b and it discharges a current I in an infinite uniform medium of resistivity, ρ_s . Using cylindrical coordinates, the potential at any point (r, z) is given by the following equations (Jackson [B89]):

$$r = \sqrt{x^2 + y^2} \quad (22)$$

$$z = 2nh_s \quad (23)$$

$$V_{r,z} = \frac{I \cdot \rho_s}{4\pi b} \sin^{-1} \left[\frac{2b}{\sqrt{(r-b)^2 + (z^q)^2} + \sqrt{(r+b)^2 + z^2}} \right] \quad (24)$$

⁸Expressions for the ground resistance of the foot given in Equation (16) through Equation (19) of the 1986 version of this guide were based on the simple procedure for hemispheric electrodes. This simplification gave lower value of the ground resistance of the foot. The error was significant for low values of the depth of the surface layer. The new revised expressions for the ground resistance of the foot given in this standard are based on the circular plate representation of the foot.

Consider another similar plate, D2, placed parallel and coaxial to the circular plate, D1, and at a distance $(2nh)$ from it. The potential produced on D2 can be determined by evaluating the average potential over the surface of the plate. It is given by

$$V_{D2} = \frac{1}{\pi b^2} \int_0^b (2\pi x \cdot V_{r,z}) dx \quad (25)$$

The mutual ground resistance, $R_{m(2nh_s)}$, between the two plates is given by

$$R_{m(2nh_s)} = \frac{V_{D2}}{I} \quad (26)$$

Comparing Equation (14) and Equation (19), C_s can be considered as a corrective factor to compute the effective foot resistance in the presence of a finite thickness of surface material. Because the quantity C_s is rather tedious to evaluate without the use of a computer, these values have been precalculated for $b = 0.08$ m and are given in the form of graphs in Figure 11.

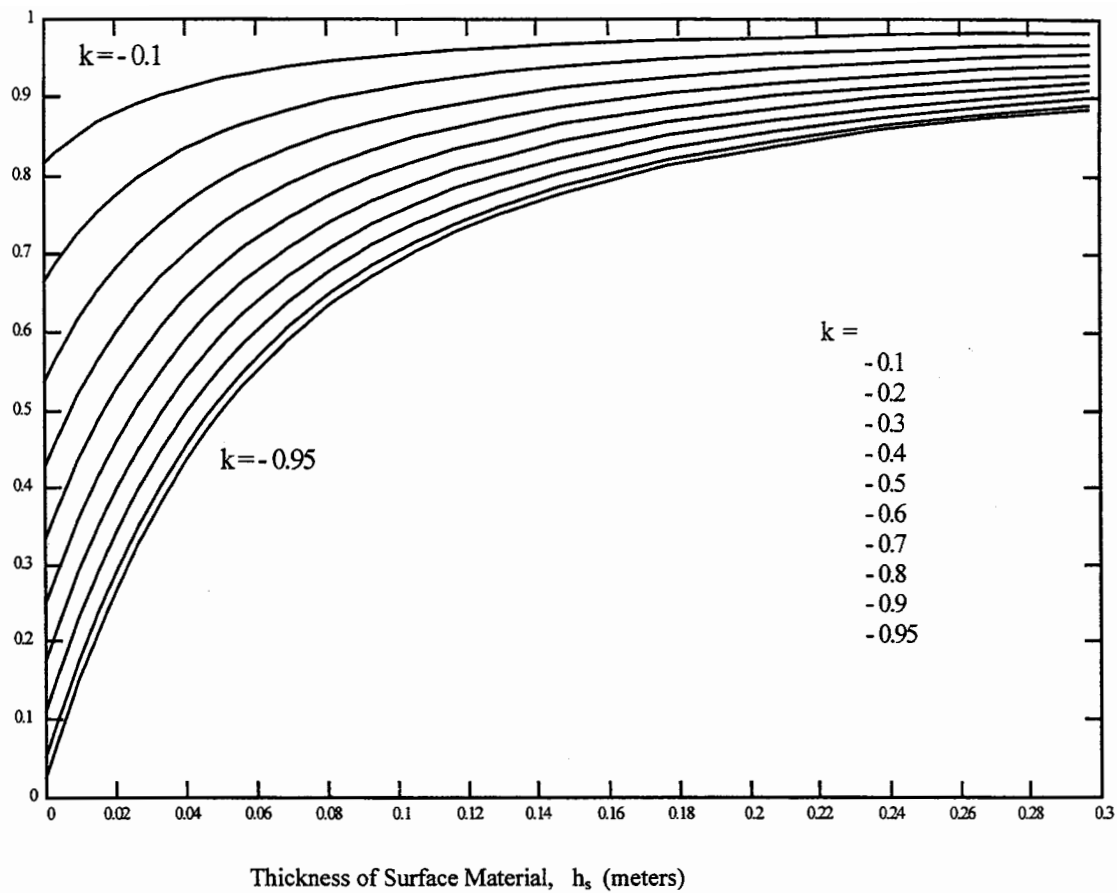


Figure 11— C_s versus h_s

Computer models have also been used to determine the value of C_s (Dawalibi, Xiong, and Ma [B50]; Meliopoulos, Xia, Joy, and Cokkonides [B107]). There is a close match in the values obtained from these computer models with the values given in Figure 11.

The following empirical equation gives the value of C_s . The values of C_s obtained using Equation (27) are within 5% of the values obtained with the analytical method (Thapar, Gerez, and Kejriwal [B143]).

$$C_s = 1 - \frac{0.09 \left(1 - \frac{\rho}{\rho_s}\right)}{2h_s + 0.09} \quad (27)$$

8. Criteria of tolerable voltage

8.1 Definitions

NOTE—The following definitions are also listed in Clause 3, but repeated here for the convenience of the reader.

8.1.1 ground potential rise (GPR): The maximum electrical potential that a substation grounding grid may attain relative to a distant grounding point assumed to be at the potential of remote earth. This voltage, GPR, is equal to the maximum grid current times the grid resistance.

NOTE—Under normal conditions, the grounded electrical equipment operates at near zero ground potential. That is, the potential of a grounded neutral conductor is nearly identical to the potential of remote earth. During a ground fault the portion of fault current that is conducted by a substation grounding grid into the earth causes the rise of the grid potential with respect to remote earth.

8.1.2 mesh voltage: The maximum touch voltage within a mesh of a ground grid.

8.1.3 metal-to-metal touch voltage: The difference in potential between metallic objects or structures within the substation site that may be bridged by direct hand-to-hand or hand-to-feet contact.

NOTE—The metal-to-metal touch voltage between metallic objects or structures bonded to the ground grid is assumed to be negligible in conventional substations. However, the metal-to-metal touch voltage between metallic objects or structures bonded to the ground grid and metallic objects internal to the substation site, such as an isolated fence, but not bonded to the ground grid may be substantial. In the case of a gas-insulated substation (GIS), the metal-to-metal touch voltage between metallic objects or structures bonded to the ground grid may be substantial because of internal faults or induced currents in the enclosures.

In a conventional substation, the worst touch voltage is usually found to be the potential difference between a hand and the feet at a point of maximum reach distance. However, in the case of a metal-to-metal contact from hand-to-hand or from hand-to-feet, both situations should be investigated for the possible worst reach conditions. Figure 12 and Figure 13 illustrate these situations for air-insulated substations, and Figure 14 illustrates these situations in GIS.

8.1.4 step voltage: The difference in surface potential experienced by a person bridging a distance of 1 m with the feet without contacting any other grounded object.

8.1.5 touch voltage: The potential difference between the ground potential rise (GPR) and the surface potential at the point where a person is standing while at the same time having a hand in contact with a grounded structure.

8.1.6 transferred voltage: A special case of the touch voltage where a voltage is transferred into or out of the substation from or to a remote point external to the substation site.

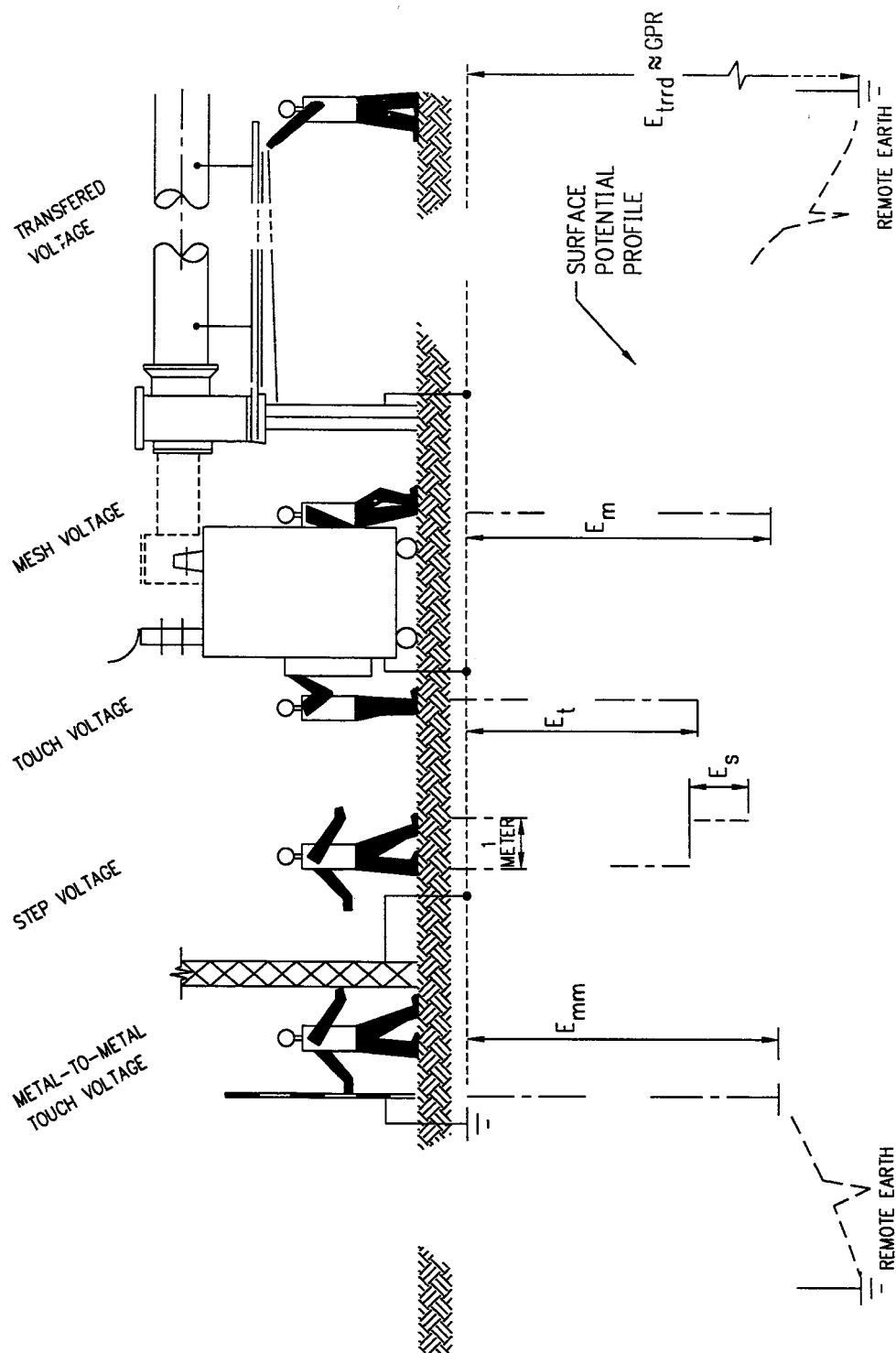


Figure 12—Basic shock situations

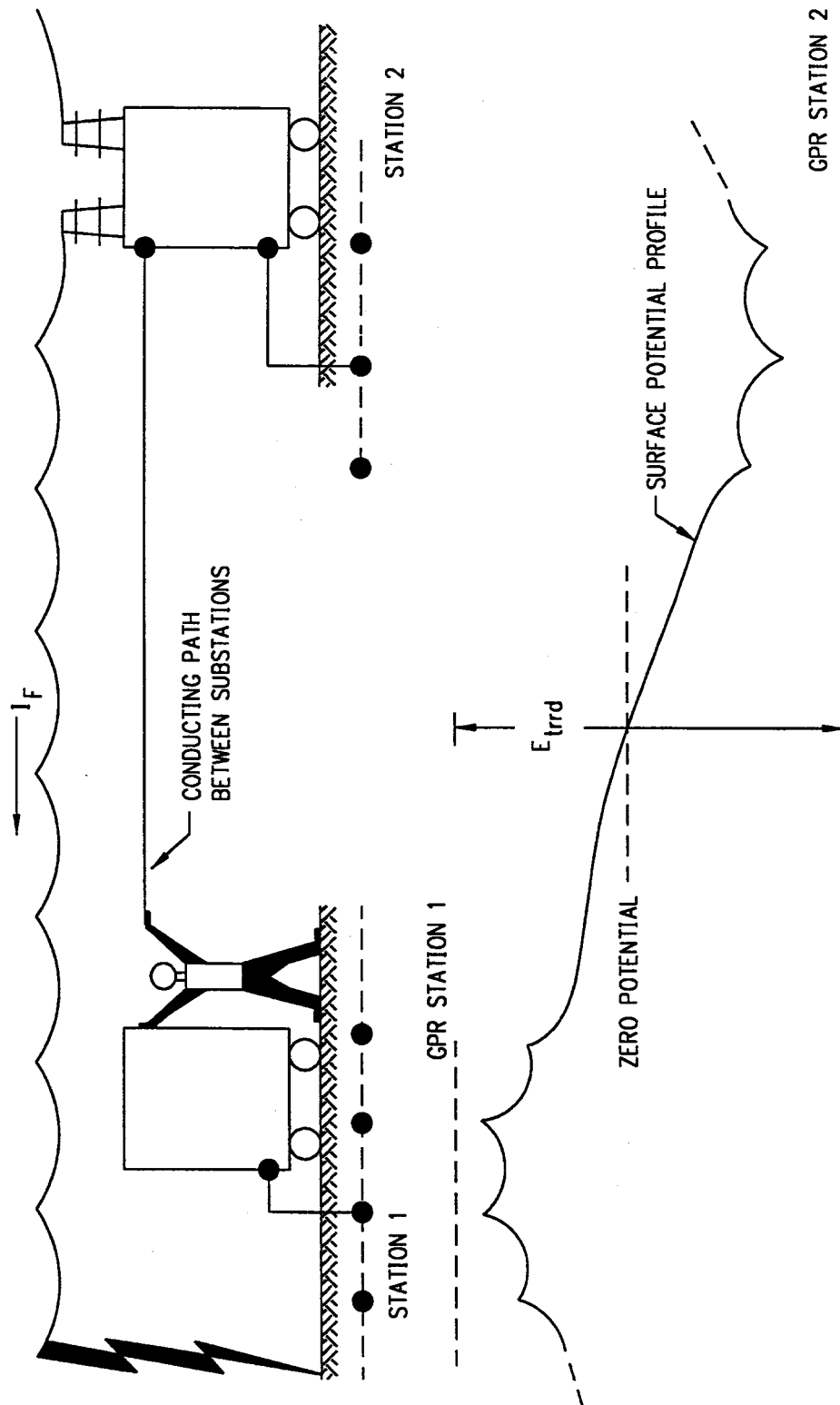


Figure 13—Typical situation of extended transferred potential

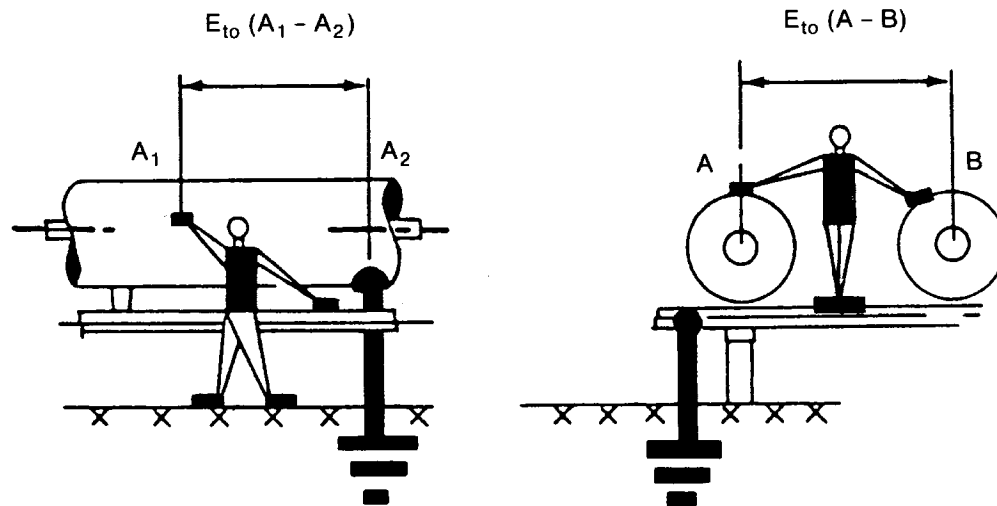


Figure 14—Typical metal-to-metal touch situation in GIS

8.2 Typical shock situations

Figure 12 and Figure 13 show five basic situations involving a person and grounded facilities during a fault. For a foot-to-foot contact, the accidental circuit equivalent is that of Figure 9, and its driving voltage U is equal to E_s (step voltage). For the three examples of hand-to-feet contact Figure 12 applies, and U is equal to E_t (touch voltage), E_m (mesh voltage), or E_{trrd} (transferred voltage), respectively. The accidental circuit involving metal-to-metal contact, either hand-to-hand or hand-to-feet, is shown in Figure 14 where U is equal to the metal-to-metal touch voltage, E_{mm} .

During a fault, the earth conducts currents that emanate from the grid and other permanent ground electrodes buried below the earth's surface. The resulting potential gradients have a primary effect on the value of U .

In the case of conventional substations, the typical case of metal-to-metal touch voltage occurs when metallic objects or structures within the substation site are not bonded to the ground grid. Objects such as pipes, rails, or fences that are located within or near the substation ground grid area, and not bonded to the ground grid, meet this criteria. Substantial metal-to-metal touch voltages may be present when a person standing on or touching a grounded object or structure comes into contact with a metallic object or structure within the substation site that is not bonded to the ground grid. Calculation of the actual metal-to-metal touch voltage is complex. In practice, hazards resulting from metal-to-metal contact may best be avoided by bonding potential danger points to the substation grid.

Typically, the case of transferred voltage occurs when a person standing within the substation area touches a conductor grounded at a remote point, or a person standing at a remote point touches a conductor connected to the substation grounding grid. During fault conditions, the resulting potential to ground may equal or exceed the full GPR of a grounding grid discharging the fault current, rather than the fraction of this total voltage encountered in the ordinary touch contact situations (see Figure 13). In fact, as discussed in Clause 17, the transferred voltage may exceed the sum of the GPRs of both substations, due to induced voltages on communication circuits, static or neutral wires, pipes, etc. It is impractical, and often impossible, to design a ground grid based on the touch voltage caused by the external transferred voltages. Hazards from these external transferred voltages are best avoided by using isolating or neutralizing devices and by treating and clearly labeling these circuits, pipes, etc., as being equivalent to energized lines.

8.3 Step and touch voltage criteria

The safety of a person depends on preventing the critical amount of shock energy from being absorbed before the fault is cleared and the system de-energized. The maximum driving voltage of any accidental circuit should not exceed the limits defined as follows. For step voltage the limit is

$$E_{step} = (R_B + 2R_f) \cdot I_B \quad (28)$$

for body weight of 50 kg

$$E_{step50} = (1000 + 6C_s \cdot \rho_s) \frac{0.116}{\sqrt{t_s}} \quad (29)$$

for body weight of 70 kg

$$E_{step70} = (1000 + 6C_s \cdot \rho_s) \frac{0.157}{\sqrt{t_s}} \quad (30)$$

Similarly, the touch voltage limit is

$$E_{touch} = \left(R_B + \frac{R_f}{2} \right) \cdot I_B \quad (31)$$

for body weight of 50 kg

$$E_{step50} = (1000 + 1.5C_s \cdot \rho_s) \frac{0.116}{\sqrt{t_s}} \quad (32)$$

for body weight of 70 kg

$$E_{step70} = (1000 + 1.5C_s \cdot \rho_s) \frac{0.157}{\sqrt{t_s}} \quad (33)$$

where

E_{step}	is the step voltage in V
E_{touch}	is the touch voltage in V
C_s	is determined from Figure 11 or Equation (27)
r_s	is the resistivity of the surface material in $\Omega \cdot m$
t_s	is the duration of shock current in seconds

If no protective surface layer is used, then $C_s = 1$ and $\rho_s = \rho$.

The metal-to-metal touch voltage limits are derived from the touch voltage equations, Equation (32) and Equation (33). Metal-to-metal contact, both hand-to-hand and hand-to-feet, will result in $\rho_s = 0$. Therefore, the total resistance of the accidental circuit is equal to the body resistance, R_B .

With the substitution of $\rho_s = 0$ in the foot resistance terms of Equation (32) and Equation (33), the metal-to-metal touch voltage limit is

for body weight of 50 kg

$$E_{mm-touch50} = \frac{116}{\sqrt{t_s}} \quad (34)$$

for body weight of 70 kg

$$E_{mm-touch70} = \frac{157}{\sqrt{t_s}} \quad (35)$$

where

E_{mm} is the metal-to-metal touch voltage in V

The actual step voltage, touch voltage, or metal-to-metal touch voltage should be less than the respective maximum allowable voltage limits to ensure safety. Hazards from external transferred voltages are best avoided by isolation or neutralizing devices and labeling these danger points as being equivalent to live lines.

8.4 Typical shock situations for gas-insulated substations

In the grounding analysis of GIS, the touch voltage considerations present several unique problems. Unlike conventional facilities, the GIS equipment features a metal sheath enclosing gas-insulated switchgear and inner high-voltage buses. Each bus is completely contained within its enclosure and the enclosures are grounded. Because a voltage is induced in the outer sheath whenever a current flows in the coaxial busbar, certain parts of the enclosure might be at different potentials with respect to the substation ground. To evaluate the maximum voltage occurring on the bus enclosure during a fault, it is necessary to determine the inductance of the outer sheath to ground, the inductance of the inner conductor, and the mutual inductances for a given phase configuration of individual buses.

A person touching the outer sheath of a GIS might be exposed to voltages resulting from two basic fault conditions

- a) An internal fault within the gas-insulated bus system, such as a flashover between the bus conductor and the inner wall of the enclosure.
- b) A fault external to the GIS in which a fault current flows through the GIS bus and induces currents in the enclosures.

Because the person may stand on a grounded metal grating and the accidental circuit may involve a hand-to-hand and hand-to-feet current path, the analysis of GIS grounding necessitates consideration of metal-to-metal touch voltage (see Figure 14).

Most GIS manufacturers consider the enclosure properly designed and adequately grounded if the potential difference between individual enclosures, and the potential difference between an enclosure and other grounded structures, does not exceed 65–130 V during a fault. The metal-to-metal touch voltage equations, Equation (34) and Equation (35), reveal that this voltage range corresponds to fault times ranging from 0.8 s to 3.2 s if a 50 kg criterion is used, and ranging from 1.46 s to 5.8 s for the assumption of a 70 kg body. This relationship is, however, better perceived in the graphical form of Figure 15, which also helps to grasp the related problem of sufficient safety margins.

The fault conditions and the corresponding circuit equivalents for determining or verifying the critical safety design parameters of GIS grounding is detailed in Clause 10.

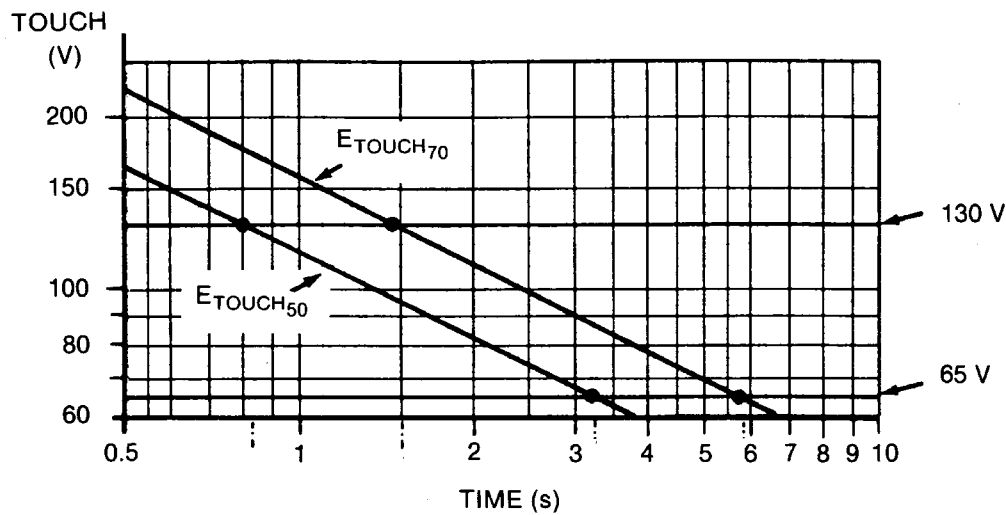


Figure 15—Touch voltage limits for metal-to-metal contact and a typical range of enclosure voltages to ground

8.5 Effect of sustained ground currents

After the safe step and touch voltage limits are established, the grounding system can then be designed based on the available fault current and overall clearing time. The designer should also consider sustained low-level (below setting of protective relays) fault magnitudes that may be above the let-go current threshold. Some sustained faults above the let-go current, but below the fibrillation threshold, may cause asphyxiation from prolonged contraction of the chest muscles. However, it would not be practical to design against lesser shocks that are painful, but cause no permanent injury.

9. Principal design considerations

9.1 Definitions

NOTE—The following definitions are also listed in Clause 3, but repeated here for the convenience of the reader.

9.1.1 auxiliary ground electrode: A ground electrode with certain design or operating constraints. Its primary function may be other than conducting the ground fault current into the earth.

9.1.2 ground electrode: A conductor imbedded in the earth and used for collecting ground current from or dissipating ground current into the earth.

9.1.3 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 surface material, are common forms of a ground mat.

9.1.4 grounding grid: A system of horizontal ground electrodes that consists 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.

NOTE—Grids buried horizontally near the earth's surface are also effective in controlling the surface potential gradients. A typical grid usually is supplemented by a number of ground rods and may be further connected to auxiliary ground electrodes, to lower its resistance with respect to remote earth.

9.1.5 grounding system: Comprises all interconnected grounding facilities in a specific area.

9.1.6 primary ground electrode: A ground electrode specifically designed or adapted for discharging the ground fault current into the ground, often in a specific discharge pattern, as required (or implicitly called for) by the grounding system design.

9.2 General concept

A grounding system should be installed in a manner that will limit the effect of ground potential gradients to such voltage and current levels that will not endanger the safety of people or equipment under normal and fault conditions. The system should also ensure continuity of service.

In the discussion that follows, it is assumed that the system of ground electrodes has the form of a grid of horizontally buried conductors, supplemented by a number of vertical ground rods connected to the grid. Based on two surveys, the first reported in an AIEE application guide in 1954 [B3], and the second published in 1980 (Dawalibi, Bauchard, and Mukhedkar [B45]), this concept represents the prevailing practice of most utilities both in the United States and in other countries.

Some of the reasons for using the combined system of vertical rods and horizontal conductors are as follows:

- a) In substations a single electrode is, by itself, inadequate in providing a safe grounding system. In turn, when several electrodes, such as ground rods, are connected to each other and to all equipment neutrals, frames, and structures that are to be grounded, the result is essentially a grid arrangement of ground electrodes, regardless of the original objective. If the connecting links happen to be buried in a soil having good conductivity, this network alone may represent an excellent grounding system. Partly for this reason, some utilities depend on the use of a grid alone. However, ground rods are of a particular value, as explained in item b).
- b) If the magnitude of current dissipated into the earth is high, it seldom is possible to install a grid with resistance so low as to assure that the rise of a ground potential will not generate surface gradients unsafe for human contact. Then, the hazard can be eliminated only by control of local potentials through the entire area. A system that combines a horizontal grid and a number of vertical ground rods penetrating lower soils has the following advantages:
 - 1) While horizontal (grid) conductors are most effective in reducing the danger of high step and touch voltages on the earth's surface, provided that the grid is installed in a shallow depth [usually 0.3–0.5 m (12–18 in) below grade], sufficiently long ground rods will stabilize the performance of such a combined system. For many installations this is important because freezing or drying of upper soil layers could vary the soil resistivity with seasons, while the resistivity of lower soil layers remains nearly constant.
 - 2) Rods penetrating the lower resistivity soil are far more effective in dissipating fault currents whenever a two-layer or multilayer soil is encountered and the upper soil layer has higher resistivity than the lower layers. For many GIS and other space-limited installations, this condition becomes in fact the most desirable one to occur, or to be achieved by the appropriate design means (extra-long ground rods, grounding wells, etc.).

- 3) If the rods are installed predominately along the grid perimeter in high-to-low or uniform soil conditions, the rods will considerably moderate the steep increase of the surface gradient near the peripheral meshes. See Clause 16 for details of this arrangement. These details are pertinent to the use of simplified methods in determining the voltage gradient at the earth's surface.

9.3 Primary and auxiliary ground electrodes

In general, most grounding systems utilize two groups of ground electrodes. Primary ground electrodes are specifically designed for grounding purposes. Auxiliary ground electrodes are electrodes that comprise various underground metal structures installed for purposes other than grounding. Typical primary electrodes include such things as grounding grids, counterpoise conductors, ground rods, and ground wells. Typical auxiliary electrodes include underground metal structures and reinforcing bars encased in concrete, if connected to the grounding grid. Auxiliary ground electrodes may have a limited current carrying capability.

9.4 Basic aspects of grid design

Conceptual analysis of a grid system usually starts with inspection of the substation layout plan, showing all major equipment and structures. To establish the basic ideas and concepts, the following points may serve as guidelines for starting a typical grounding grid design:

- a) A continuous conductor loop should surround the perimeter to enclose as much area as practical. This measure helps to avoid high current concentration and, hence, high gradients both in the grid area and near the projecting cable ends. Enclosing more area also reduces the resistance of the grounding grid.
- b) Within the loop, conductors are typically laid in parallel lines and, where practical, along the structures or rows of equipment to provide for short ground connections.
- c) A typical grid system for a substation may include 4/0 bare copper conductors buried 0.3–0.5 m (12–18 in) below grade, spaced 3–7 m (10–20 ft) apart, in a grid pattern. At cross-connections, the conductors would be securely bonded together. Ground rods may be at the grid corners and at junction points along the perimeter. Ground rods may also be installed at major equipment, especially near surge arresters. In multilayer or high resistivity soils, it might be useful to use longer rods or rods installed at additional junction points.
- d) This grid system would be extended over the entire substation switchyard and often beyond the fence line. Multiple ground leads or larger sized conductors would be used where high concentrations of current may occur, such as at a neutral-to-ground connection of generators, capacitor banks, or transformers.
- e) The ratio of the sides of the grid meshes usually is from 1:1 to 1:3, unless a precise (computer-aided) analysis warrants more extreme values. Frequent cross-connections have a relatively small effect on lowering the resistance of a grid. Their primary role is to assure adequate control of the surface potentials. The cross-connections are also useful in securing multiple paths for the fault current, minimizing the voltage drop in the grid itself, and providing a certain measure of redundancy in the case of a conductor failure.

9.5 Design in difficult conditions

In areas where the soil resistivity is rather high or the substation space is at a premium, it may not be possible to obtain a low impedance grounding system by spreading the grid electrodes over a large area, as is done in more favorable conditions. Such a situation is typical of many GIS installations and industrial substations, occupying only a fraction of the land area normally used for conventional equipment. This often makes the control of surface gradients difficult. Some of the solutions include

- a) Connection(s) of remote ground grid(s) and adjacent grounding facilities, a combined system utilizing separate installations in buildings, underground vaults, etc. A predominant use of remote ground electrodes requires careful consideration of transferred potentials, surge arrester locations, and other critical points. A significant voltage drop may develop between the local and remote grounding facilities, especially for high-frequency surges (lightning).
- b) Use of deep-driven ground rods and drilled ground wells.
- c) Various additives and soil treatments used in conjunction with ground rods and interconnecting conductors are more fully described in 14.5.
- d) Use of wire mats. It is feasible to combine both a surface material and fabricated mats made of wire mesh to equalize the gradient field near the surface. A typical wire mat might consist of copper-clad steel wires of No. 6 AWG, arranged in a 0.6 m × 0.6 m (24 in × 24 in) grid pattern, installed on the earth's surface and below the surface material, and bonded to the main grounding grid at multiple locations.
- e) Where feasible, controlled use of other available means to lower the overall resistance of a ground system, such as connecting static wires and neutrals to the ground (see 15.3). Typical is the use of metallic objects on the site that qualify for and can serve as auxiliary ground electrodes, or as ground ties to other systems. Consequences of such applications, of course, have to be carefully evaluated.
- f) Wherever practical, a nearby deposit of low resistivity material of sufficient volume can be used to install an extra (satellite) grid. This satellite grid, when sufficiently connected to the main grid, will lower the overall resistance and, thus, the ground potential rise of the grounding grid. The nearby low resistivity material may be a clay deposit or it may be a part of some large structure, such as the concrete mass of a hydroelectric dam (Verma, Merand, and Barbeau [B148]).

9.6 Connections to grid

Conductors of adequate ampacity and mechanical strength (see Clause 11) should be used for the connections between

- a) All ground electrodes, such as grounding grids, rodbeds, ground wells, and, where applicable, metal, water, or gas pipes, water well casings, etc.
- b) All above-ground conductive metal parts that might accidentally become energized, such as metal structures, machine frames, metal housings of conventional or gas-insulated switchgear, transformer tanks, guards, etc. Also, conductive metal parts that might be at a different potential relative to other metal parts that have become energized should be bonded together, usually via the ground grid.
- c) All fault current sources such as surge arresters, capacitor banks or coupling capacitors, transformers, and, where appropriate, machine neutrals and lighting and power circuits.

Copper cables or straps are usually employed for these ground connections. However, transformer tanks are sometimes used as part of a ground path for surge arresters. Similarly, most steel or aluminum structures may be used for the ground path if it can be established that their conductance, including that of any connections, is and can be maintained as equivalent to that of the conductor that would normally be installed. Where this practice is followed, any paint films that might otherwise introduce a highly resistive connection should be removed, and a suitable joint compound should be applied, or other effective means, such as jumpers across the connections, should be taken to prevent subsequent deterioration of the connection. In the case of GIS installations, extra attention should be paid to the possibility of unwanted circulation of induced currents. Clause 10 covers the subject in more detail.

Equal division of currents between multiple ground leads at cross-connections or similar junction points should not be assumed.

All accessible ground leads should be inspected on a periodic basis. Exothermic weld, brazed, or pressure-type connectors can be used for underground connections (see 11.4). Soldered connections should be avoided because of the possibility of failure under high fault currents.

Open circuits, even in exposed locations, can escape detection, and it obviously is impractical to inspect buried portions of the grounding network once it is installed. More detailed discussion of test methods used to determine the continuity of buried grounding systems is included in 19.4. Those facilities that are most likely to supply or carry a high current, such as transformer and circuit breaker tanks, switch frames, and arrester pads, should be connected to the grid with more than one ground lead. The leads should preferably be run in opposite directions to eliminate common mode failure.⁹

10. Special considerations for GIS

10.1 Definitions

NOTE—The following definitions are also listed in Clause 3, but repeated here for the convenience of the reader.

10.1.1 continuous enclosure: A bus enclosure in which the consecutive sections of the housing along the same phase conductor are bonded together to provide an electrically continuous current path throughout the entire enclosure length. Cross-bondings, connecting the other phase enclosures, are made only at the extremities of the installation and at a few selected intermediate points.

10.1.2 enclosure currents: Currents that result from the voltages induced in the metallic enclosure by the current(s) flowing in the enclosed conductor(s).

10.1.3 gas-insulated substation: A compact, multicomponent assembly, enclosed in a grounded metallic housing in which the primary insulating medium is a compressed gas, and that normally consists of buses, switchgear, and associated equipment (subassemblies).

10.1.4 main ground bus: A conductor or system of conductors provided for connecting all designated metallic components of the GIS to a substation grounding system.

10.1.5 noncontinuous enclosure: A bus enclosure with the consecutive sections of the housing of the same phase conductor electrically isolated (or insulated from each other), so that no current can flow beyond each enclosure section.

10.1.6 transient enclosure voltage (TEV): Very fast transient phenomena, which are found on the grounded enclosure of GIS systems. Typically, ground leads are too long (inductive) at the frequencies of interest to effectively prevent the occurrence of TEV. The phenomenon is also known as transient ground rise (TGR) or transient ground potential rise (TGPR).

10.1.7 very fast transient (VFT): A class of transients generated internally within GIS characterized by short duration and very high frequency. VFT is generated by the rapid collapse of voltage during breakdown of the insulating gas, either across the contacts of a switching device or line-to-ground during a fault. These transients can have rise times in the order of nanoseconds implying a frequency content extending to about 100 MHz. However, dominant oscillation frequencies, which are related to physical lengths of GIS bus, are usually in the 20–40 MHz range.

⁹One possible exception is grounding of the secondaries of potential and current transformers. The grounding of such devices usually must be restricted to a single point to avoid any parallel path that could cause undesirable circulation of currents affecting the performance of relays and metering devices.

10.1.8 very fast transients overvoltage (VFTO): System overvoltages that result from generation of VFT. While VFT is one of the main constituents of VFTO, some lower frequency (≈ 1 MHz) component may be present as a result of the discharge of lumped capacitance (voltage transformers). Typically, VFTO will not exceed 2.0 per unit, though higher magnitudes are possible in specific instances.

10.2 GIS characteristics

GIS are subjected to the same magnitude of ground fault current and require the same low-impedance grounding as conventional substations.

Typically, the GIS installation necessitates 10–25% of the land area required for conventional equipment. Because of this smaller area, it may be difficult to obtain adequate grounding solely by conventional methods. Particular attention should be given to the bonding of the metallic enclosures of the GIS assembly, as these enclosures carry induced currents of significant magnitude, which must be confined to specific paths. In this respect, grounding recommendations by the manufacturer of a given GIS usually need to be strictly followed.

As a result of the compact nature of GIS and its short distances, electrical breakdown in the insulating gas, either across the contacts of a switching device during operation or in a fault that generates very high frequency transients that can couple onto the grounding system. In some cases, these transients may have to be considered in the overall grounding design. These transients may cause high magnitude, short duration ground rises and are also the source of electromagnetic interference (EMI) in the GIS. While EMI is beyond the scope of this document, the EMI mitigation techniques often involve special considerations in the grounding design (Harvey [B79]).

10.3 Enclosures and circulating currents

The shielding effectiveness of the bus enclosure is determined by its impedance, which governs the circulation of induced currents.

With separate enclosures for each phase, the magnitude and direction of the enclosure current is influenced by the size of the enclosure and the phase spacing between the buses, as well as by the method of interconnecting the enclosures.

In a *continuous* enclosure design, a voltage is induced in an enclosure by the current in the conductor that it surrounds, producing a longitudinal current flow in the enclosure. When a continuity of all phase enclosures is maintained through short connections at both ends, the enclosure current is only slightly less than that flowing in the inner bus in the opposite direction. This current returns through the housing (enclosures) of adjacent phases when the load is equalized between phases. The magnetizing current lags the enclosure current by approximately 90°. The flux is mainly contained within the enclosure.

In a *noncontinuous* enclosure design, there are no external return paths for enclosure currents. Thus the voltage induced in a noncontinuous enclosure by the current of an inner bus(es) that it surrounds cannot produce any longitudinal current flow. Also, voltages might be induced in each enclosure by the currents in the conductors not enclosed by it. Nonuniform voltages result, causing local current flows in each isolated enclosure section, with the currents flowing in nonuniform patterns. Because of these properties, the noncontinuous design is generally considered less advantageous than that of the continuous type. As such, it is not currently used by the industry.

10.4 Grounding of enclosures

Normally, the continuous-type enclosures provide a return path for induced currents so that the conductor and enclosure form a concentric pair with effective external shielding of the field internal to the enclosure. However, under asymmetrical faults, the dc component is not shielded and causes an external voltage drop due to enclosure resistance.

Frequent bonding and grounding of GIS enclosures is the best solution to minimize hazardous touch and step voltages within the GIS area. Additional measures¹⁰ include the use of conductive platforms (ground mats) that are connected to GIS structures and grounded.

To limit the undesirable effects caused by circulating currents, the following requirements should be met:

- a) All metallic enclosures should normally operate at ground voltage level.
- b) When grounded at the designated points, the bus enclosure design should ensure that no significant voltage differences exist between individual enclosure sections and that neither the supporting structures nor any part of the grounding systems is adversely influenced by the flow of induced currents.
- c) To avoid the circulation of enclosure currents beyond regular return path within the GIS assembly, power cable sheath grounds should be tied to the grounding system via connections that are separated from the GIS enclosures. To facilitate this isolation, the design of cable terminations should be such that an isolating air gap or proper insulation elements are provided. Very fast transients generated by switching or by faults in the GIS may cause these insulation elements to flashover. In such cases, the consequences of such flashovers on current distribution within the grounding system should be considered (Fujimoto, Croall, and Foty [B68]).
- d) Enclosure return currents also cannot be permitted to flow through any mounted current transformers.

10.5 Cooperation between GIS manufacturer and user

Usually it is the GIS manufacturer who defines clearly what constitutes the main ground bus of the GIS and specifies what is required of the user for connecting the GIS assembly to the substation ground. Ample documentation is necessary to assure that none of the proposed connections from the main ground bus to the grounding grid will interfere with the required enclosure current path or any other operational feature of the GIS design. That may be especially pertinent if the main ground bus consists of a system of interconnections between the GIS components and structures, and no separate busbar (continuous common ground bus loop) is furnished.

Usually the GIS manufacturer also provides, or is responsible for

- a) Providing the subassembly-to-subassembly bonding to assure safe voltage gradients between all intentionally grounded parts of the GIS assembly and between those parts and the main ground bus of the GIS.
- b) Furnishing readily accessible connectors of sufficient mechanical strength to withstand electromagnetic forces and normal abuse, and that are capable of carrying the anticipated maximum fault current in that portion of the circuit without overheating.
- c) Providing ground pads or connectors, or both, allowing, at least, for two paths to ground from the main ground bus, or from each metallic enclosure and auxiliary piece of GIS equipment designated

¹⁰Despite all measures described, the presence of circulating currents can cause different parts of the GIS metal housing to have a slightly different potential to ground. Although the resulting voltage differences are small and generally of no concern to a shock hazard, accidental metallic bridging of adjacent enclosures can cause annoying sparks.

for a connection to the substation ground if the main ground bus of the GIS assembly does not actually exist.

- d) Recommending proper procedures for connections between dissimilar metals, typically between a copper cable or a similar ground conductor and aluminum enclosures.

The user usually provides information on the sources of fault current and the expected magnitudes and durations that should be considered. Moreover, the user should assist the GIS manufacturer in reviewing all proposed grounding provisions to assure proper interfacing of

- a) Connections for the neutral current of grounded equipment or apparatus and for dissipating surges caused by lightning and switching within the GIS.
- b) Devices for dissipating lightning and switching surge currents external to the GIS assembly.
- c) Requirements of protective relaying, and satisfying the provisions necessary for telephone and communication facilities.
- d) Ground connections to all GIS supporting frames and structures, metallic sheaths, and installation of shielding for cable terminations where applicable.
- e) Connections to all pads or connectors furnished by the GIS manufacturer.
- f) Safe voltage for step and touch, under both normal and abnormal operating conditions external to the GIS assembly.
- g) Compliance with the grounding specifications, related to correct grounding practices, as mutually agreed to by the GIS manufacturer and the user.

10.6 Other special aspects of GIS grounding

Precautions should be taken to prevent excessive currents from being induced into adjacent frames, structures, or reinforcing steel, and to avoid establishment of current loops via other substation equipment, such as transformers or separate switchgear. If there is the possibility of undesirable current loops via ground connections, or if any sustained current path might partially close or pass through grounded structures, the substation grounding scheme and the physical layout should be carefully reviewed with the GIS manufacturer.

Equal care is needed in the proximity of discontinuities in enclosure grounding paths at the transformer connections to GIS and at the interface points to conventional switchgear to prevent circulating currents in the circuit breaker and transformer tank steel.

Where applicable, all isolating elements should be able to withstand the full potential difference that may occur between the locally grounded system and that external to the GIS. In many cases, the very fast transients generated by switching or by faults in the GIS may cause very high transient voltages to appear at these points. For instance, the isolation of high-pressure oil pipe cables from the GIS grounding system often involves difficulties. Although the individual HV or EHV terminators may provide adequate separation from the external grounds (by the virtue of a design that usually includes the use of base plate insulators made of high-voltage rated porcelain or fiberglass), problems sometimes arise if the same level of insulation is also expected at other interface points. One typical problem area is the auxiliary piping between the oil chamber of individual GIS terminators and the oil diffusion chamber at the end of a pipe cable that frequently branches to a variety of oil pressure monitoring instruments and alarm devices (Graybill, Koehler, and Nadkarni, and Nicholas [B77]). There the isolation of metal parts is often achieved by the means of ceramic or plastic inserts. Adequate creepage distance should be ensured where possible. To protect against transient voltages, other precautions might be necessary (Dick, Fujimoto, Ford, and Harvey [B52]; Ford and Geddes [B67]; Fujimoto, Croall, and Foty [B68]).

In these and similar circumstances,¹¹ a close cooperation with the GIS manufacturer in the early stages of the design is very important.

10.7 Notes on grounding of GIS foundations

Since the earth path of ground currents is strongly affected by the relative position of conductive objects that are in the ground, more attention should be paid to those portions of the GIS grounding system that include discontinuities, or where the design requires an abrupt change in the pattern of ground electrodes. The following circumstances are of concern.

In the limited space of GIS substations, a substantial part of the substation area is often occupied by concrete foundations, which may cause irregularities in a current discharge path. In this respect, a simple monolithic concrete steel reinforced slab is advantageous both as an auxiliary grounding device and for seismic reasons.

If a continuous floor slab is used, a good adjunct measure is to tie its reinforcing steel mesh to the common ground bus (main ground bus) so that both the GIS enclosures and the structural steel in and above the foundation will be approximately the same potential level. The assumption is that this measure should produce a better ground and the reinforcing bars, being considerably closer together than the wires of a typical ground grid, should produce more even potentials within the floor and at the surface.¹²

GIS foundations, which include reinforcing bars and other metals, can act as auxiliary ground electrodes and may be so used provided that under no circumstances the discharge of current would result in a damage of concrete because of local overheating or a gradual erosion of the concrete-steel bonds. For further details, refer to 14.6.

10.8 Touch voltage criteria for GIS

Although the GIS manufacturer generally designs the equipment to meet the already mentioned requirements for safe operation and usually performs most, if not all, calculations that are necessary for determining the sheath voltages and currents during faults, there still are circumstances when the user has to ascertain that the entire installation is safe. Having this possibility in mind, some of the critical aspects of interconnecting the GIS with a grounding system are briefly discussed next.

A certain paradox, inherent to the GIS design, may occur when one tries to determine the best concept of GIS grounding. In contrast to the general wisdom that a large ground connection necessarily equals a good grounding practice, the circulating currents generated in the GIS enclosures during a fault should also be taken into account. To be considered are: 1) where these currents will circulate, and 2) where and to what degree the design engineer or GIS manufacturer, or both, prefer these currents to circulate.

Typically in a continuous enclosure design, the path of enclosure currents includes some structural members of the GIS frame and the enclosures themselves. With each phase enclosure tied to the enclosures of adjacent phases at both ends, several loops are formed. Because a cross section of the mentioned structural members is usually much smaller than that of the enclosure and comparable to that of the grounding straps that connect the GIS assembly to a ground grid (and for that matter, also to the reinforcing bars of the concrete foundation), several questions need to be asked

¹¹The direct effect of transmitted enclosure voltage (TEV) on humans may not be fatal, but its secondary effect on personnel should be of concern to the design engineer and the manufacturer. In addition, TEV might necessitate that more stringent electromagnetic compatibility requirements be considered for auxiliary equipment.

¹²It might be argued that the concrete slab, being a fairly good conductor itself, could produce a more uniform voltage at the floor level if no current would flow into the reinforcing bars from the ground system. If the bars are connected, the electrical field in the earth between the bars of the slab and the underlying grid would be zero. (As both mats are at the same potential, hardly any current would flow out of the bars into the concrete and toward the ground grid.) Therefore, the concrete with reinforcing bars will produce a substantially uniform potential field across the floor surface.

- a) If the currents divide and flow via all available metallic paths, what ratio is to be expected between the currents circulating within the GIS assembly and those circulating via a ground connection?
- b) How much current circulating via a ground connection loop is too much?
- c) Should the GIS be designed to be safe if no circulating current would (at least for an external fault) circulate via ground connections?
- d) And finally, how much grounding is needed for the best balance between operational and safety-related requirements?

Presently, there are no clear-cut answers and solutions to the questions listed above. Some manufacturers prefer to supply a special ground bus (main ground bus) as a part of the GIS package, with clearly designated ground connection points. Others do not use any main ground bus at all, but simply designate certain points on the enclosure as grounding pads and let the utility complete the grounding.

In either case, it becomes necessary to limit the body current to some value in a milliampere range, while the fault currents that are of concern range from hundreds to thousands of amperes. Thus, one can safely assume that the full potential difference existing prior to a contact would not change while forcing the current through an alternate path including the body. Then the case of a person touching the GIS sheath metal can be reduced to the problem of finding the voltage drop between two points of contact along one or between two enclosures and a common ground. For the hand-to-feet contact made by a person standing on a nonmetallic surface (for instance, a concrete slab or the soil layer above the grounding grid), only a minor modification of the application criterion of Equation (32) and Equation (33) is required in order to take into account the maximum inductive voltage drop occurring within the GIS assembly.

The touch voltage criterion for GIS is

$$\sqrt{E_t^2 + (E'_{to \max})^2} < E_{touch} \quad (36)$$

where

E_t	is the maximum touch voltage, as determined for the point underneath a person's feet
$E'_{to \max}$	is the (predominantly inductive) maximum value of metal-to-metal voltage difference on and between GIS enclosures, or between these enclosures and the supporting structures, including any horizontal or vertical members for which the GIS assembly is designed

In practical situations, as shown in Figure 16, a multiplicity of return paths and considerable cross-coupling occurs. This makes the calculation of longitudinally induced currents difficult and for some remote external faults often outright impractical, as too many parameters remain undefined. As a rule, because of a great variety in possible physical arrangements of the GIS assembly, the GIS manufacturers perform detailed calculations for determining the basic design parameters, such as spacing and location of bonds.

10.9 Recommendations

The following recommendations should be considered for GIS installations:

- a) When applying the touch voltage criterion Equation (36), the following facts should be considered. The case of an internal fault with ground return requires the addition of the resistive and inductive voltage drop to the resistive drop representing the difference of potentials between the substation ground and the point beneath a person's feet. This generally is not necessary for faults external to the GIS. For an external line-to-ground fault, the voltages induced on the sheath should be checked for a hand-to-hand metal-to-metal contact, but the calculation of step and touch voltages at the earth's surface is the same as that for conventional installations [i.e., the inductive term $E'_{to \max}$ in Equation (36) is zero].

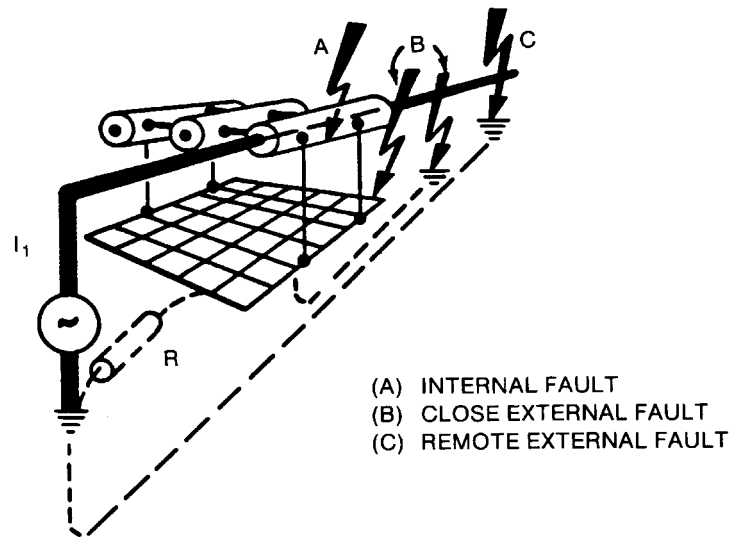


Figure 16—Typical faults in GIS

- b) In evaluating the magnitude of induced voltages caused by faults external to the GIS, only the case of a close-in fault [case (B) in Figure 16] needs to be analyzed because remote external faults will cause less of a problem.

11. Selection of conductors and connections

In assessing which conductor material and what conductor size or what maximum allowable temperature limit needs to be applied in individual design situations, the final choice should always reflect the considerations outlined in 11.1–11.4.

11.1 Basic requirements

Each element of the grounding system, including grid conductors, connections, connecting leads, and all primary electrodes, should be so designed that for the expected design life of the installation, the element will

- Have sufficient conductivity, so that it will not contribute substantially to local voltage differences.
- Resist fusing and mechanical deterioration under the most adverse combination of a fault magnitude and duration.
- Be mechanically reliable and rugged to a high degree.
- Be able to maintain its function even when exposed to corrosion or physical abuse.

11.2 Choice of material for conductors and related corrosion problems

11.2.1 Copper

Copper is a common material used for grounding. Copper conductors, in addition to their high conductivity, have the advantage of being resistant to most underground corrosion because copper is cathodic with respect to most other metals that are likely to be buried in the vicinity.

11.2.2 Copper-clad steel

Copper-clad steel is usually used for underground rods and occasionally for grounding grids, especially where theft is a problem. Use of copper, or to a lesser degree copper-clad steel, therefore assures that the integrity of an underground network will be maintained for years, so long as the conductors are of an adequate size and not damaged and the soil conditions are not corrosive to the material used.

11.2.3 Aluminum

Aluminum is used for ground grids less frequently. Although at first glance the use of aluminum would be a natural choice for GIS equipment with enclosures made of aluminum or aluminum alloys, there are the following disadvantages to consider:

- a) Aluminum itself may corrode in certain soils. The layer of corroded aluminum material is nonconductive for all practical grounding purposes.
- b) Gradual corrosion caused by alternating currents may also be a problem under certain conditions.

Thus, aluminum should be used only after full investigation of all circumstances, despite the fact that, like steel, it would alleviate the problem of contributing to the corrosion of other buried objects. However, aluminum is anodic to many other metals, including steel and, if interconnected to one of these metals in the presence of an electrolyte, the aluminum will sacrifice itself to protect the other metal. If aluminum is used, the high purity electric conductor grades are recommended as being more suitable than most alloys.

11.2.4 Steel

Steel may be used for ground grid conductors and rods. Of course, such a design requires that attention is paid to the corrosion of the steel. Use of a galvanized or corrosion resistant steel, in combination with cathodic protection, is typical for steel grounding systems (Mahonar and Nagar [B101]).

11.2.5 Other considerations

A grid of copper or copper-clad steel forms a galvanic cell with buried steel structures, pipes, and any of the lead-based alloys that might be present in cable sheaths. This galvanic cell may hasten corrosion of the latter. Tinning the copper has been tried by some of the utilities. That reduces the cell potential with respect to steel and zinc by about 50% and practically eliminates this potential with respect to lead (tin being slightly sacrificial to lead). The disadvantage of using a tinned copper conductor is that it accelerates and concentrates the natural corrosion, caused by the chemicals in the soil, of the copper in any small bare area. Other often-used methods are

- a) Insulation of the sacrificial metal surfaces with a coating such as plastic tape, asphalt compound, or both.
- b) Routing of buried metal elements so that any copper-based conductor will cross water pipe lines or similar objects made of other uncoated metals as nearly as possible at right angles, and then applying an insulated coating to one metal or the other where they are in proximity. The insulated coating is usually applied to the pipe.

- c) Cathodic protection using sacrificial anodes or impressed current systems.
- d) Use of nonmetallic pipes and conduits.

In GIS, the use of cathodic protection may also be required for other reasons. Cathodic protection is commonly used to protect facilities that are external to the GIS, such as pressurized pipe-type cables, lead shielded cables, etc. Because of the complexity of GIS installations, it is essential to consider all aspects of corrosion prevention before designing the grounding system. Specific guidelines are difficult to establish because substation conditions may be different due to location and application in the electric power system.

The subject of underground corrosion and cathodic protection is complex. Many studies have been made and much has been published on this subject. A detailed discussion of these phenomena is beyond the scope of this guide.

11.3 Conductor sizing factors

11.3.1 Symmetrical currents

The short time temperature rise in a ground conductor, or the required conductor size as a function of conductor current, can be obtained from Equation (37) through Equation (42), which are taken from the derivation by Sverak [B133]. These equations are also included as Appendix B in IEEE Std 837-1989. These equations evaluate the ampacity of any conductor for which the material constants are known, or can be determined by calculation. Material constants of the commonly used grounding materials are listed in Table 1. Equation (37) through Equation (42) are derived for symmetrical currents (with no dc offset).

$$I = A_{mm^2} \sqrt{\left(\frac{TCAP \cdot 10^{-4}}{t_c \alpha_r \rho_r} \right) \ln \left(\frac{K_o + T_m}{K_o + T_a} \right)} \quad (37)$$

where

I	is the rms current in kA
A_{mm^2}	is the conductor cross section in mm ²
T_m	is the maximum allowable temperature in °C
T_a	is the ambient temperature in °C
T_r	is the reference temperature for material constants in °C
α_o	is the thermal coefficient of resistivity at 0 °C in 1/°C
α_r	is the thermal coefficient of resistivity at reference temperature T_r in 1/°C
ρ_r	is the resistivity of the ground conductor at reference temperature T_r in μΩ-cm
K_o	1/α _o or (1/α _r) – T_r in °C
t_c	is the duration of current in s
$TCAP$	is the thermal capacity per unit volume from Table 1, in J/(cm ³ ·°C) (further defined in 11.3.1.1)

It should be noted that α_r and ρ_r are both to be found at the same reference temperature of T_r °C. Table 1 provides data for α_r and ρ_r at 20 °C.

If the conductor size is given in kcmils (mm² × 1.974 = kcmils), Equation (37) becomes

$$I = 5.07 \cdot 10^{-3} A_{kcmil} \sqrt{\left(\frac{TCAP}{t_c \alpha_r \rho_r} \right) \ln \left(\frac{K_o + T_m}{K_o + T_a} \right)} \quad (38)$$

Table 1—Material constants

Description	Material conductivity (%)	α_r factor at 20 °C (1/°C)	K_o at 0 °C (0 °C)	Fusing ^a temperature T_m (°C)	ρ_r 20 °C ($\mu\Omega\cdot\text{cm}$)	TCAP thermal capacity [$\text{J}/(\text{cm}^3\cdot^\circ\text{C})$]
Copper, annealed soft-drawn	100.0	0.003 93	234	1083	1.72	3.42
Copper, commercial hard-drawn	97.0	0.003 81	242	1084	1.78	3.42
Copper-clad steel wire	40.0	0.003 78	245	1084	4.40	3.85
Copper-clad steel wire	30.0	0.003 78	245	1084	5.86	3.85
Copper-clad steel rod ^b	20.0	0.003 78	245	1084	8.62	3.85
Aluminum, EC grade	61.0	0.004 03	228	657	2.86	2.56
Aluminum, 5005 alloy	53.5	0.003 53	263	652	3.22	2.60
Aluminum, 6201 alloy	52.5	0.003 47	268	654	3.28	2.60
Aluminum-clad steel wire	20.3	0.003 60	258	657	8.48	3.58
Steel, 1020	10.8	0.001 60	605	1510	15.90	3.28
Stainless-clad steel rod ^c	9.8	0.001 60	605	1400	17.50	4.44
Zinc-coated steel rod	8.6	0.003 20	293	419	20.10	3.93
Stainless steel, 304	2.4	0.001 30	749	1400	72.00	4.03

^aFrom ASTM standards.^bCopper-clad steel rods based on 0.254 mm (0.010 in) copper thickness.^cStainless-clad steel rod based on 0.508 mm (0.020 in) No. 304 stainless steel thickness over No. 1020 steel core.

Equation (37) and Equation (38), in conjunction with Equation (39) (which defines *TCAP*), reflect two basic assumptions

- That all heat will be retained in the conductor (adiabatic process).
- That the product of specific heat (*SH*) and specific weight (*SW*), *TCAP*, is approximately constant because *SH* increases and *SW* decreases at about the same rate. For most metals, these premises are applicable over a reasonably wide temperature range, as long as the fault duration is within a few seconds.