

IEEE Guide for Generating Station Grounding

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Abstract: Grounding practices that have generally been accepted by the electric utility industry as contributing to effective grounding systems for personnel safety and equipment protection in generating stations are identified. A guide for the design of generating station grounding systems and for grounding practices applied to generating station indoor and outdoor structures and equipment, including the interconnection of the station and substation grounding systems, is provided.

Keywords: electric utilities, generating stations, grounding, grounding systems, personnel safety, substation grounding systems

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Introduction

(This introduction is not part of IEEE Std 665-1995, IEEE Guide for Generating Station Grounding.)

This guide is intended to complement the recommendations and information presented in existing grounding practices for industrial and commercial power systems (IEEE Std 142-1991, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems), substations (IEEE Std 80-1986, IEEE Guide for Safety in AC Substation Grounding), and measurements (IEEE Std 81.2-1991, IEEE Guide for Measurement of Impedance and Safety Characteristics of Large, Extended or Interconnected Grounding Systems), while drawing particular attention to specific requirements for generating stations.

This guide was prepared by a Task Force of the Grounding Practices Working Group. The working group is part of the Station Design Subcommittee and was sponsored by the Energy Development and Power Generation Committee of the IEEE Power Engineering Society. Comments were also solicited from the following groups:

- National Electric Safety Code® Committee
- Power System Communications Committee
- Power System Instrumentation and Measurements Committee
- Power System Relaying Committee
- Transmission and Distribution Committee
- Surge Protective Devices Committee
- Substation Committee
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IEEE Guide for Generating Station Grounding

1. Overview

This guide was developed to identify grounding practices that have generally been accepted by the electric utility industry as contributing to effective grounding systems for personnel safety and equipment protection in generating stations.

It provides a guide for the design of generating station grounding systems and for grounding practices applied to generating station indoor and outdoor structures and equipment, including the interconnection of the station and substation grounding systems. Guidance for the grounding of control and instrumentation equipment in generating stations can be found in IEEE Std 1050-1989.¹

Generating station grounding designs are complicated by considerations such as physically large outdoor areas with multiple buildings and associated transfer voltages, grounding effects of buried infrastructure, rotating electrical apparatus, large indoor areas, auxiliary systems with multiple voltage levels, and the need for increasingly “clean” signal ground sources for control systems. This guide has been developed in recognition that the complexities of generating stations are such that the generally accepted techniques and programs for the design of electrical substation grounding systems for safety may not address all of the issues. While these complexities may be suitably analyzed with the computerized methods that are available, this guide presents a manual calculation method based on the principles presented in IEEE Std 80-1986.

It is not intended that this document provide grounding test methods or quantitative analysis of the effects of lightning surges. This document should not be interpreted as requiring any specific design for a particular installation; instead, it is a guide to the process and special techniques that the designer should recognize and consider. The necessary supporting detail is to be found in other relevant standards and documents; these are referenced in the text where appropriate.

2. References

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

ANSI C2-1993, National Electrical Safety Code®.²

¹Information on references can be found in clause 2.

²The NESC® is available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

IEEE Std C37.101-1993, IEEE Guide for Generator Ground Protection (ANSI).³

IEEE Std C62.92-1987 (Reaff 1993), IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems, Part I—Introduction (ANSI).

IEEE Std C62.92.2-1989, IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems, Part II—Grounding of Synchronous Generator Systems (ANSI).

IEEE Std C62.92.3-1993, IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems, Part III—Generator Auxiliary Systems.

IEEE Std C62.92.4-1991, IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems, Part IV—Distribution (ANSI).

IEEE Std C62.92.5-1992, IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems, Part V—Transmission Systems and Subtransmission Systems (ANSI).

IEEE Std 80-1986 (Reaff 1991), IEEE Guide for Safety in AC Substation Grounding (ANSI).

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

IEEE Std 81.2-1991, IEEE Guide for Measurement of Impedance and Safety Characteristics of Large, Extended or Interconnected Grounding Systems (ANSI).

IEEE Std 100-1992, The New IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI).

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

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

IEEE Std 666-1991, IEEE Design Guide for Electric Power Service Systems for Generating Stations (ANSI).

IEEE Std 1050-1989, IEEE Guide for Instrumentation and Control Equipment Grounding in Generating Stations (ANSI).

IEEE Std 1100-1992, IEEE Recommended Practice for Powering and Grounding Sensitive Electronic Equipment (IEEE Emerald Book) (ANSI).

NFPA 50A-1994, Gaseous Hydrogen Systems at Consumer Sites.⁴

NFPA 77-1993, Static Electricity.

NFPA 780-1992, Lightning Protection Code.

³IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

⁴NFPA publications are available from Publications Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA.

3. Definitions

There is other terminology for grounding conductors used in the industry. Terminology provided for the purposes of this guide is demonstrated in the accompanying figures and in the following definitions:

3.1 bonding: The permanent joining of metallic parts to form an electrically conductive path that will ensure electrical continuity and the capacity to conduct safely any current likely to be imposed.

3.2 bonding jumper: A reliable conductor to ensure the required electrical conductivity between metal parts that need to be electrically connected.

3.3 equipment grounding conductor: The conductor used to connect the noncurrent-carrying metal parts of equipment, raceways, and other enclosures to the service equipment, the service power source(s) ground, or both.

3.4 four-wire system: A three-phase system consisting of three phase conductors and a neutral conductor.

3.5 generating station: A plant wherein electric energy is produced by conversion from some other form of energy (for example, chemical, nuclear, solar, mechanical, or hydraulic) by means of suitable apparatus. This includes all generating station auxiliaries and other associated equipment required for the operation of the plant. Not included are stations producing power exclusively for use with communications systems.

3.6 grid mesh: Any one of the open spaces enclosed by the grounding grid conductors.

3.7 ground grid: A system of horizontal ground electrodes that consists of a number of interconnected bare conductors buried in the earth, providing a common ground for electrical devices or metallic structures, usually in one specific location.

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

3.8 ground well: A hole with a diameter greater than an inserted ground rod, drilled to a specified depth, and backfilled with a highly conductive material. The backfill will be in intimate contact with the earth.

3.9 grounding conductor: A conductor used to connect equipment or the grounded circuit of a wiring system to a grounding electrode or electrodes (i.e., ground grid).

3.10 high-voltage system: An electric system having a maximum root-mean-square ac voltage above 72.5 kV.

3.11 isolated-phase bus: A metal-enclosed bus in which each phase conductor is enclosed by an individual metal housing separated from adjacent conductor housings by an air space.

3.12 metal-enclosed bus: An assembly of conductors with associated connections, joints, and insulating supports within a grounded metal enclosure.

3.13 neutral ground: An intentional ground applied to the neutral conductor or neutral point of a circuit, transformer, machine, apparatus, or system.

3.14 nonsegregated-phase bus: A metal-enclosed bus in which all phase conductors are in a common metal enclosure without barriers between the phases.

3.15 overhead ground wire: A grounded, bare conductor suspended horizontally between supporting rods or masts to provide protection from lightning strikes for structures, equipment, or suspended conductors within the zone of protection created by the combination of the masts and the overhead ground wire.

3.16 safety ground: The connection between a grounding system and metallic parts that are not usually energized but that may become live due to a fault or an accident; often referred to as equipment or frame ground.

3.17 substation: An enclosed assemblage of equipment (e.g., switches, circuit breakers, buses, and transformers) under the control of qualified persons, through which electric energy is passed for the purposes of switching or modifying its characteristics.

3.18 system ground: The connection between a grounding system and a point of an electric circuit (for example, a neutral point).

3.19 transferred voltage: That voltage between points of contact, hand to foot or feet, where the grounded surface touched is intentionally grounded at a remote point (or unintentionally touching at a remote point a conductor connected to the station ground system). Here the voltage rise encountered due to ground fault conditions may equal or exceed the ground potential rise of the ground grid discharging the fault current (and not a fraction of this total as is encountered in the usual touch contact).

3.20 zone of protection: The adjacent space provided by a grounded air terminal, mast, or overhead ground wire that is protected against most direct lightning strikes.

4. Design objectives

4.1 Neutral ground, equipment ground, and safety ground

Figure 1 and the following list are intended to clarify the differences between neutral ground, equipment ground, and safety ground.

- a) The neutral ground (e.g., solid grounding, resistance grounding, etc.) is intended to establish the ground reference of the electrical system. The neutral ground connection is usually made to the neutral point of the supply equipment (the generator or the transformer). Recommendations for neutral grounding are included in IEEE Std C62.92-1987, IEEE Std C62.92.2-1989, IEEE Std C62.92.3-1993, IEEE Std C62.92.4-1991, IEEE Std C62.92.5-1992, IEEE Std 142-1991, and IEEE Std 666-1991.
- b) The safety ground connections are made for protecting personnel from injury and property from damage. These connections are made to parts of the system that are not usually energized but may become live due to an abnormal condition.
- c) The equipment ground ensures a low impedance return path for ground current should an electrical fault occur between the live conductors and the equipment enclosure. If such a return path is ensured, the circuit protection will be able to trip the faulted circuit in a short time.

4.2 Station grounding system

Due to the size of a generating station and to the variety of equipment and structures included, grounding design should provide for equipment and safety grounding and should consider all of the areas in the following list:

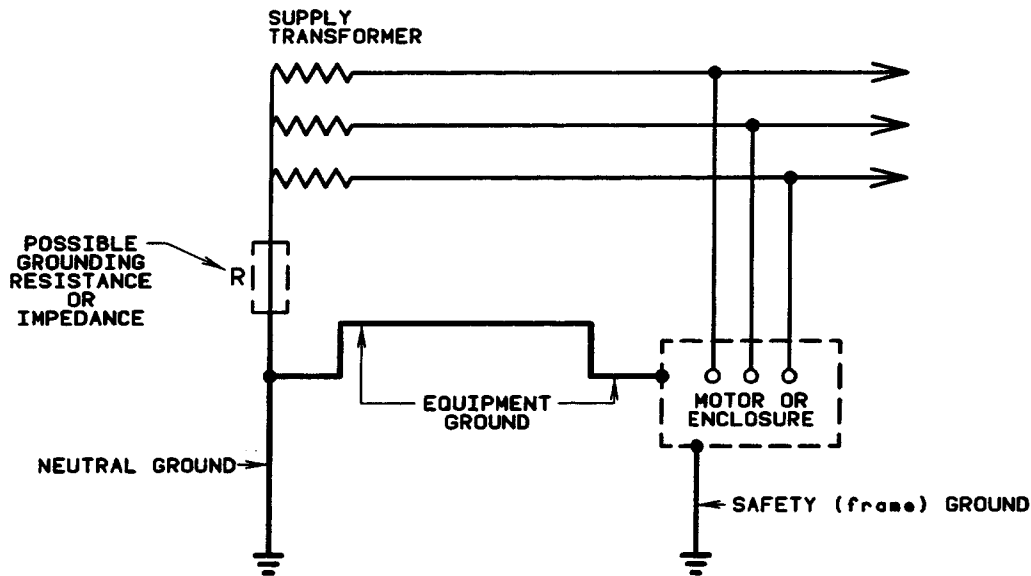


Figure 1—Definitions of neutral, safety, and equipment grounds

- a) *Ground grid.* This safely conducts to ground the largest ground fault current that may occur and limits the touch and step voltages in the outdoor areas of concern.
- b) *Generator isolated-phase bus grounding.* This limits the touch voltage on the enclosures in the event of a fault in the bus enclosure. The arrangement and sizing of the grounding conductors should consider circulating currents.
- c) *Grounding of structures.* This prevents dangerous touch voltages from faults or from static induction.
- d) *Grounding of station auxiliaries.* This is intended to prevent dangerous touch voltages due to local faults or equipment failures in the station auxiliaries.
- e) *Lightning protection of structures.* This is intended to protect the station from the direct and indirect effects of lightning strikes.
- f) *Grounding of buried structures.* This is mainly intended to avoid the transfer of high ground voltages.
- g) *Grounding of instrumentation and control systems.* This is intended to keep touch voltages within safe limits and ensure proper operation of equipment. Station controls are usually grounded at a single point, and control cables may extend throughout the station, resulting in significant voltages between the “control ground” and the “local ground.”

4.3 Preventing the transfer of high ground voltages

Besides buried structures, ground voltages may be transferred into or out of the station by many other means, including piping, cable ground or neutral wires, control cable shields, telephone lines, rail conveyors, and other metallic structures. Guidance may be found in clause 15 of IEEE Std 80-1986.

4.4 Design objectives

The grounding practices included in this guide are intended to protect personnel in the generating station against dangerous touch and step voltages and also to protect property from damage. For personnel this pro-

tection is ensured, in the case of a fault, by either rapid automatic disconnection of the power supply or by limitation of the resulting touch and step voltages to acceptable levels.

This is achieved by the following design objectives:

- a) Provide a low-impedance ground fault current return path in order to activate the protection and clear or alarm the ground fault as soon as possible (equipment ground).
- b) Limit the voltages on station structures and accessible equipment both during normal operation and during electrical transients to safe levels (safety ground).
- c) Minimize electrical noise interference in control and instrumentation systems (safety and equipment grounds).
- d) Minimize the effect of lightning strikes on personnel, equipment and structures (safety and equipment grounds).

5. Detailed design considerations

5.1 Grounding principles

The safety and equipment grounding systems of generating stations should meet the following principles or requirements:

- a) All metallic enclosures on equipment and exposed noncurrent-carrying conductive materials capable of becoming energized due to either insulation failure, inadvertent contact with an energized conductor, or building up of a static or induced voltage should be grounded.
- b) The grounding arrangement should ensure a deliberate ground fault current return path, so that the (overcurrent or ground fault) protection will sense the fault and either trip the faulty circuit or provide an alarm to the station operator.
- c) The grounding should limit the step and touch voltage to acceptable limits during a ground fault on the enclosed equipment.
- d) The grounding conductors and connections should withstand the ground fault current for the duration of the fault, without being damaged by thermal, thermomechanical or electromechanical stresses.
- e) The grounding conductors should be continuous; no switching device should be inserted in the grounding conductors (except where the operation of the switching device will also automatically disconnect all power sources to the equipment grounded by that conductor). Structural changes after installation should not interrupt the grounding conductor. In general, equipment enclosures should not be used as part of the grounding conductor.
- f) The grounding conductors should be mechanically reliable or protected in order to withstand any possible mechanical stress imposed on them. The exposed connections of grounding conductors should be accessible for inspection.
- g) The grounding system should be designed to minimize corrosion to adjacent structures, equipment and enclosures (see 5.7).

5.2 Ground grid design

5.2.1 General

The predominant industry guide for the design of ground grid systems is IEEE Std 80-1986. The differences between generating stations and substations are significant enough that IEEE Std 80-1986 cannot usually be directly applied to the design of generating station ground grids. While other design approaches are acceptable, the design procedure presented in this guide is based on the widely recognized concepts of IEEE Std

80-1986. This manual calculation procedure recognizes that successful grounding systems have been developed without sophisticated calculation techniques. There may, however, be cases where a more detailed analysis should be performed with computer-aided engineering tools.

5.2.2 Differences between substations and generating stations

Two major differences between substations and generating stations are that generating stations usually occupy a much larger physical area and have numerous large buried structures and foundations. Although both of these characteristics have a significant impact in lowering the overall resistance of the station, the effect of such supplemental grounding structures is not taken into account by the simplified design equations in IEEE Std 80-1986. In addition, many generating stations are located close to a source of cooling water, which may be useful as a low-resistance reference point.

From the aspect of ground grid design, generating stations differ from substations in that the personnel to be protected are generally working indoors. Because they are not in direct contact with the earth or with a layer of crushed rock covering the earth, they are not exposed to many of the step and touch voltage conditions that personnel in substations are. This is a valid assumption if the floor surfaces either assure an effective insulation from earth potentials or else are effectively equivalent to a plate or closely spaced mesh grid that is always at the station ground potential. This includes the building structure and its fixtures. In this respect, generating stations are similar to fully enclosed indoor substations.

Different design philosophies exist regarding the treatment of concrete floor surfaces within buildings. While some feel it is necessary to provide a separate ground grid within the concrete, others take credit for the closely spaced mesh of the rebar and the fact that rebar will have numerous connections to the grounded building structural steel. If credit is taken for the rebar, the only grounding conductors placed within the slab are those required for equipment connection points. This guide will assume that a separate grid within concrete slabs that is sized according to step and touch voltage criteria is not required.

This clause, therefore, presents a procedure for evaluating the safety of those portions of the station grid outside of the main station building(s) where personnel are expected to be working, such as the step-up transformer area, the water intake pumping areas, and fuel and hydrogen handling areas. The following subclauses are presented in the order in which a design would generally proceed.

5.2.3 Soil resistivity

One of the most important parameters in designing the station grounding system is the resistivity of the soil in the station area. To obtain these values, an extensive soil resistivity survey should be conducted in the station area. The most common test methods are the Wenner Four-Probe method, which is used to measure large volumes of soil, and the Soil Box Method, which is used to measure soil samples.

Very early in the generating station design phase, extensive soils exploration is required before detailed civil and structural design can begin. Soil boring logs or a formal soils report is usually available, or a cognizant civil engineer has knowledge of subsurface conditions. If test pits are dug, there will be an opportunity to measure subsurface soils directly.

If the extreme values of all soil resistivity data points fall within 30% of each other, a uniform soil assumption can be made. Because the simplified design equations of IEEE Std 80-1986 require a uniform soil assumption in order to proceed with a preliminary design, a single value for soil resistivity will have to be chosen. Even though a uniform soil assumption may not be possible for the entire station site, it may be appropriate for the portions of the site that will be analyzed by calculation. If a uniform soil resistivity assumption cannot be made, then the final design should be based on an analysis technique that can incorporate a two-layer or more sophisticated soil model.

In determining a resistivity value to be used, attention should be paid to the conditions that existed at the time the measurements were taken. Soil moisture content, temperature, and salt content have a significant effect on resistivity measurements.

Caution should be used when determining a design resistivity value because large volumes of soil are frequently excavated and replaced by fill. The depth of the excavation may invalidate a single or two-layer soil model that is based on resistivity measurements from the ungraded site. This would require re-evaluation and/or the use of additional computational techniques.

5.2.4 Ground grid outer dimensions

The area of the ground grid is the variable that has the greatest effect on lowering the overall grid resistance. Measures such as adding an additional grid conductor do not reduce the grid resistance to the extent that increasing the area does.

Depending on the arrangement of the station, the boundary of the station grounding area may be defined by perimeter fencing or a cluster of buildings. If a building cluster is chosen as the desired design area, then a perimeter grounding conductor should be established that encloses these buildings.

Although it is unlikely that the chosen grid area will be rectangular, the simplified design equations require a square or rectangular site. On a layout drawing of the station site, determine the largest rectangle that will fit within the chosen grid area. This represents the four outer grid conductors and will conservatively define the area of the grid to be used in the calculations.

5.2.4.1 Generating station to substation interconnection

Generally, one or more high-voltage substations are located on the generating station site. When the substation is located in close proximity to the generating station (250 m), the substation ground grid should be tied into the generating station grid by multiple conductors. These connections should include conductors installed directly under the tie lines to the station step-up transformers. This should benefit both the generating station and substation grounding system by increasing the available area.

When the substation and generating station are separated by a distance that makes it impractical to tie the two grids together, any interconnections between the two ground grids (control wiring, multiplexing leads, telephone lines, etc.) can be subjected to the difference in voltage between the two ground grids. Under fault conditions, voltage differences of 5 kV are common. Even if the remote substation ground grid is tied to the generating station ground grid by either buried or shield wires, there may be significant voltage differences between the two grids.

5.2.5 Available ground fault current

During a system fault, the fault current may use the earth as a return path to the system neutral. The current that is injected into the earth during a fault results in a ground potential rise (GPR). Typically, only a fraction of the total fault current flows from the grounding system into the earth. Faults occurring within a generating station may not produce the worst earth currents, since there are direct conductive paths that the fault current can follow to reach the system neutral (assuming the station has a circuit reference ground, such as a grounded-wye generator step-up transformer). The faults that produce the largest ground currents may be line-to-ground faults occurring some distance away from the generating station.

5.2.5.1 Zero-sequence rms fault current

Since three-phase faults are balanced in nature, they generally produce only small amounts of earth current and are therefore usually not considered in the ground grid design. The maximum single line-to-ground fault is the value typically used in the ground grid design. Line-to-line-to-ground values are also commonly

investigated. Values should be considered for all voltage levels in the generating station and its adjoining substation. The largest of these fault current (I_f) values, which results in the highest grid-to-earth current, will be the design I_f value.

Some designs have used the short-circuit rating of the equipment. This value can often be ten times higher than the ultimate single-line-to-ground fault current. Use of such a large safety factor in the initial design may make it difficult to design the grid to meet the tolerable touch and step voltage criteria by any means. Rather than using the short-circuit rating of the equipment to increase the safety factor of the design, it may be more appropriate to build in any desired additional safety factors when determining the corrective projection factor in 5.2.5.5.

5.2.5.2 Determine the split factor (S_f)

The split factor is used to take into account the fact that not all of the fault current uses the earth as a return path. The most accurate method for determining the percentage of the total fault current that flows into the earth is to use one of the computerized solution methods that is available. These programs do, however, require an involved data collection effort. For the purposes of this guide, the graphical method of reference will be used (see [B11]). This method requires that the total three-phase zero-sequence fault current ($3I_0$) at the generating station be calculated using a conventional short-circuit program, such as those routinely used by system relay engineers. Since generating stations usually contain sources of zero-sequence fault current, the ratio of local versus remote contribution should be calculated for a fault at each transmission system voltage level. Depending on the ratio of remote to local zero-sequence fault current contribution, the appropriate figure from the reference is selected in order to determine the split factor. Once the appropriate graph has been chosen, the intersection of the preliminary grid resistance (see 5.2.5.3) and the appropriate curve yields the value for the split factor on the y-axis. Note that this value is given in percent and should be converted to decimal notation.

The greater the local contribution, the lower the earth current, since the locally contributed fault current usually has a direct conductive path to the system neutral.

In calculating the number of transmission lines and feeders, only those that have either overhead shield wires or solidly grounded neutrals should be counted. If the number of lines falls between the given curve values, use the curve with the lower number of lines to be conservative.

5.2.5.3 Preliminary grid resistance

In order to use the graphs from [B11], a value for the grid resistance (R_g) should be calculated. Since the design has not yet been started, an approximate value can be calculated by using the following equation:

$$R_g = \frac{\rho}{4} \sqrt{\frac{\pi}{A}} \quad (1)$$

where

- ρ is the soil resistivity (in $\Omega\cdot\text{m}$) as determined in 5.2.3
- A is the area (in m^2) as determined in 5.2.4

Since the soil resistivity and the ground grid area are the two most important variables controlling the grid resistance, equation (1) yields a sufficiently accurate answer to be used for the x-coordinate on the graphs.

Equation (1) does not take into account items such as foundations, ground wells, or large hydro plant structures that may contribute significantly to lowering the overall resistance to ground. To take advantage of the

effect of these items (in a simplified manner), the following modified formula from IEEE Std 80-1986 for calculating a ground system resistance that includes both a ground grid and rods may be used:

$$R_g = \frac{R_1 R_2 - R_{12}^2}{R_1 + R_2 - 2R_{12}} \quad (2)$$

where

- R_1 is the resistance of ground conductors
- R_2 is the resistance of all ground rods (rodbed)
- R_{12} is the mutual resistance between the group of grid conductors and the group of ground rods

R_1 is

$$\left(\frac{\rho_1}{\pi l_1} \right) \left[\ln \left(\frac{2l_1}{h'} \right) + K_1 \left(\frac{l_1}{\sqrt{A}} \right) - K_2 \right] \quad (3)$$

R_2 is

$$\left(\frac{\rho_a}{2n\pi l_2} \right) \left[\ln \left(\frac{8l_2}{d_2} \right) - 1 + 2K_1 \left(\frac{l_2}{\sqrt{A}} \right) (\sqrt{n} - 1)^2 \right] \quad (4)$$

R_{12} is

$$\left(\frac{\rho_a}{\pi l_1} \right) \left[\ln \left(\frac{2l_1}{l_2} \right) + K_1 \left(\frac{l_1}{\sqrt{A}} \right) - K_2 + 1 \right] \quad (5)$$

where

- ρ_1 is the soil resistivity encountered by grid conductors buried at depth h (in $\Omega \cdot \text{m}$)
- ρ_a is the apparent soil resistivity as seen by a ground rod (in $\Omega \cdot \text{m}$)

NOTE—The resistivity at the lower portion of the rod is the most important, since most current is injected into the earth through the lower portion.

- l_1 is the total length of grid conductors (in m)
- l_2 is the average length of a ground rod (in m)
- h is the depth of grid burial (in m)
- h' is $\sqrt{d_1 \cdot h}$ for conductors buried at depth h , or $0.5d_1$ for conductors at $h = 0$ (on the surface of the earth)
- A is the area covered by a grid of dimensions $a \cdot b$ (in m^2)
- a is the short-side grid length (in m)
- b is the long-side grid length (in m)
- n is the number of ground rods placed in area A
- K_1, K_2 are constants related to the geometry of the system (see figures 2a and 2b)
- d_1 is the diameter of the grid conductors (in m)
- d_2 is the diameter of the ground rods (in m)

Rather than use R_2 in equation (2) to represent the perimeter ground rods, foundations may be modeled as a ring of closely spaced cylindrical concrete ground rods using the methods found in [B10].

Similarly, a single point of ground resistance, such as a ground well, could be treated as a single ground rod with a resistance equal to its measured value.

Because equations (1) through (5) assume a single grid with a single type of ground rod, if there are multiple structures of different types that serve as equivalent ground rods, a resistance for each structure should be calculated and then the lowest resistance could be used to combine with the grid. This provides a conservative method for factoring in the effect of generating station structures. Alternatively, a method that can sometimes be used for combining grid resistances can be found in [B18].

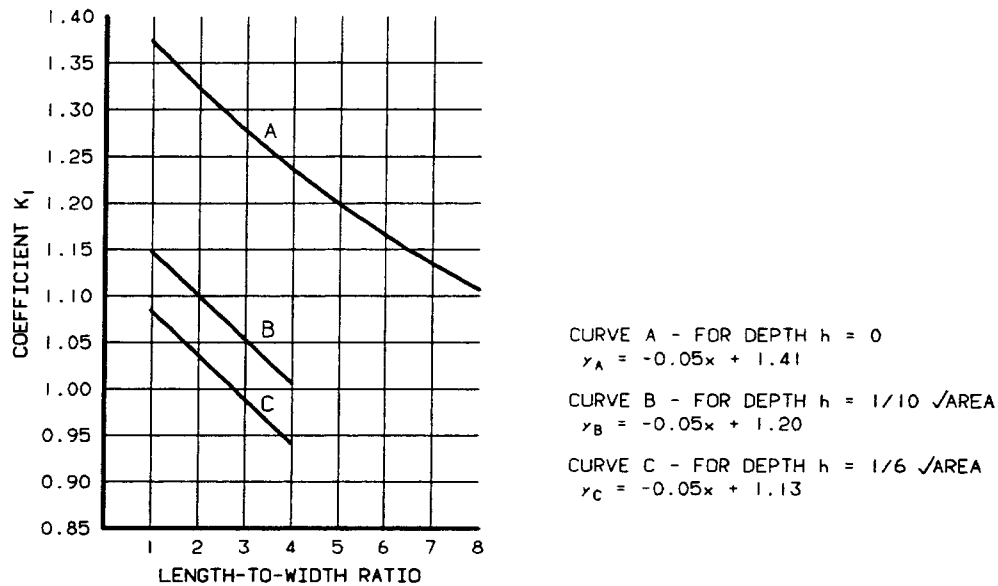


Figure 2a—Coefficient K_1 of Schwarz's formula

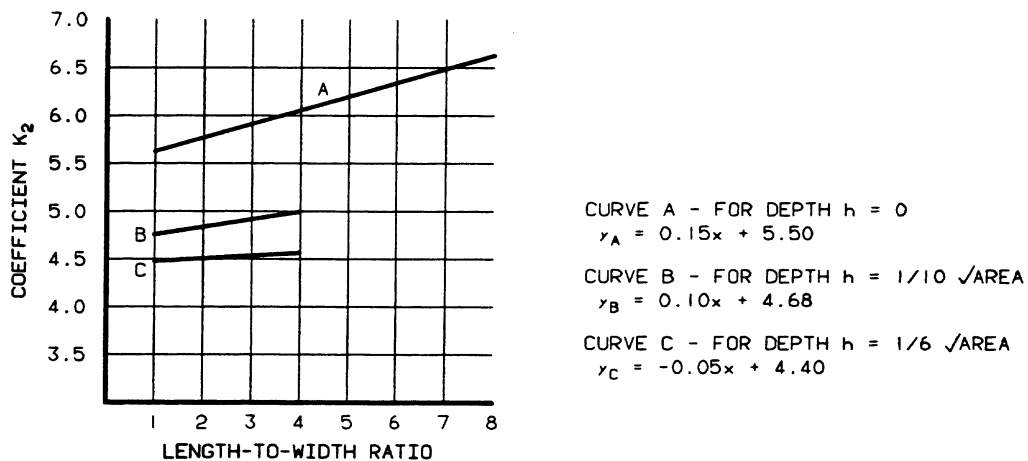


Figure 2b—Coefficient K_2 of Schwarz's formula

5.2.5.4 Determine the decrement factor (D_f)

The decrement factor (D_f) accounts for the asymmetrical fault current waveshape during the early cycles of a fault as a result of the dc current offset.

$$D_f = \sqrt{1 + \frac{T_a}{t_f} \left(1 - e^{-\frac{2t_f}{T_a}} \right)} \quad (6)$$

where

- t_f is the fault duration (in s)
- T_a is the time constant of the equivalent system subtransients (in s)
- $T_a = X''/\omega R''$ for 60 Hz
- $T_a = X''/120\pi R''$
- where
- X''/R'' is the system X/R ratio at the fault location

Using the shortest primary breaker clearing time will result in the highest D_f .

5.2.5.5 Determine the corrective projection factor (C_p)

The corrective projection factor (C_p) is used to account for future increases in fault current. This is an extremely difficult factor to determine accurately. For example, even though the addition of a transmission line to a station may result in more total fault current, the amount of current injected into the earth may actually decrease because the overhead shield wires of the new transmission line present an additional conductive path for the fault current to follow.

Even though the planned ultimate station configuration should be considered during the initial design, this assumes that no major changes from the proposed final configuration would occur. Major design changes that increase the interrupting rating of a station beyond what was initially designed do, however, occur. These changes could include the expansion of the site to include additional generating units or transmission lines. Since changes to the grounding system are difficult and costly, it may be appropriate to be conservative in the original design. For the initial design, a suggested conservative value for C_p is 1.25. If a safe design can be produced with the resulting ground current (I_G), then the value for C_p can be increased in steps to investigate how much additional safety factor can be gained for a nominal additional cost in grounding materials.

5.2.6 Ground conductor sizing

Conductor size may be calculated using the method listed in 5.8.4. This method assumes that any conductor and its joints should be capable of conducting the entire ground fault current without exceeding a specified temperature.

A common assumption is that once the fault current from the equipment conductor(s) reaches the ground grid conductor to which it is attached, the fault current divides equally. Therefore, the grid conductors need to be sized to carry only one-half of the total fault current.

For mechanical reasons and long service life, the grid conductors are typically not smaller than 4/0.