

IEEE Guide for Safety in AC Substation Grounding

IEEE Power and Energy Society

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Substations Committee



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IEEE Guide for Safety in AC Substation Grounding

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Abstract: This guide is primarily concerned with outdoor ac substations, either conventional or gas-insulated. These include distribution, transmission, and generating plant substations. 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, IEEE 80™, substation design, substation grounding

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Introduction

This introduction is not part of IEEE Std 80™-2013, IEEE Guide for Safety in AC Substation Grounding.

This fifth edition represents the third major revision of this guide since its first issue in 1961. Previous editions extended the equations for calculating touch and step voltages to include L-shaped and T-shaped grids; they introduced curves to help determine current division, changed the criteria for selection of conductors and connections, and provided more information on resistivity measurement interpretation; and added the discussion of multilayer soils.

This edition introduces the calculations to determine *TCAP* for materials not listed in Table 1. This information can be used to calculate *TCAP* for different combinations of bi-metallic electrodes used in grounding systems. This edition also introduces benchmarks. The benchmarks have two purposes. First, the benchmarks compare the equations in IEEE Std 80 to commercially available ground grid design software. The benchmarks show where IEEE Std 80 equations work well and their limitations. Second, the benchmarks provide software users a way to verify their understanding of the software.

The fifth edition continues to build on over 50 years of work by dedicated members of working groups: AIEE Working Group 56.1 and IEEE Working Groups 69.1, 78.1, and D7.

As required by IEEE Std 80-2013/Cor 1-2015, corrections were made to Clause 11, Clause 17, Annex C, Annex H as well as to Table 1 and Table 2; two equations following Figure 45; Table H.5 was replaced by a new Table H.5, and Table H.6 through Table H.10 were added.

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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

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.

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~~ safety 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 safety criteria for 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 [voltage gradient](#) problems.
- e) [Provide benchmarks cases to compare the results of IEEE Std 80™ equations to commercially available software programs.](#)

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 H.

This guide is primarily concerned with safe grounding practices for power frequencies in the range of 50 Hz to 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.

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.

- ~~— 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. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

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.

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

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

~~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.~~

¹ IEEE publications are available from The Institute of Electrical and Electronics Engineers, ~~445 Hoes Lane, P.O. Box 1331, Piscataway,~~ (<http://standards.ieee.org/>).

~~IEEE Std 665-1995, IEEE Guide for Generating Station 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

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.²

~~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~~

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.

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.

²*IEEE Standards Dictionary Online* subscription is available at:

http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.

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

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.

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.

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

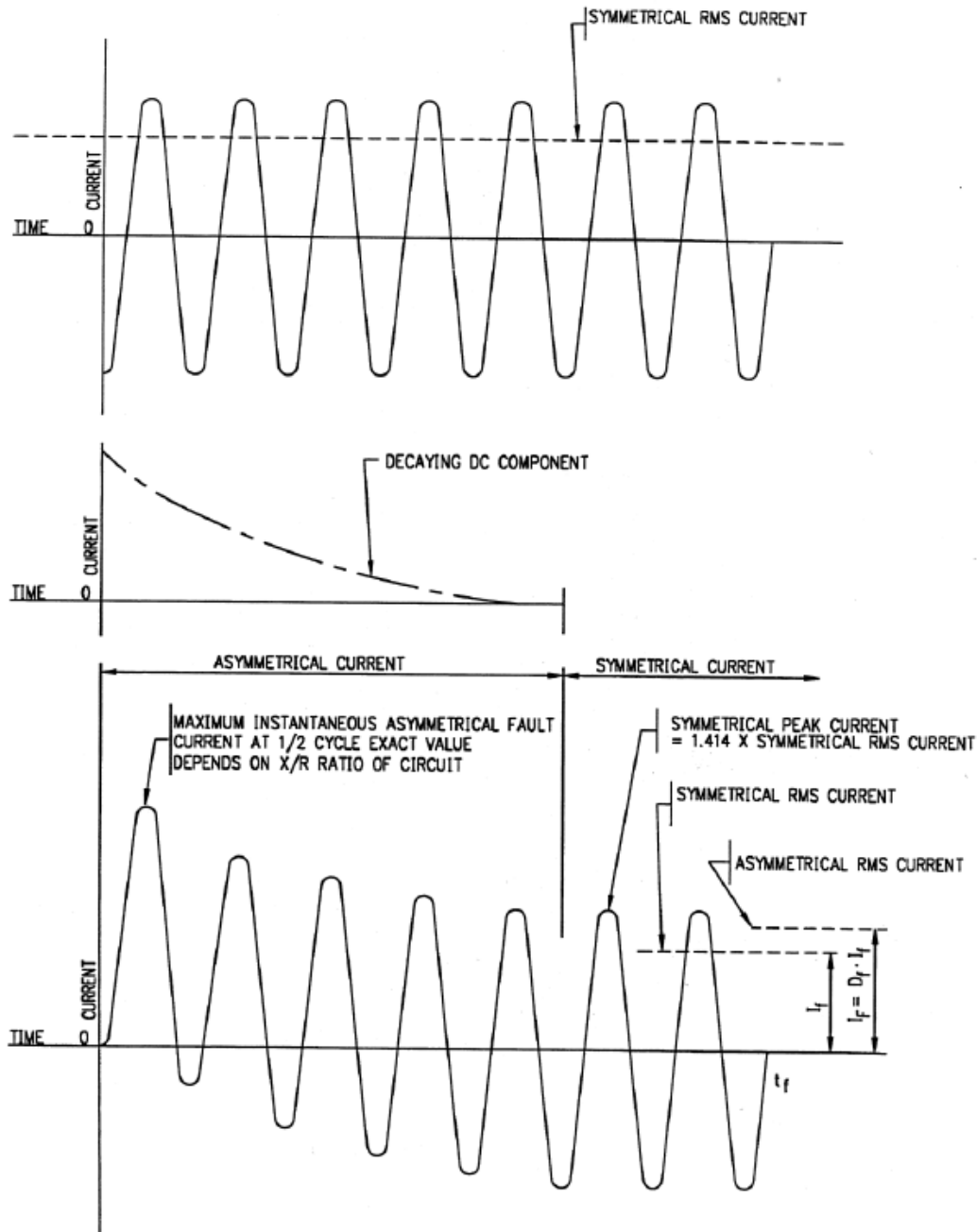


Figure 1—Relationship between actual values of fault current and values of I_F , I_f , and D_f for fault duration t_f

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

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 ground 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

gas-insulated substation (GIS): A compact, multi-component 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 [Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.](#)

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.

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.

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

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

ground grid: A system of interconnected 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~~ arranged in a pattern over a specified area and buried below the surface of the earth.

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.

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.

ground potential rise (GPR): The maximum electrical potential that a ~~substation grounding grid~~ [ground electrode](#) 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~~ [multiplied by](#) 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 ground grid into the earth causes the rise of the grid potential with respect to remote earth.

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.

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

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

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

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

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.

non-continuous 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.

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.

step voltage: The difference in surface potential [that could be](#) experienced by a person bridging a distance of 1 m with the feet without contacting any grounded object.

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.

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.

symmetrical grid current: That portion of the symmetrical ground fault current that flows between the ground 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

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 reactance 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.

touch voltage: The potential difference between the ground potential rise (GPR) [of a ground grid or system](#) and the surface potential at the point where a person ~~is~~ [could be](#) standing while at the same time having a hand in contact with a grounded structure. [Touch voltage measurements can be “open circuit” \(without the equivalent body resistance included in the measurement circuit\) or “closed circuit” \(with the equivalent body resistance included in the measurement circuit\).](#)

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.

transient enclosure voltage (TEV): Very fast transient phenomena, which are found on the grounded enclosure of [gas-insulated substation \(GIS\)](#) 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).

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 [MHz to](#) 40 MHz range.

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.

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~~ reduce the risk of a person in the vicinity of grounded facilities ~~is not~~ being 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~~ less dangerous or can be made ~~safe~~ less dangerous 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~~ important factors ~~in-protecting~~ for reducing the risk to human life, ~~the most precious element of the accidental circuit.~~

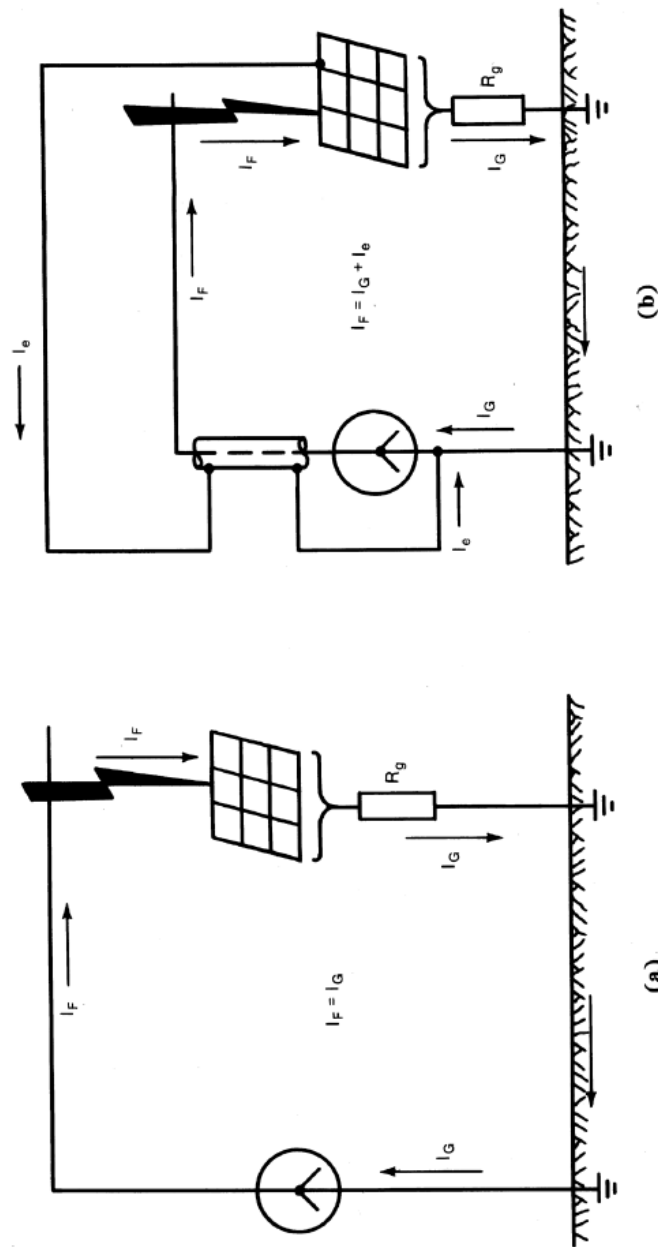


Figure 2—Faulted substation ~~Equipotential contours of a typical~~
~~grounding grid~~ with and without multiple grounds ~~rods~~

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 ground grid in homogeneous soil.

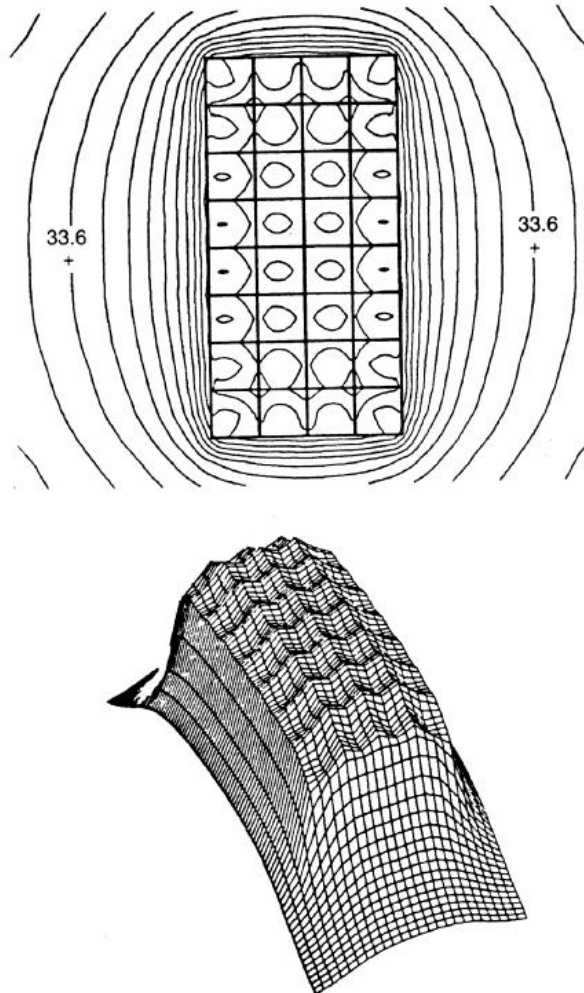


Figure 3—Equipotential contours ~~if~~ of a typical ~~grounding grid with and~~
~~without~~ ground ~~rods~~ grid

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~~ can include the following:

- 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~~ low frequency 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 [Hz to](#) 10 000 Hz, even higher currents can be tolerated (Dalziel and Mansfield [B34]⁴; Dalziel, Ogden, and Abbott [B37]). 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) [B84]). Other studies of the effects of both direct and oscillatory impulse currents are reported in Dalziel [B26][B28].

Information regarding special problems of dc grounding is contained in the 1957 report of the AIEE Substations Committee [B22]. 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 [B91]. 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 [B59].

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 [B75]; IEC 60479-1 (1994-09) [B83]).

⁴ [The numbers in brackets correspond to those of the bibliography in Annex A.](#)

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 [mA to](#) 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 [B35]).

In the 9 [mA to](#) 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 [B30]).

~~It is not until magnitudes~~ In the range of 60 [mA to](#) 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 [after the current source is removed and it is safe to do so](#), until the victim can be treated at a medical facility (Dalziel [B31]; Dalziel and Lee [B32]).

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 [B36]; Dalziel and Massogilia [B35]), the non-fibrillating current of magnitude I_B at durations ranging from 0.03 [s to](#) 3.0 s is related to the energy absorbed by the body as described by the following equation:

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

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~~ can be advantageous for two reasons:

- a) The probability of exposure to electric shock ~~is greatly~~ can be 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~~ can be 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~~ provide 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 s to 0.3 s.

In reality, high ground gradients from faults are usually infrequent, and shocks from high ground gradients are ~~even more~~ also 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 [B27]; Dalziel and Lee [B33]), 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. [B67] 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 [B8][B10] proposed the threshold values at 500 mA and 50 mA, respectively. Other studies on this subject were carried out by Lee [B102] and Kouwenhoven [B31][B95] [B98]. 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 [B29] and Dalziel and Lee [B33], 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

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

Users of this guide may select $k = 0.157$ provided that the average population weight can be expected to be at least 70 kg.⁵

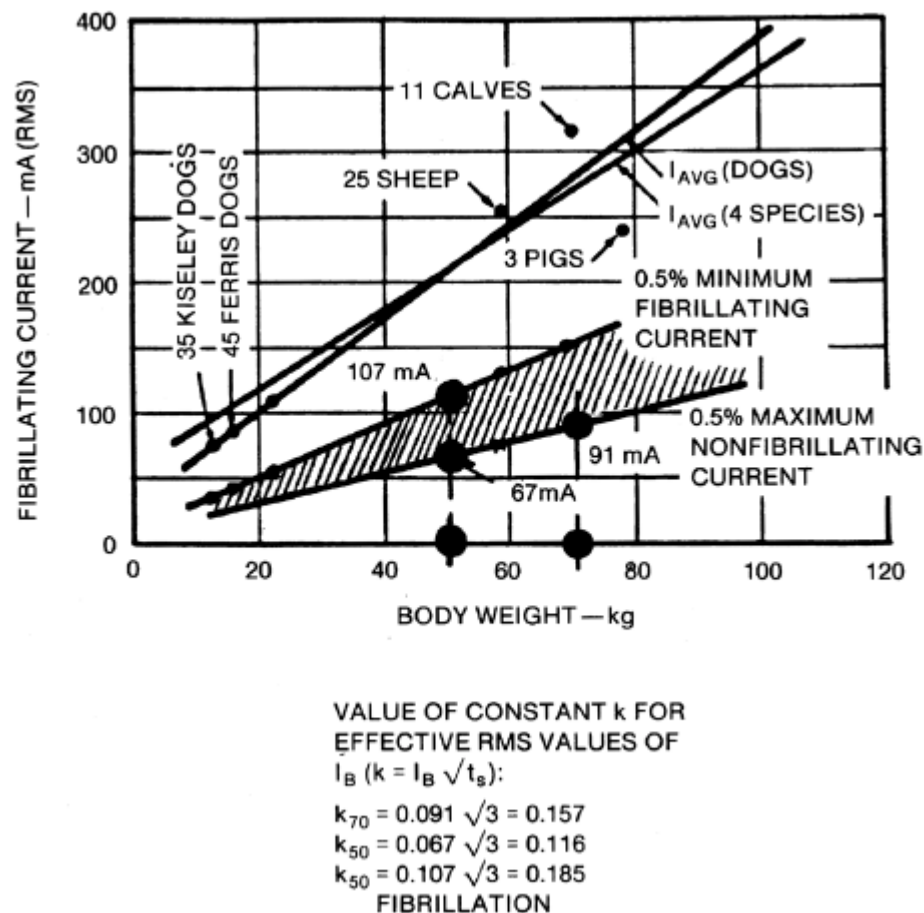


Figure 4—Fibrillating current versus body weight for various animals based on a 3 s duration of the electrical shock

⁵ Typically, 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.

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.

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.

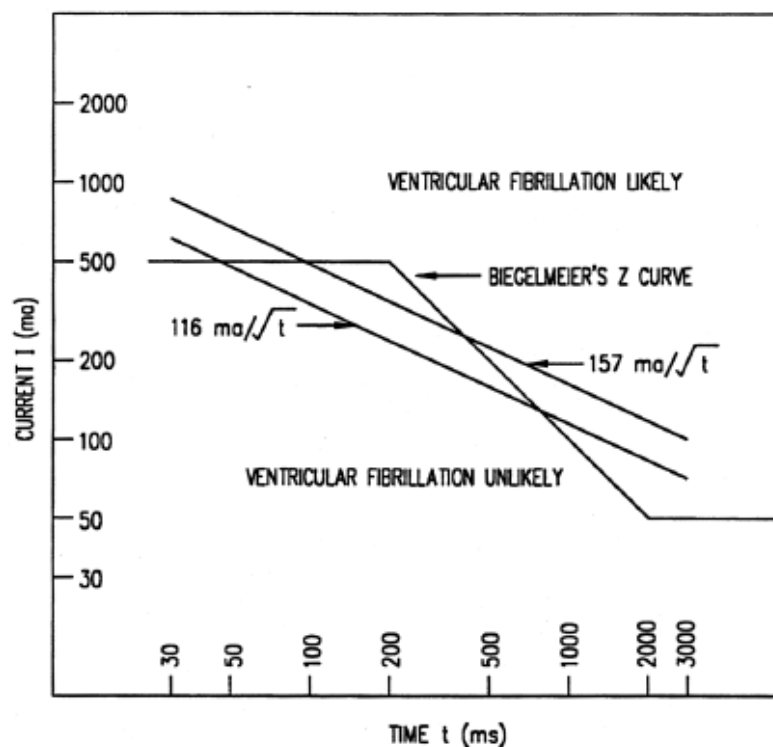


Figure 5— Body current versus time

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~~ can be 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 [B27], Geddes and Baker [B75], Geiges [B76], Kiselev [B97], and Osypka [B121]. The human body resistance is decreased by damage or puncture of the skin at the point of contact.

As mentioned in 5.2, Dalziel [B35] 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 $2330\ \Omega$, and the hand-to-feet resistance equals $10.2/0.009$ or $1130\ \Omega$, 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 $1000\ \Omega$ 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.

$$R_B = 1000\ \Omega \tag{10}$$

7.2 Current paths through the body

It should be remembered that the choice of a $1000\ \Omega$ 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 [B103] 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 $1000\ \Omega$ 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~~ appear to be 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 [B15]; Langer [B99]).

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_f is the total fault current in A

I_g is the current flowing in the grid in A

I_b is the body current (body is part of the accidental circuit) in A

$R_{A\ B}$ is the ~~total effective~~ resistance of the ~~accidental circuit~~ body in Ω

V_A is the total effective voltage of the accidental circuit (touch or step voltage) in V

H and F are points of contact of the body

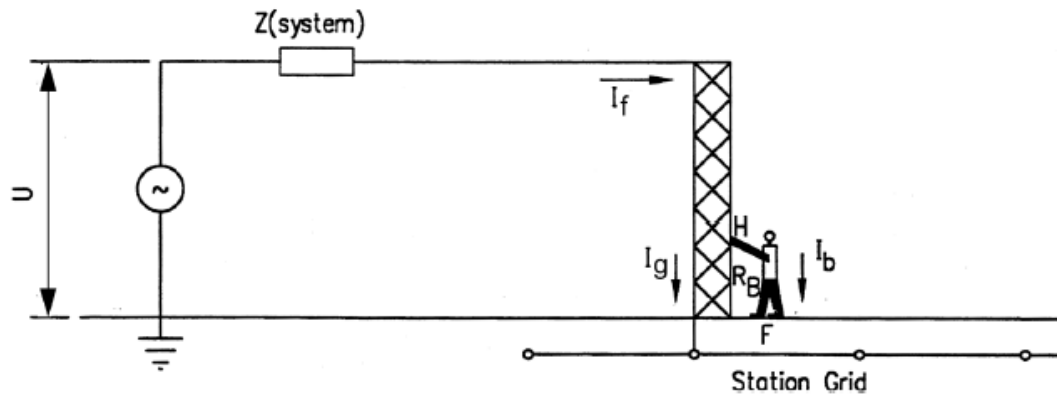


Figure 6—Exposure to touch voltage

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 [B50]; Dawalibi, Xiong, and Ma [B51]).

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

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

where

R_B is the resistance of the human body in Ω

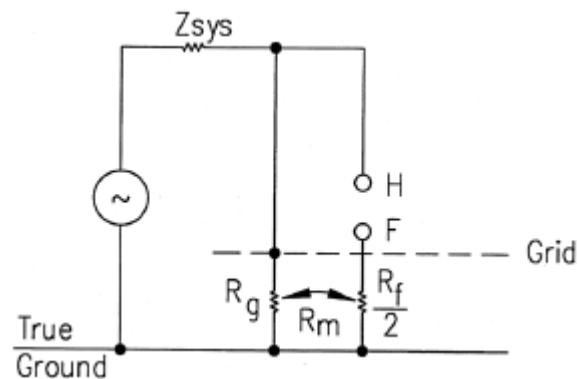


Figure 7—Impedances to touch voltage circuit

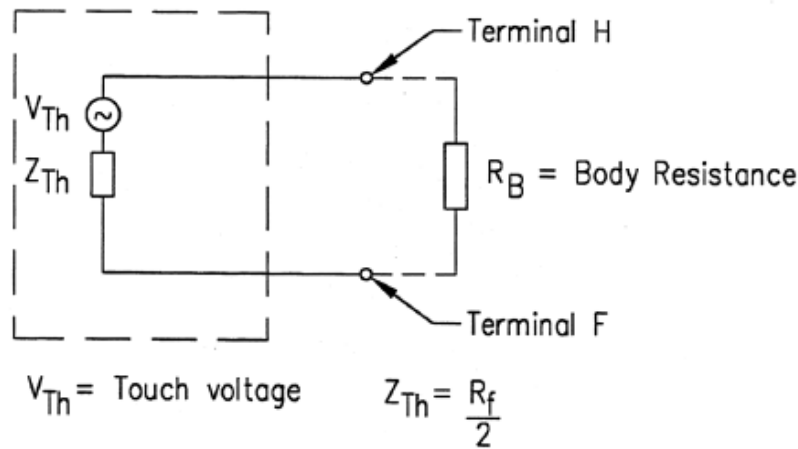


Figure 8—Touch voltage circuit

For most practical cases, the effects of Z_{sys} , grid resistance and the mutual resistance between the grid and the person's feet can be neglected on the total circuit Thevenin equivalent impedance. Thus, Z_{Th} is represented by the equivalent impedance of the person's feet.

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 F1 through the body of the person to the other foot, F2. Terminals F1 and F2 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 (F1, F2) network in Figure 10. The Thevenin voltage V_{Th} is the voltage between terminals F1 and F2 when the person is not present. The Thevenin impedance Z_{Th} is the impedance of the system as seen from the terminals F1 and F2 with the voltage sources of the system short-circuited. The current I_b through the body of a person is given by Equation (11).