

ANSI/IEEE S41-80-1986

IEEE Guide for Safety in AC Substation Grounding



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An American National Standard

**IEEE Guide for Safety in
AC Substation Grounding**



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**IEEE Guide for Safety in
AC Substation Grounding**

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**The Substation Committee
of the
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Foreword

(This Foreword is not a part of ANSI/IEEE Std 80-1986, IEEE Guide for Safety in AC Substation Grounding.)

This third edition represents the first major revision of this guide since its first issue in 1961. Major modifications include the redefinition of simplified equations for calculating touch and step voltages, changes in safety criteria, and expansion of examples illustrating the use of this guide. Other changes and additions concern a section on gas-insulated substations, introduction of a derating factor for crushed stone surfacing, the effects of ground rods, equations for calculation of grid resistance, current division among available ground paths, sizing of conductors of various materials, and discussion of multilayer soil models. Although the scope of this document is considerably larger than those of the 1961 and 1976 editions, there is a continuity of principles and in the general approach to safe grounding practices. The third edition thus continues to build upon the foundations laid by two earlier working groups, AIEE Working Group 56.1 and IEEE Working Group 69.1.

The work of preparing this standard was done by Working Group 78.1 of the Distribution Substation Subcommittee and was sponsored by the Substation Committee of the IEEE Power Engineering Society. The membership of this working group was as follows:

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IEEE Guide for Safety in AC Substation Grounding

1. Introduction

1.1 Purpose and Scope. The intent of this guide is to provide guidance and information pertinent to safe grounding practices in ac substation design. This guide is primarily concerned with outdoor 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.¹

The specific purposes of this guide are:

- (1) To 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
- (2) To review substation grounding practices with special reference to safety, and develop criteria for a safe design
- (3) To provide a procedure for the design of practical grounding systems, based on these criteria
- (4) To develop analytical methods as an aid in the understanding and solution of typical gradient problems
- (5) To provide a bibliography of pertinent literature on grounding, and English translations of some of the more valuable foreign language articles

¹ Obviously, 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 Section 6. Furthermore, in the case of indoor gas-insulated facilities, the effect of circulating enclosure currents may be of concern, as discussed in Section 8.

The concept and use of safety criteria are described in Sections 1–6, practical aspects of designing a grounding system are covered in Sections 7–11, and procedures and evaluation techniques for the grounding system assessment (in terms of safety criteria) are described in Sections 12–18. Supporting material is organized in Appendixes A–J.

Some of the special hazards encountered in gas-insulated substations and techniques for analyzing these problems are discussed in Section 8 and Appendix D.

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. However, the listed references contain further information on both subjects.

A grounding system designed as recommended herein will, nonetheless, provide a high degree of protection against steep wave front surges entering the station and passing to earth through its ground electrodes.²

1.2 Relation to Other Standards. This guide only briefly discusses the field tests required to evaluate soil resistivity. The procedures for measuring the resistance of the installed grounding system, the surface gradients, and the continuity of the grid conductors are described in more detail in ANSI/IEEE Std 81-1983 [3].³

ANSI/IEEE Std 142-1982 [5] generally takes its recommended grounding practices from this guide. Also known as “The IEEE Green Book,” it covers some of the practical aspects of grounding in more detail, such as equipment grounding, cable routing to avoid induced ground currents, cable sheath grounding, static and lightning protection, indoor installations, etc. However, as such, it refers to the previous edition of this guide.

IEEE Std 367-1979 [9] 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.

Finally, a guide that is presently being developed by the IEEE Power Generation Committee's Working Group on Generator Station Grounding Practices will give more detailed information on specific generating plant grounding problems. These include stack and cooling tower grounding, building grounds, etc. See 1.5.

1.3 Key Definitions. Most of the definitions given herein pertain solely to the applications of this guide, though those approved or standardized by other bodies

² The 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 or 60 Hz currents.

³ The numbers in brackets correspond to those of the references listed in 1.4.

are used whenever possible. No further reference will be made to any of the key definitions stated below, unless necessary for clarity. All other definitions are placed within the text of individual sections. An alphabetical index of all definitions used is given in Appendix F. For additional definitions refer to ANSI/IEEE Std 100-1984 [4].

In spite of the fact that grounding concepts are generally well understood, some design solutions are more a reflection of a routine rather than of a well-conceived design approach. For this reason, the following point is made prior to the first definition: No ground current or ground fault current will flow into the earth unless at least one ground return circuit exists. This return circuit enables the current produced by a source, however distant, to return through the earth to that source. The definition of a *ground return circuit* is primary, and all other *ground* related definitions are secondary, following from it.

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.

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 referred to is provided with ground 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.

initial 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. Generally,

$$I_{f(0+)} = 3I_0'' \quad (\text{Eq 1})$$

where

$I_{f(0+)}$ = initial symmetrical ground fault current

I_0'' = rms value of zero-sequence symmetrical current that develops immediately after the instant of fault initiation, that is, reflecting the sub-transient reactances of rotating machines contributing to the fault

NOTE: Elsewhere in the guide, this initial 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.

decrement factor. An adjustment factor used in conjunction with the initial symmetrical ground fault current parameter in safety-oriented grounding calcula-

tions. It allows us to obtain an rms equivalent of the asymmetrical current wave for a given fault duration, 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 entire interval of fault duration. (See Fig 1.)

NOTE: In terms of this guide, it can be expressed as

$$I_F = D_f(t_f) I_f \quad (\text{Eq 2})$$

where

I_F = effective asymmetrical fault current in A
 I_f = (initial) symmetrical ground fault current in A
 $D_f(t_f)$ = decrement factor accounting for the effect of a dc offset during the subtransient period of fault current wave on an equivalent time basis of the entire fault duration, t_f , for t_f given in s

1.4 References. The following publications shall be used in conjunction with this standard.

- [1] ANSI C2-1984, National Electrical Safety Code (note particularly Rule 93C).⁴
- [2] ANSI/ASTM D448-80, Specifications for Standard Sizes of Coarse Aggregate for Highway Construction.⁵
- [3] ANSI/IEEE Std 81-1983, IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System — Part I: Normal Measurements.
- [4] ANSI/IEEE Std 100-1984, IEEE Standard Dictionary of Electrical and Electronics Terms.
- [5] ANSI/IEEE Std 142-1982, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems.
- [6] ANSI/IEEE Std 837-1984, IEEE Standard for Qualifying Permanent Connections Used in Substation Grounding.
- [7] ANSI/IEEE C37.010-1979, IEEE Application Guide for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.
- [8] ANSI/IEEE C57.12.00-1980, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power and Regulating Transformers.

⁴ ANSI publications are available from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY, 10018.

⁵ ANSI/ASTM publications are available from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY, 10018 and the Sales Department, American Society of Testing and Materials, 1916 Race St, Philadelphia, PA 19103.

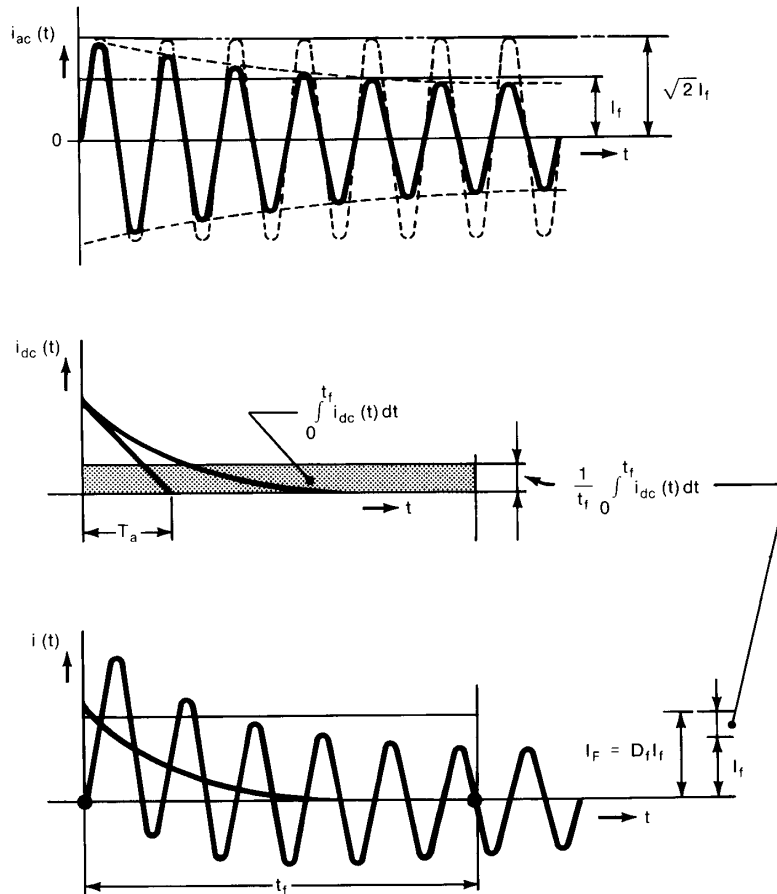


Fig 1
Relationship Between Actual Values of Fault Current and Values of I_F , I_f , and D_f for Fault Duration t_f

[9] IEEE Std 367-1979, IEEE Guide for the Maximum Electric Power Station Ground Potential Rise and Induced Voltage from a Power Fault.⁶

[10] IEEE Std 590-1977, IEEE Cable Plowing Guide.

⁶ IEEE publications are available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, Piscataway, NJ 08854.

2. Safety in Grounding

2.1 Basic Problem. In principle, a safe grounding design has two objectives:

(1) 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

(2) 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:

(1) The intentional ground, consisting of ground electrodes buried at some depth below the earth surface

(2) 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 object grounded, however crudely, can be safely touched. This misconception probably contributed to accidents in the past, as a low station 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 station of relatively low ground resistance may be dangerous under some circumstances⁷, while another station 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. A substantial part of the total ground fault current enters the earth causing an often steep rise of the local ground potential; Fig 2(a).

If a shield 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; Fig 2(b).

In either case, the effect of that portion of fault current that enters the earth within the station 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 surface, the grounding system may be inadequate despite its capacity to carry the fault current in magnitudes and durations permitted by protective relays.

⁷ One exception is the case in which the product of the maximum grid current I_G flowing in the earth via the grounding system resistance R_g results in a voltage low enough to be contacted safely.

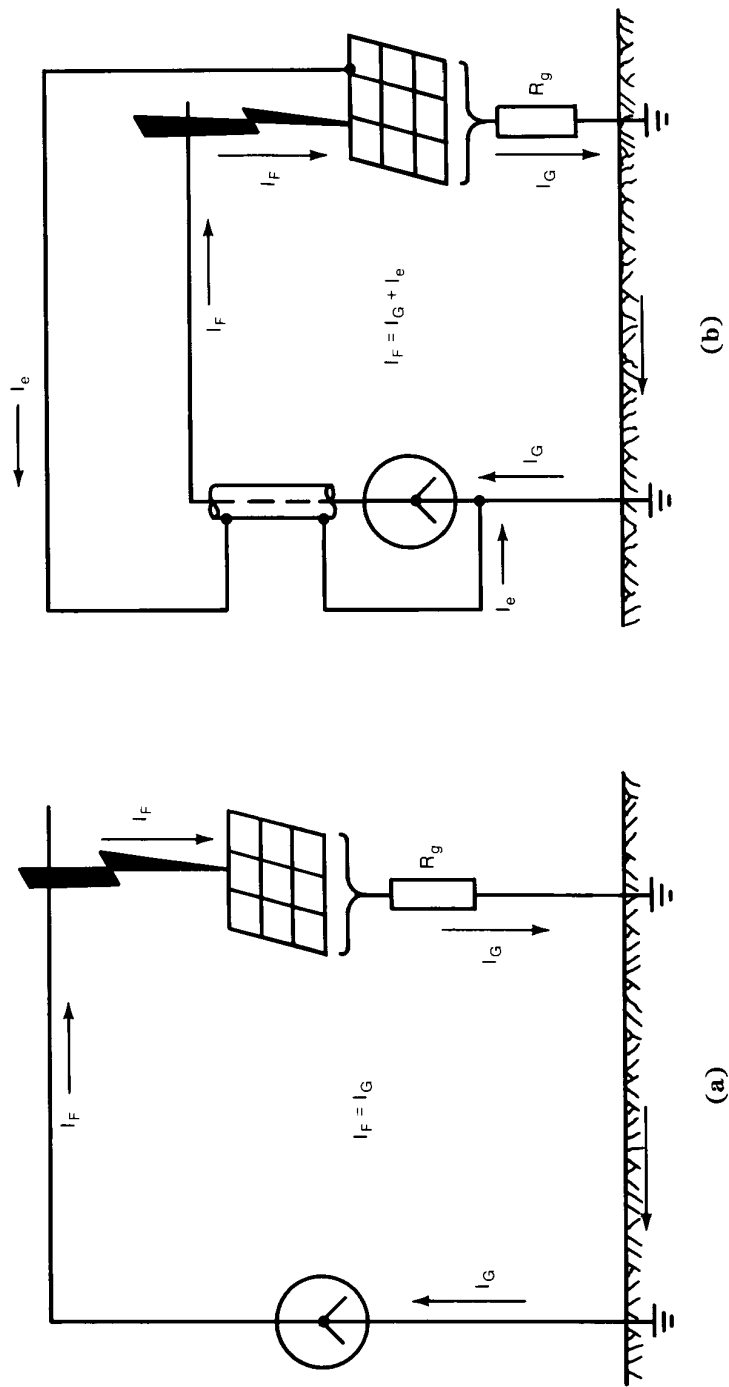
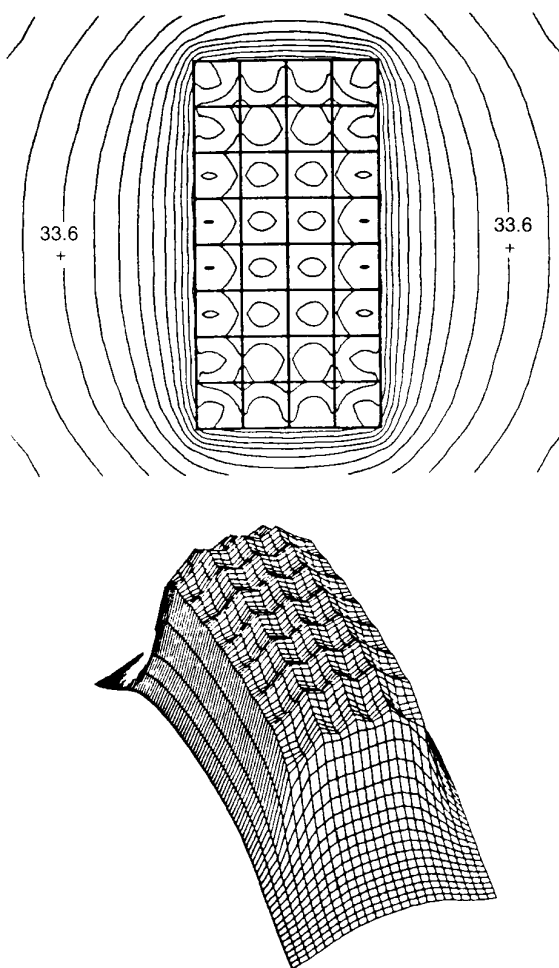


Fig 2
Typical Faulted Substation With and Without Multiple Ground Return Paths

The following Sections 3-6 cover in detail those principal assumptions and criteria that enable us to evaluate all necessary factors in protecting the most precious element of the accidental circuit, human life.

2.2 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 station with a simple rectangular grounding grid in homogeneous soil.

Fig 3
Equipotential Contours of a Typical Grounding Grid
With and Without Ground Rods



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

The circumstances that make electric shock accidents possible are:

- (1) Relatively high fault current to ground in relation to the area of ground system and its resistance to remote earth
- (2) Soil resistivity and distribution of ground currents such that high potential gradients may occur at points at the earth surface
- (3) Presence of an individual at such a point, time, and position that the body is bridging two points of high potential difference
- (4) Absence of sufficient contact resistance or other series resistance to limit current through the body to a safe value under the above circumstances
- (5) 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 of the type being studied, as compared to accidents of other kinds, is due largely to the low probability of coincidence of all the unfavorable conditions mentioned above.⁸

Nevertheless, some fatalities due to gradients have occurred in the past. Therefore, it is the responsibility of the engineer to lower this possibility.

⁸ German Grounding Standard DIN 57141 (1977 edition) recognizes this low probability and allows reduction for grounding calculations of a given fault current magnitude by a certain factor. For instance, a 0.7 value is recommended for stations of 110 kV class and above.

3. 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.

3.1 Effect of Frequency. Humans are very vulnerable to the effects of electric current at frequencies of 50 or 60 Hz. Currents of approximately 0.1 A can be lethal. Authorities generally agree 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 [B28], [B30]⁹. In some cases the human body is able to tolerate very high currents due to lightning surges.

Detailed studies of the effects of both direct and oscillatory impulse currents are reported in the literature [B19], [B21].

Information regarding special problems of dc grounding is contained in the 1958 Report of the Conversion Substation Committee [B16]. The hazards of an electric shock produced by the electrostatic effects of overhead transmission lines are reviewed in Part 1 of the 1971 Report of the General Substations Subcommittee [B59]. Additional information on the electrostatic effects of overhead transmission lines can be found in Chapter 8 of the *Transmission Line Reference Book 345 kV and Above* (the EPRI Red Book) [B46].

3.2 Effects of Magnitude and Duration. The most common physiological effects of electric current on the body, stated in order of increasing current magnitude, are perception, muscular contraction, unconsciousness, fibrillation of the heart, respiratory nerve blockage, and burning [B53].

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 [B21].

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 [B29].

In a 9–25 mA range, currents may be painful and can make it hard or impossible to release energized objects grasped by the hand. For still higher currents

⁹ The numbers in brackets with the prefix B refer to those of the bibliography in Chapter 20.

muscular contractions could make breathing difficult. Unlike the cases of respiratory inhibition from the much greater current mentioned next, these effects are not permanent and disappear when the current is interrupted — unless the contraction is very severe and breathing is stopped, not for seconds, but for minutes. Yet even such cases often respond to resuscitation [B25].

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 should administer CPR until the victim can be treated at a medical facility [B27].

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 [B26], [B29], 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:

$$(I_B)^2 t_s = S_B \quad (\text{Eq 3})$$

where

I_B = rms magnitude of the current through the body

t_s = duration of the current exposure in s

S_B = empirical constant related to the electric shock energy tolerated by a certain percent of a given population

A more detailed discussion of this equation is provided in Section 4.

3.3 Importance of High-Speed Fault Clearing. Considering the significance of fault duration both in terms of Eq 3 and implicitly as an accident-exposure factor, high-speed clearing of ground faults is advantageous for two reasons:

(1) The probability of 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

(2) Both 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 back-up protection

A good case could be made for the former because of the low combined probability that relay malfunctions will coincide with all other adverse factors necessary for an accident, as has already been described in Section 2.

If the probabilistic aspects are neglected, choice of the backup relay clearing times is more conservative since it assures greater safety margins with regard to Eq 3.

An additional incentive to use switching times less than 0.5 s results from the research done by Biegelmeier and Lee [B8]. 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 this cause still more so. Furthermore, both events are often of very short duration. Thus, it would not be practical to design against shocks that are merely painful and cause no serious injury, that is, for currents below the fibrillation threshold.

4. Permissible Body Current Limit

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

4.1 Duration Formula. The duration for which a 50–60 Hz current can be tolerated by most people is related to its magnitude by Eq 3. Based on the results of Dalziel's studies, it is assumed that 99.5% of all persons can safely withstand, without ventricular fibrillation, the passage of a current in magnitude and duration determined by the following formula:

$$I_B = k/\sqrt{t_s} \quad (\text{Eq 4})$$

where, in addition to the terms previously defined, for Eq 3,

$$k = \sqrt{S_B}$$

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

$$I_B = 0.116/\sqrt{t_s} \quad \text{for 50 kg body weight} \quad (\text{Eq 5})$$

Note that the above equation results in values of 116 mA for 1 s and 367 mA for 0.1 s.

Since Eq 4 is based on tests limited to a 0.03–3.0 s range, it obviously is not valid for very short or long times, and some values of current can be tolerated indefinitely [B20], [B24].

In a perspective of the past 40 years of researching I_B , in 1936 Ferris *et al.* [B49] suggested 100 mA as the fibrillation threshold if shock durations are not specified. The value 100 mA was derived from extensive experience at Columbia University, on animals having body and heart weights comparable to man, for a maximum shock duration of 3 s. Some of the more recent experiments suggest the existence of two distinct thresholds: one where the exposure time is shorter than one heartbeat period and another one for the current exposure longer than one heartbeat. For a 50 kg (110 lbs) adult, Biegelmeier proposes the threshold values at 500 and 50 mA, respectively [B6], [B7]. Other recent works on this subject are by Lee and Kouwenhoven [B27], [B65], [B68].

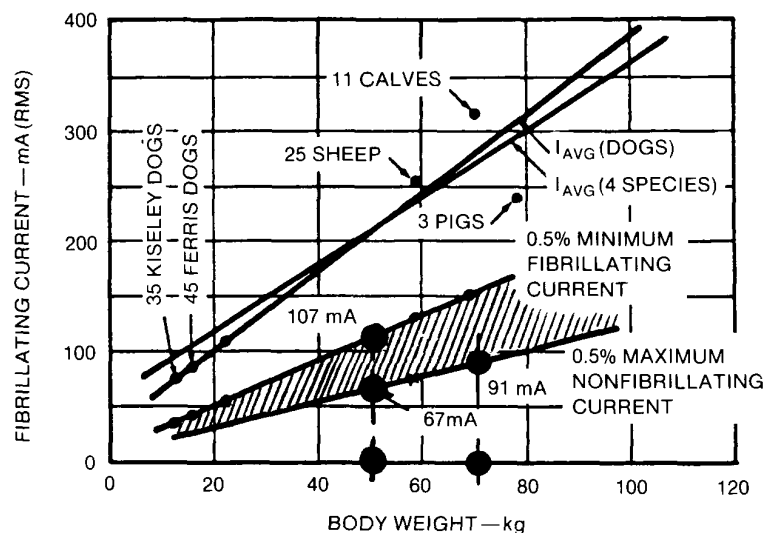
4.2 Alternative Assumptions. Fibrillation current is actually a function of individual body weight, as illustrated in Fig 4. This shows the relationship between the critical current and body weight for several species of animals (calves, dogs, sheep, pigs), and a 0.5% common threshold region for mammals.

In the 1961 edition of this guide, constants S_B and k in Eqs 3 and 4, given as 0.0272 and 0.165, respectively, had been assumed valid for 99.5% of all men weighing approximately 70.3 kg (155 lbs). Dalziel's more recent studies (in 1968), on which Eq 4 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 lbs) [B22], [B24]. Thus,

$$I_B = 0.157/\sqrt{t_s} \text{ for 70 kg body weight} \quad (\text{Eq 6})$$

The maximum 3 s nonfibrillating current of 91 mA at the 70 kg base is still below the threshold of fibrillation of 107 mA at 50 kg (110 lbs), as shown in Fig 4.

Fig 4
Fibrillating Current Versus Body Weight for Various Animals
Based on a Three-Second Shock



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

Users of this guide may select $k = 0.157$ provided that the average population weight can be expected to be at least 70 kg.¹⁰

Equation 4 indicates that much higher currents can be allowed where fast operating protective devices can be relied upon to limit fault duration. A judgment decision is needed as to whether to use the clearing time of regular high-speed relays, or that of the back-up protection, as the basis for calculation.

4.3 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, which would not permanently injure him, but would upset and disturb him temporarily. Next, a single fast automatic reclosure could result in a second shock, initiated within less than 0.5 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 since 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. This is discussed in more detail in 13.4.

¹⁰ 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 (Eq 5) ought to be used for areas outside the fence.

5. Accidental Ground Circuit

5.1 Resistance of the Human Body. For dc and ac at normal power frequency, the human body can be represented by a noninductive resistance. The resistance is between extremities, that is, from one hand to both feet, or from one foot to the other one. In either case, the value of this resistance is difficult to establish. The resistance of the internal body tissues, not including skin, is approximately 300 Ω , whereas values of body resistance including skin, ranging from 500–3000 Ω , have been suggested in the literature [B20], [B53], [B54], [B64], [B83].

As already mentioned in 3.2, Dalziel conducted extensive tests to determine safe let-go currents, with hands and feet wet, in salt water. Values obtained using 60 Hz for men were as follows: the current was 9.0 mA; corresponding voltages were, hand-to-hand, 21.0 V, and, hand-to-feet, 10.2 V. Hence, the ac resistance for a hand-to-hand contact is equal to 21.0/0.009 or 2330 Ω and the resistance hand-to-feet equals 10.2/0.009 or 1130 Ω , based on this experiment [B29].

For higher voltages (above 1 kV) and currents (above 5 A), the human resistance is decreased by damage or puncture of the skin at the point of contact. However, a wet hand contact resistance may be very low at any voltage. The resistance of shoes is uncertain, though it may be very low for damp leather.

Thus, for the purposes of this guide:

- (1) Hand and shoe contact resistances will be assumed as equal to zero
- (2) A value of 1000 Ω is selected for the calculations that follow as representing the resistance of a human body from hand-to-both-feet and also from hand-to-hand, or from one foot to the other foot:

$$R_B = 1000 \Omega \quad (\text{Eq 7})$$

5.2 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 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 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, stating that the ratio is as high as 25:1 [B69].

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.

(1) A voltage between the two feet, painful but not fatal, might result in a fall that could cause a current flow through the chest area. The degree of this danger would further depend on the fault duration and the possibility of another, successive fault — perhaps on reclosure.

(2) 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 the former, it is a hazard that should not be ignored [B10], [B66].

5.3 Accidental Circuit Equivalents. Using the value of tolerable body current established by Eq 5 or 6 and the appropriate circuit constants, it is possible to determine the tolerable voltage between any two critical points of contact.

Let it be noted that for the accidental circuit equivalent, the following notation applies:

- I_A = current through the accidental circuit
- R_A = total effective resistance of the accidental circuit
- I_B = permissible body current, defined by Eq 5 or 6

Obviously,

$I_A < I_B$ is always required for safety

Since the body resistance is assumed constant, to require $I_A < I_B$ is equivalent to saying that fibrillation may be prevented by keeping the total watts-seconds (Ws) of energy absorbed in the body during a shock below a certain value. This value is 0.0135 Ws for $k_{50} = 0.116$ A, and 0.0246 Ws for $k_{70} = 0.157$ A, respectively. Thus, it can be seen that Dalziel's formula actually represents the relationship between shock current magnitude and duration for a constant shock energy.

Resistance of the accidental circuit R_A is a function of the body resistance R_B and the footing resistance R_F (resistance of the ground just beneath the feet). The footing resistance may affect appreciably the value of R_A , a fact that may be most helpful in some difficult situations. For the purposes of circuit analysis, the human foot is usually represented as a conducting metallic disk and the contact resistance of shoes and socks is neglected. As shown by Sunde [B98], the self and mutual resistances for two metallic disks of radius b , separated by a distance d_F on the surface of a homogeneous earth of resistivity ρ , are:

$$R_{\text{foot}} = \rho/(4b) \quad (\text{Eq 8})$$

$$R_{M\text{foot}} = \rho/(2\pi d_{\text{foot}}) \quad (\text{Eq 9})$$

where

- R_{foot} = self-resistance of each foot to remote earth in Ω
- $R_{M\text{foot}}$ = mutual resistance between the feet in Ω
- b = equivalent radius of a foot in m
- d_{foot} = separation distance of the feet in m

The resistances of the ground beneath the two feet in series and in parallel are:

$$R_{2Fs} = 2 (R_{\text{foot}} - R_{M\text{foot}}) \quad (\text{Eq 10})$$

$$R_{2Fp} = \frac{1}{2} (R_{\text{foot}} + R_{M\text{foot}}) \quad (\text{Eq 11})$$

where, in addition to the symbols described above,

R_{2Fs} = resistance of two feet in series

R_{2Fp} = resistance of two feet in parallel

Figure 5 defines the circuit equivalent of a foot-to-foot contact. Here the potential U , shunted by the body, is the maximum potential difference between two accessible points on the ground surface, separated by the distance of one pace. The equivalent circuit resistance for the step potential circuit is given by Eq 12:

$$R_A = R_B + 2 (R_{\text{foot}} - R_{M\text{foot}}) \quad (\text{Eq 12})$$

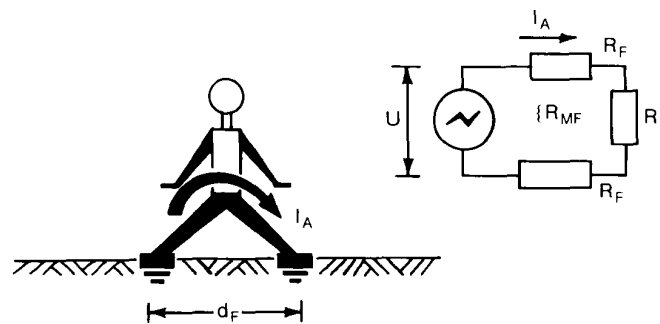
Next, the equivalent circuit for a hand-to-two-feet contact is illustrated in Fig 6.

The equivalent circuit resistance for the touch potential circuit is given by Eq 13:

$$R_A = R_B + \frac{1}{2} (R_{\text{foot}} + R_{M\text{foot}}) \quad (\text{Eq 13})$$

Bibliographic references [B10], [B43], [B59], and [B66] choose a 0.08 m (3 in) radius for the disk representing one foot and neglect the mutual resistance term.

Fig 5
Step Voltage Circuit



$$\begin{aligned} d_F &= 1 \text{ m} \\ R_A &= R_B + 2R_F - 2R_{MF} \\ I_A &= U/R_A \\ R_B &= 1000 \, \Omega \end{aligned}$$

where

I_A = the current of accidental circuit
 R_A = the total resistance of accidental circuit

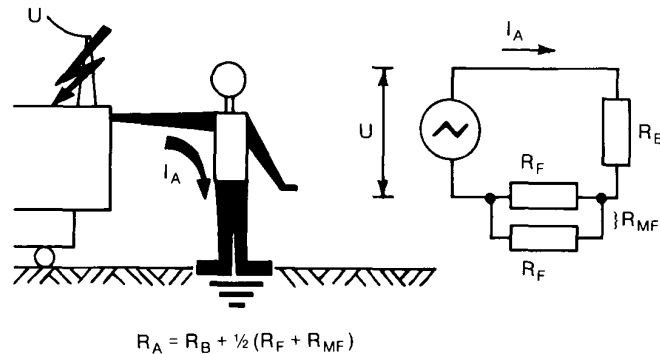


Fig 6
Touch Voltage Circuit

With only slight approximation, equations for the series and parallel resistances of two feet can be obtained in numerical form and expressed in terms of ρ , as shown below:

$$R_{2Fs} = 6(\rho) \quad (\text{Eq 14})$$

$$R_{2Fp} = 1\frac{1}{2}(\rho) \quad (\text{Eq 15})$$

Therefore, for all practical purposes, the resistance of a foot is equal to 3ρ . Equation 14 is used when computing the body current resulting from step voltages and Eq 15 applies when calculating the body current produced by a mesh or touch potential with both feet *buried* at zero depth in the soil near the surface.

For example, if $\rho = 2000 \Omega\text{-m}$, Eqs 14 and 15 yield 12 000 and 3000 Ω for the series and parallel resistances, respectively.

A more exact calculation of the self and mutual resistances using 1 m separation yields $R_{2Fs} = 11863 \Omega$ and $R_{2Fp} = 3284 \Omega$. Use of a value of $d_{\text{foot}} = 1 \text{ m}$ is conservative in calculating R_{2Fs} . Though it might produce a slightly higher value of resistance than would a smaller separation between the feet, the resulting step voltage also is much higher with a larger separation than it would be with a smaller one, and that would be the dominant effect on body current.

The large separation is also conservative in computing R_{2Fp} because it produces a lower resistance than a small separation would.

5.4 Effect of a Thin Surface Layer of Crushed Rock. Equations 8 and 9 are derived based on the assumption of uniform soil resistivity. However, a 0.08–0.15 m (3–6 in) layer of crushed rock is often spread on the earth's surface above the ground grid to increase the contact resistance between the soil and the feet of people in the substation. The crushed rock also improves the surface for the movement of equipment and vehicles in the substation. The area covered by this crushed rock layer is generally of sufficient size to validate the assumption of the

feet being in contact with a material of uniform resistivity in the lateral direction. However, the relatively shallow depth of the crushed rock as compared to the equivalent radius of the foot precludes the assumption of uniform resistivity in the vertical direction when computing the self and mutual resistances of the feet.

If the underlying soil has a lower resistivity than the crushed rock, only some grid current will go upward into the thin upper layer of crushed rock, and the surface voltage will be very nearly the same as that without the rock layer. The current through the body will be lowered considerably with the addition of the crushed rock surface because of the greater contact resistance between the earth and the feet. However, this resistance may be considerably less than that of a crushed rock layer of great thickness (that is, thick enough to assume uniform resistivity in all directions). How much less depends on the relative values of earth and crushed rock resistivities and in the thickness of the rock layer. A typical case described in the literature shows that the effective resistance of a 0.25 m layer of limestone having a 5000 Ω -m (wet) resistivity is roughly equivalent to 75% of its nominal value if the resistivity of the earth's soil is 250 Ω -m [B58].

The following equations for R_{foot} and $R_{M\text{foot}}$ are derived from [29]:

$$R_{\text{foot}} = \frac{\rho_1}{4b} F(X_1) \quad (\text{Eq 16})$$

$$R_{M\text{foot}} = \frac{\rho_1}{2\pi d_{\text{foot}}} F(X_2) \quad (\text{Eq 17})$$

In Eqs 16 and 17, b and d_{foot} are defined in 5.3 and $F(X)$ is a function based on the feet spacing and the relative values of the earth and crushed rock resistivities:

$$F(X) = 1 + 2 \sum_{n=1}^{\infty} Q \quad (\text{Eq 18})$$

$$Q = \frac{K^n}{\sqrt{1 + (2nX)^2}} \quad (\text{Eq 19})$$

$$K = \frac{\rho - \rho_s}{\rho + \rho_s} \quad (\text{Eq 20})$$

where

- ρ_s = crushed rock resistivity in Ω -m
- ρ = earth resistivity in Ω -m
- $X = X_1 = h_s/b$ for R_{foot}
- $X = X_2 = h_s/d_{\text{foot}}$ for $R_{M\text{foot}}$
- h_s = thickness of the crushed rock surface layer in m

These equations could also be derived by applying the method of images to Sunde's equations in [B98]. However, since the quantity $F(X)$ is rather tedious to evaluate without a computer or programmable calculator, these values have been

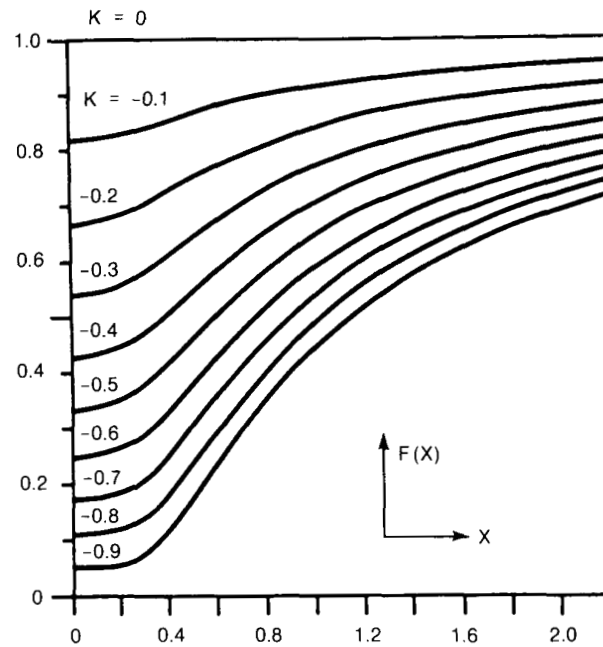


Fig 7
Function $F(X)$ Versus X and Reflection Factor K

precalculated and graphed for a wide range of values (X) and factor K , as shown in Fig 7.

Example 1. Let a layer of surface material be 0.1 m (4 in) thick, and have the nominal resistivity of 2000 Ω -m; the underlying soil resistivity is 222 Ω -m, $b = 0.08$ m, and $d_{\text{foot}} = 1$ m. From these data it follows that $K = -0.80$, $X_1 = 1.25$, and $X_2 = 0.1$. Using Fig 7, one can find $F(X_1) = 0.57$ and $F(X_2) = 0.11$. Substitute into Eqs 16 and 17: $R_{\text{foot}} = 3562 \Omega$ and $R_{M\text{foot}} = 35 \Omega$. Finally, using Eqs 10 and 11 one obtains $R_{2Fs} = 7054 \Omega$ and $R_{2Fp} = 1798 \Omega$.

In order to simplify the above procedure for routine use, the mutual resistance term can be neglected and b assumed always equal to 0.08 m. On this basis, the equations for the series and parallel resistances of two feet can alternatively be expressed in a form that is analogous to that of Eqs 14 and 15, used for uniform soil:

$$R_{2Fs} = 6.0 C_s (h_s, K) \rho_s \quad (\text{Eq 21})$$

and

$$R_{2Fp} = 1.5 C_s (h_s, K) \rho_s \quad (\text{Eq 22})$$

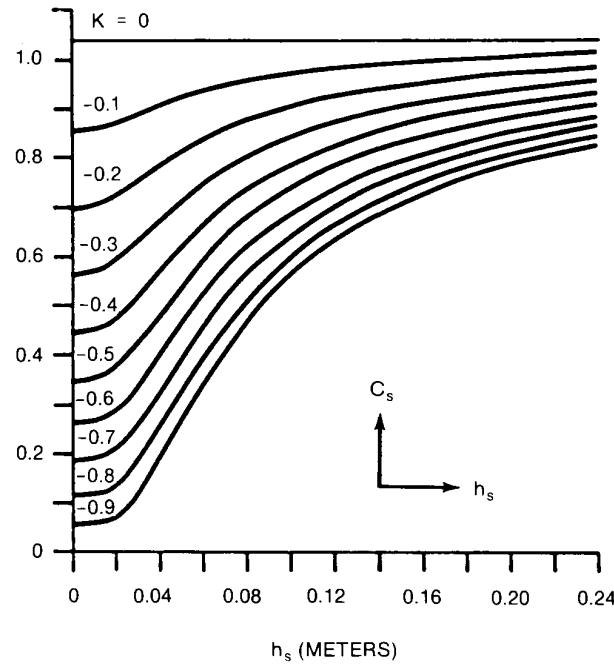


Fig 8
Reduction Factor C_s As a Function of Reflection Factor K and
Crushed Rock Layer Thickness h_s

where

C_s = reduction factor for derating the nominal value of surface layer resistivity determined as follows:

$C_s = 1$ for crushed stone resistivity equal to soil resistivity

Otherwise,¹¹

$$C_s = \frac{1}{0.96} \left[1 + 2 \sum_{n=1}^{\infty} \frac{K^n}{\sqrt{1 + (2n h_s / 0.08)^2}} \right]$$

For the latter case of $C_s < 1$, in which C_s is a function of (h_s, K) and which distinguishes Eqs 21 and 22 from Eqs 14 and 15, the values of C_s are plotted in Fig 8.

¹¹ Simple alternative approaches, based on the equivalent hemisphere concept, such as

$$C_s \approx 1 - a \left[\frac{1 - \frac{\rho}{\rho_s}}{2h_s + a} \right] ; a = 0.106 \text{ m, which avoids the infinite summation series, are also possible;}$$

refer to pp 14-15 of [B100] and to Jackson's discussion of Sverak's equations on p 19 of the same reference.

Example 2. For the same resistivity data used in Example 1, and also assuming again $h_s = 0.1$ m, and $K = -0.8$, factor C_s can be found from Fig 7. Here, C_s is determined to be approximately 0.6. R_{2Fs} is 7200 Ω and R_{2Fp} is 1800 Ω .

The converse of the derating principle is also true. If the underlying soil has a higher resistivity than the crushed rock, a substantial portion of the grid current will go upward into the thin layer of crushed rock. However, unlike the case described above, the surface potentials will be altered substantially, due to this concentration of current near the surface. Although Eqs 16 and 17 are valid for computing the self and mutual resistances of the feet even if the soil has a higher resistivity than the crushed rock, these equations do not account for the alteration of the surface potentials. Thus, the effective resistivity of the crushed rock 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 Section 11).

6. Criteria of Permissible Potential Difference

6.1 Typical Shock Situations. Figures 9 and 10 show four basic situations involving a person and grounded facilities during a fault. For a foot-to-foot contact the accidental circuit equivalent is that of Fig 5, and its driving voltage U is equal to E_s (step voltage). For the three remaining examples of a hand-to-both-feet contact, Fig 6 applies, and U is equal to E_t (touch voltage), E_m (mesh voltage), or E_{trrd} (transferred voltage), respectively.

During a fault, the earth becomes saturated by the currents emanating from the grid and other permanent ground electrodes buried below the earth surface. The resulting potential gradients have a primary effect on the value of U .

For clarity, let the following be defined:

ground potential rise (GPR). The maximum voltage that a station grounding grid may attain relative to a distant grounding point assumed to be at the potential of remote earth.

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 station grounding grid into the earth causes the rise of the grid potential with respect to remote earth. This voltage rise, GPR, is proportional to the magnitude of the grid current, and to the grid resistance.

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

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 his hands in contact with a grounded structure.

NOTE: 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, which is of concern in the gas-insulated substations, both situations should be investigated for the possible worst reach condition, including both hands; Fig 11.

mesh voltage. The maximum touch voltage to be found within a mesh of a ground grid.

transferred voltage. A special case of the touch voltage where a voltage is transferred into or out of the substation.

Typically, the case of transferred voltage occurs when a person standing within the station area touches a conductor grounded at a remote point or a person

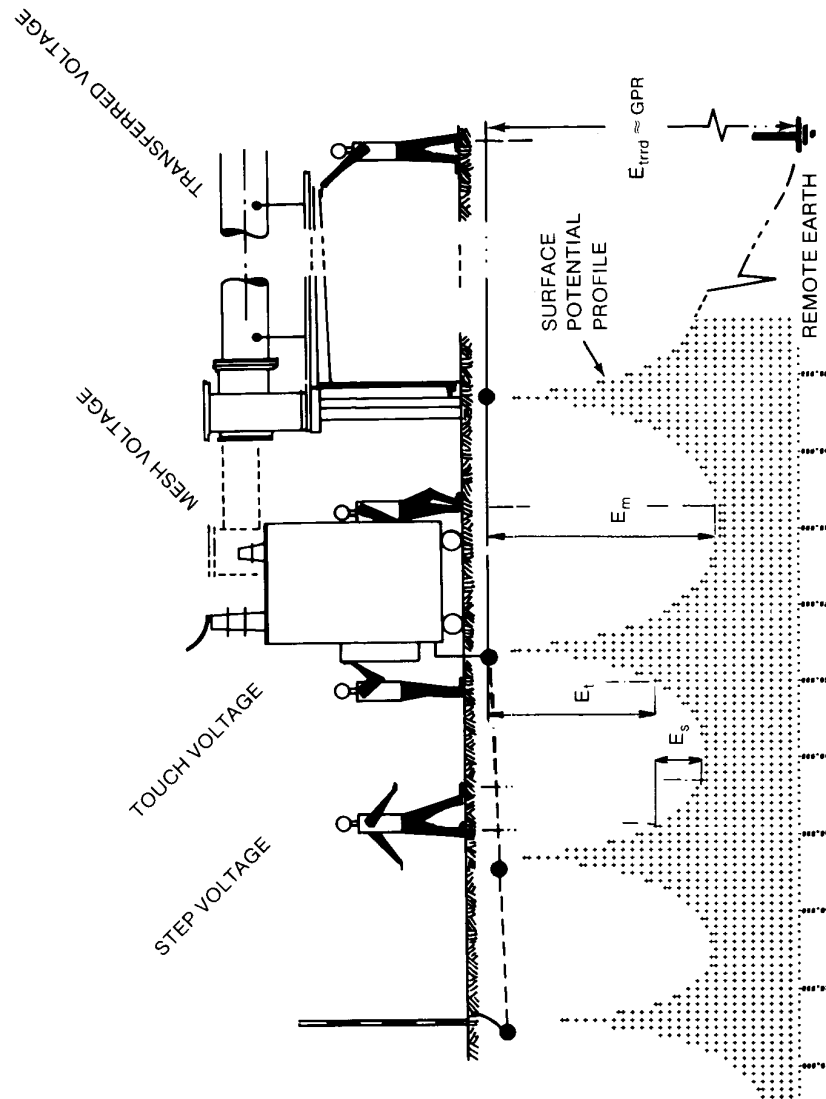


Fig 9
Basic Shock Situations

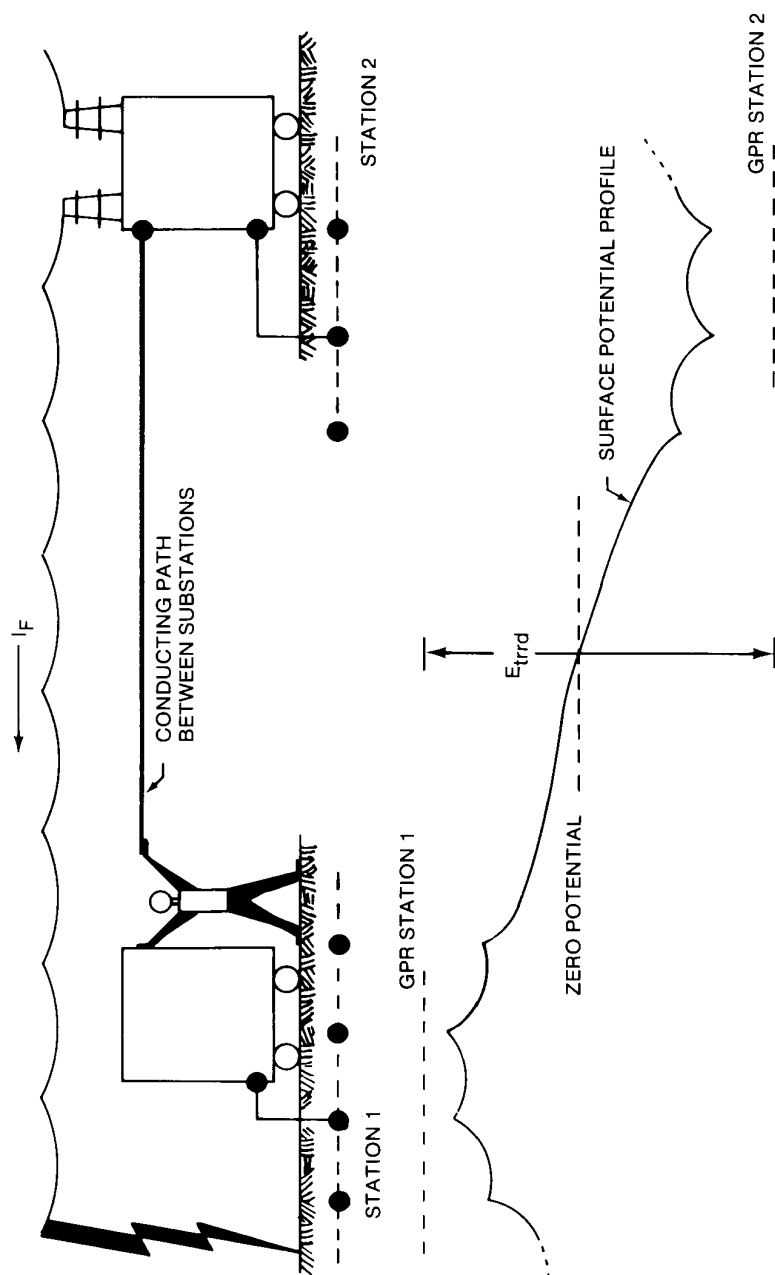


Fig 10
Typical Situation of External Transferred Potential

standing at a remote point touches a conductor connected to the station 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 Fig 10). In fact, as discussed in Section 15, the transferred voltage may exceed the sum of the GPR's 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 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 *live* lines.

6.2 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 below. For step voltage the limit is

$$E_{\text{step}} = (R_B + R_{2Fs}) I_B \quad (\text{Eq 23})$$

Combining Eqs 23, 21, 7, and either 5 or 6,

$$E_{\text{step}_{50}} = (1000 + 6C_s(h_s, K) \rho_s) 0.116 / \sqrt{t_s} \quad (\text{Eq 24})$$

or

$$E_{\text{step}_{70}} = (1000 + 6C_s(h_s, K) \rho_s) 0.157 / \sqrt{t_s} \quad (\text{Eq 24a})$$

The actual step voltage, E_s , should be less than the maximum allowable step voltage, E_{step} , to ensure safety. Similarly, the touch voltage limit is

$$E_{\text{touch}} = (R_B + R_{2Fp}) I_B \quad (\text{Eq 25})$$

Combining Eqs 25, 22, 7, and either 5 or 6,

$$E_{\text{touch}_{50}} = (1000 + 1.5C_s(h_s, K) \rho_s) 0.116 / \sqrt{t_s} \quad (\text{Eq 26})$$

or

$$E_{\text{touch}_{70}} = (1000 + 1.5C_s(h_s, K) \rho_s) 0.157 / \sqrt{t_s} \quad (\text{Eq 26a})$$

where

C_s = 1 for no protective surface layer or is determined from Fig 8 if a protective surface layer of high resistivity and small thickness is used

ρ_s = the resistivity of the surface material in $\Omega\text{-m}$

t_s = duration of shock current in s

The actual touch voltage, mesh voltage, or transferred voltage should be less than the maximum allowable touch voltage, E_{touch} , to ensure safety.

6.3 Typical Shock Situations for Gas-Insulated Substations. In the grounding analysis of gas-insulated substations (GIS), the touch voltage considerations pre-

sent 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. Since 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 station 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.

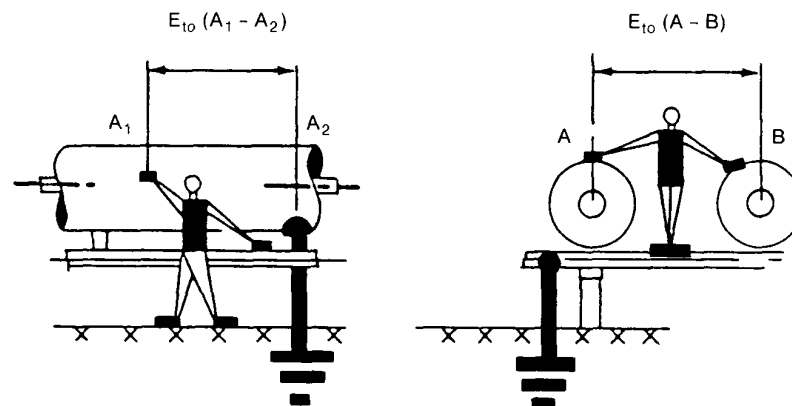
A person touching the outer sheath of a GIS might be exposed to voltages resulting from two basic fault conditions:

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

Since 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 an additional problem — that of the permissible touch voltage for a metal-to-metal contact; Fig 11.

Most GIS manufacturers consider the enclosure properly designed and adequately grounded if the potential difference between individual enclosures and, with respect to the voltage level of other grounded structures, does not exceed 65–130 V during a fault. As shown below, the substitution of $\rho = 0$ in the foot

Fig 11
Typical Metal-to-Metal Touch Situations in GIS



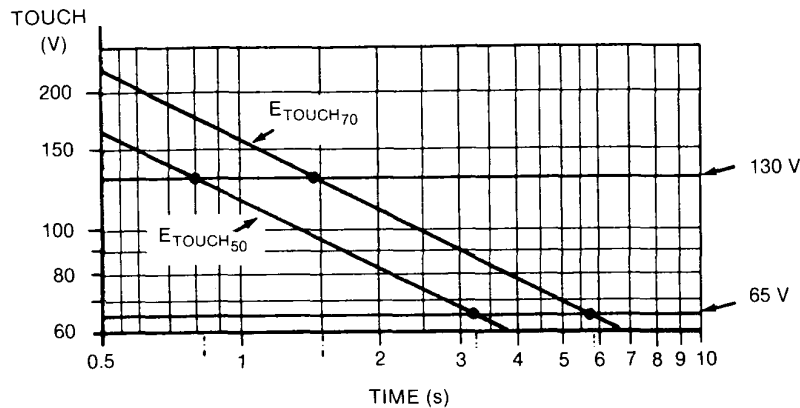


Fig 12
Touch Voltage Limits for Metal-to-Metal Contact and a Typical Range of Enclosure Voltages to Ground

resistance terms of Eqs 26 and 26a reveals that this voltage range corresponds to fault times ranging from 0.8–3.2 s if a 50 kg criterion is used, and ranging from 1.46–5.8 s for the assumption of a 70 kg body. This relationship is, however, better perceived in the graphical form of Fig 12, which also helps to grasp the related problem of sufficient safety margins.

The reduced equations for a metal-to-metal contact are:

$$E'_{touch_{50}} = 116/\sqrt{t_s} \quad (\text{Eq 27})$$

and

$$E'_{touch_{70}} = 157/\sqrt{t_s} \quad (\text{Eq 28})$$

The fault conditions and the corresponding circuit equivalents for determining or verifying the critical safety design parameters of GIS grounding will be discussed in more detail in Section 8 and Appendix D.

6.4 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 short-circuit 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.