PDHonline Course E477 (4 PDH)

Substations – Volume X – Grounding

Instructor: Lee Layton, PE

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PDH Online | PDH Center

5272 Meadow Estates Drive
Fairfax, VA 22030-6658
Phone: 703-988-0088
www.PDHonline.com

Substation Design
Volume X - Grounding

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This series of courses are based on the "Design Guide for Rural Substations", published by the Rural Utilities Service of the United States Department of Agriculture, RUS Bulletin 1724E-300, June 2001.

Preface

This course is one of a series of thirteen courses on the design of electrical substations. The courses do not necessarily have to be taken in order and, for the most part, are stand-alone courses. The following is a brief description of each course.

Volume I, Design Parameters. Covers the general design considerations, documents and drawings related to designing a substation.

Volume II, Physical Layout. Covers the layout considerations, bus configurations, and electrical clearances.

Volume III, Conductors and Bus Design. Covers bare conductors, rigid and strain bus design.

Volume IV, Power Transformers. Covers the application and relevant specifications related to power transformers and mobile transformers.

Volume V, Circuit Interrupting Devices. Covers the specifications and application of power circuit breakers, metal-clad switchgear and electronic reclosers.

Volume VI, Voltage Regulators and Capacitors. Covers the general operation and specification of voltage regulators and capacitors.

Volume VII, Other Major Equipment. Covers switch, arrestor, and instrument transformer specification and application.

Volume VIII, Site and Foundation Design. Covers general issues related to site design, foundation design and control house design.

Volume IX, Substation Structures. Covers the design of bus support structures and connectors.

Volume X, Grounding. Covers the design of the ground grid for safety and proper operation.

Volume XI, Protective Relaying. Covers relay types, schemes, and instrumentation.

Volume XII, Auxiliary Systems. Covers AC & DC systems, automation, and communications.

Volume XIII, Insulated Cable and Raceways. Covers the specifications and application of electrical cable.

Chapter 1
Issues Affecting Substation Grounding

This chapter is concerned with safe grounding practices and design for outdoor 60 Hz AC substations. DC substations and the effect of lightning surges are not covered.

An effective substation grounding system typically consists of driven ground rods, buried interconnecting grounding cables or grid, equipment ground mats, connecting cables from the buried grounding grid to metallic parts of structures and equipment, connections to grounded system neutrals, and the ground surface insulating covering material. Currents flowing into the grounding grid from lightning arrester operations, impulse or switching surge flashover of insulators, and line-to-ground fault currents from the bus or connected transmission lines all cause potential differences between grounded points in the substation and remote earth. Without a properly designed grounding system, large potential differences can exist between different points within the substation itself. Under normal circumstances, it is the current flow through the grounding grid from line-to-ground faults that constitutes the main threat to personnel.

An effective grounding system has the following objectives:

1. Ensure such a degree of human safety that a person working or walking in the vicinity of grounded facilities is not exposed to the danger of a critical electric shock. The touch and step voltages produced in a fault condition have to be at safe values. A safe value is one that will not produce enough current within a body to cause ventricular fibrillation.

2. Provide means to carry and dissipate electric currents into earth under normal and fault conditions without exceeding any operating and equipment limits or adversely affecting continuity of service.

3. Provide grounding for lightning impulses and the surges occurring from the switching of substation equipment, which reduces damage to equipment and cable.

4. Provide a low resistance for the protective relays to see and clear ground faults, which improves protective equipment performance, particularly at minimum fault.

While line-to-ground faults may result in currents of tens of thousands of amperes lasting several seconds, modern relay systems generally reduce the fault duration to a few cycles. During fault current flow, a low ground grid resistance to remote earth, although desirable, will not, in itself, necessarily provide safety to personnel. It is necessary that the entire grounding system be designed and installed so that, under reasonably conceivable circumstances, personnel are not exposed to hazardous potential differences across the body.

Designing a proper substation grounding system is complicated. Numerous parameters affect its design, and it is often difficult to obtain accurate values for some of these parameters. Furthermore, temperature and moisture conditions can cause extreme variations in the actual resistivity of the ground in which the system is installed. Methods of dealing with the design problem are necessarily based to some extent on approximations and the exercise of engineering judgment. The design approach has to be conservative because of the aforementioned uncertainties.

A good grounding system provides a low resistance to remote earth in order to minimize the ground potential rise. For most transmission and other large substations, the ground resistance is usually about 1 ohm or less. In smaller distribution substations the usually acceptable range is from 1 to 5 ohm, depending on local conditions.

For reference material, IEEE Std. 80, “Guide for Safety in Substation Grounding,” is generally recognized as one of the most authoritative guides available. It is recommended for any person concerned with the design of substation grounding systems.

This course describes some of the different modes in which ground fault current may flow with respect to substation grounding systems. Included is discussion of safety considerations in and near substations when all or a portion of this fault current flows through the substation grounding system. Specific recommendations for the design, installation, and testing of safe and effective grounding systems for substations are included.

Definitions

Listed below are a few definitions related to substation grounding.

DC Offset is the 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.

Earth Current is the current that circulates between the grounding system and the ground fault current source that uses the earth as the return path.

Ground Fault Current is a current flowing into or out of the earth or an equivalent conductive path during a fault condition involving ground.

Ground Potential Rise (GPR) is the maximum voltage that a ground grid may attain relative to a distant grounding point assumed to be at the potential of remote earth. The GPR is equal to the product of the earth current and the equivalent impedance of the grounding system.

Mesh Voltage is the maximum touch voltage within a mesh of a ground grid.

Soil Resistivity is the electrical characteristic of the soil with respect to conductivity. The value is typically given in ohmmeters.

Step Voltage is the difference in surface potential experienced by a person bridging a distance of 1 meter with his feet without contacting any other grounded object.

Touch Voltage is the potential difference between the ground potential rise and the surface potential at the point where a person is standing while at the same time having his hands in contact with a grounded structure.

Transferred Voltage is 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.

Soil Resistivity Measurements

Before the design process can begin, soil resistivity measurements should be taken at the substation site. Make these at a number of places within the site. Substation sites where the soil may possess uniform resistivity throughout the entire area and to a considerable depth are seldom found. Typically, there are several layers, each having a different resistivity. Often, lateral changes also occur, but, in comparison to the vertical ones, these changes usually are more gradual. Make soil resistivity tests to determine if there are any important variations of resistivity with depth. The number of such readings taken should be greater where the variations are large, especially if some readings are so high as to suggest a possible safety problem.

The *Wenner four-pin method* as shown in Figure 1 is the most commonly used technique for taking soil resistivity measurements.

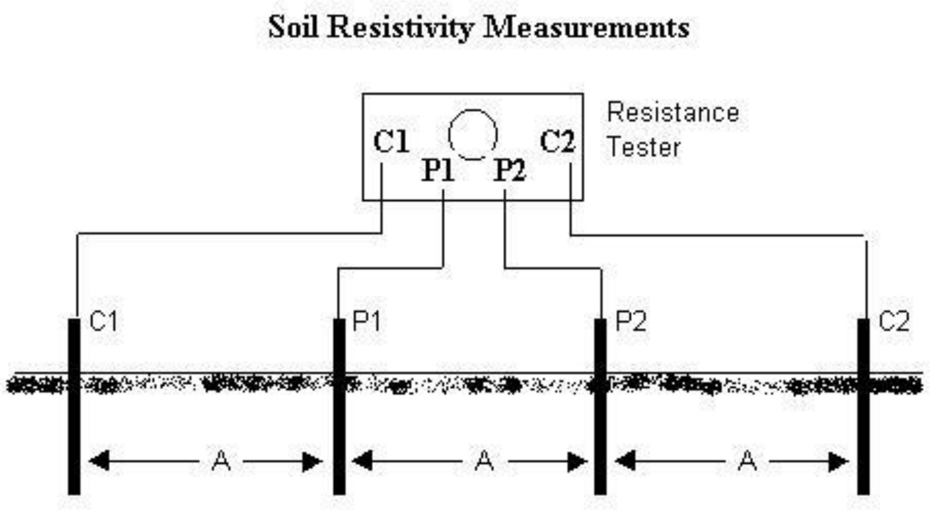


Figure 1

In brief, four probes are driven into the earth along a straight line, at equal distances “a” apart, driven to a depth “b”. The voltage between the two inner (potential) electrodes is then measured and divided by the current between the two outer (current) electrodes to give a value of resistance, R. Then, the apparent soil resistivity is found from,

$$\rho_a = \frac{1.22 * \pi * a * R}{\left(1 + \frac{2 * a}{\sqrt{(a^2 + 4 * b^2)}} - \frac{a}{\sqrt{(a^2 + b^2)}}\right)}$$

Where:

ρ_a = Apparent resistivity of the soil in ohm-m
R = Measured resistance in ohms
a = Distance between adjacent electrodes in feet
b = Depth of the electrodes in feet

If “b” is small compared to “a”, as is the case of probes penetrating the ground only a short distance, the equation can be reduced to,

$$\rho_a = 0.61 * \pi * a * R$$

The current tends to flow near the surface for the small probe spacing, whereas more of the current penetrates deeper soils for large spacing. Thus, it is usually a reasonable approximation to assume that the resistivity measured for a given probe spacing a represents the apparent resistivity of the soil to a depth of a when soil layer resistivity contrasts are not excessive. Therefore, these equations can be used to determine the apparent resistivity "ρ_a" at a depth "a".

There are a number of reasons for the popularity of the Wenner four-pin method. The four-pin method obtains the soil resistivity data for deeper layers without driving the test pins to those layers. No heavy equipment is needed to perform the four-pin test. The results are not greatly affected by the resistance of the test pins or the holes created in driving the test pins into the soil.

Resistivity measurement records should include temperature data and information on the moisture content of the soil at the time of measurement. Also record all data available on known buried conductive objects in the area studied. Buried conductive objects in contact with the soil can invalidate resistivity measurements if they are close enough to alter the test current flow pattern. This is particularly true for large or long objects.

Analyzing Soil Resistivity Measurements

Interpretation of apparent resistivity obtained in the field is perhaps the most difficult part of the measurement program. The basic objective is to derive a soil model that is a good approximation of the actual soil. Soil resistivity varies laterally and with respect to depth, depending on the soil stratification. Seasonal variations may occur in soil resistivity due to varying weather conditions. It has to be recognized that the soil model is only an approximation of the actual soil conditions and that a perfect match is unlikely.

The most commonly used soil resistivity models are the *uniform soil model* and the *two-layer soil model*. Two-layer soil models are often a good approximation of many soil structures while multi-layer soil models may be used for more complex soil conditions. Interpretation of the soil resistivity measurements may be accomplished either manually or by use of computer analysis techniques described in numerous references.

A uniform soil model should be used only when there is a moderate variation in apparent resistivity. In homogeneous soil conditions, which rarely occur in practice, the uniform soil model may be reasonably accurate. If there is a large variation in measured apparent resistivity, the uniform soil model is unlikely to yield accurate results.

A more accurate representation of the actual soil conditions can be obtained through use of a two-layer model. The two-layer model consists of an upper layer of finite depth and with different resistivity than a lower layer of infinite thickness. There are several techniques to determine an equivalent two-layer model from apparent resistivity obtained from field tests. In some instances a two-layer model can be approximated by visual inspection of a plot of the apparent resistivity versus depth from driven rod measurements or apparent resistivity versus probe spacing from Wenner four-pin measurements. Computer programs available to the industry may also be used to derive two-layer and multi-layer soil models. Since the simplified design procedures of IEEE Std. 80 require a uniform soil assumption, a single value for soil resistivity will have to be chosen.

Uniform Soil Assumption

A uniform soil model can be used instead of the multi-layer soil model whenever the two-layer or multi-layer computation tools are not available. Unfortunately, an upper bound of the error on all relevant grounding parameters is difficult to estimate. In general, however, when the contrast between the various layer resistivities is moderate, an average soil resistivity value may be used as a first approximation or to establish orders of magnitude. The approximate uniform soil resistivity may be obtained by taking a mathematical average of the measured apparent resistivity data as shown in this equation,

$$\boldsymbol{\rho}_{\mathbf{a(av1)}} = \frac{\boldsymbol{\rho}_{\mathbf{a(1)}} + \boldsymbol{\rho}_{\mathbf{a(2)}} + \boldsymbol{\rho}_{\mathbf{a(3)}} + \dots + \boldsymbol{\rho}_{\mathbf{a(n)}}}{\mathbf{n}}$$

Where:

ρa(1), ρa(2), ρa(3) ...ρa(n) = Measured apparent resistivity data obtained at different spacing in the four-pin method or at different depths in the driven ground rod method in ohm-m.

n = Total number of measurements

Area of the Ground Grid

The area of the ground grid should be as large as possible, preferably covering the entire substation site. All of the available area should be used since this variable has the greatest effect in lowering the grid resistance. Measures such as adding additional grid conductor are expensive and do not reduce the grid resistance to the extent that increasing the area does.

In general, the outer grid conductors should be placed on the boundary of the substation site with the substation fence placed a minimum of three feet inside the outer conductors. This results in the lowest possible grid resistance and protects persons outside the fence from possibly hazardous touch voltages. It is therefore imperative that the fence and the ground grid layout be coordinated early in the design process.

The simplified design equations require square, rectangular, triangular, T-shaped, or L-shaped grids. For preliminary design purposes, on a layout drawing of the substation site, draw in the largest square, rectangular, triangular, T-shaped, or L-shaped grids that will fit within the site. These represent the outer grid conductors and will define the area of the grid to be used in the calculations. A square, rectangular, triangular, T-shaped, or L-shaped grid site generally requires no additional conductors once the design is complete. For irregular sites, once the design has been completed, additional conductors will be run along the perimeter of the site that were not included in the original grid design and connected to the grid. This will take advantage of the entire site area available and will result in a more conservative design.

Chapter 2
Ground Fault Currents

When a substation bus or transmission line is faulted to ground, the flow of ground current in both magnitude and direction depends on the impedances of the various possible paths. The flow may be between portions of a substation ground grid, between the ground grid and surrounding earth, along connected overhead ground wires, or along a combination of all these paths.

The relay engineer is interested in the current magnitudes for all system conditions and fault locations so that protective relays can be applied and coordinating settings made. The designer of the substation grounding system is interested primarily in the maximum amount of fault current expected to flow through the substation grid, especially that portion from or to remote earth, during the service lifetime of the installed design.

Some of the cases governing ground fault current flow include,

- Faults within a local substation with the local neutral grounded.
- Faults within a local substation with the neutral grounded at remote location.
- Faults within a substation and the system grounded at the local station and also at other points.
- Faults on high side of distribution substation.

The worst case for fault current flow between the substation grounding grid and surrounding earth in terms of effect on substation safety has to be determined. The maximum symmetrical RMS fault current at the instant of fault initiation is usually obtained from a network analyzer study or by direct computation of the maximum symmetrical RMS fault current.

Symmetrical Grid Current

That portion of the symmetrical ground fault current that flows between the grounding grid and surrounding earth may be expressed by,

$$\mathbf{I_g = S_F * I_f}$$

Where:
I_g = RMS symmetrical grid current in amperes
I_f = RMS symmetrical ground fault current in amperes
S_f = Fault current division factor

For the assumption of a sustained flow of the initial ground fault current, the symmetrical grid current can be expressed by,

$$\mathbf{I_g = S_f - (3 * I_o)}$$

Where:
I_0 = Symmetrical RMS value of Zero Sequence fault current in amperes.

For transmission substations, calculate the maximum symmetrical value of zero sequence fault current for a single-phase-to-ground fault for both the present station configuration and the ultimate station configuration. Obtain values for all voltage levels in the station. Use the largest of these fault current values.

For distribution stations, since the fault current at distribution stations will not increase significantly over the life of the station as a result of the high impedance of the 34 and 69 kV feeders, the future fault current can be modeled using a suitable growth factor (perhaps $1.1 * I_0$).

For an extremely conservative design, the interrupting rating of the equipment can be used for I_0. This value may be as high as ten times the ultimate single-phase-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.

Determine the Split Factor, Sf

The *split factor* is used to take into account the fact that not all the fault current uses the earth as a return path. Some of the parameters that affect the fault current paths are:

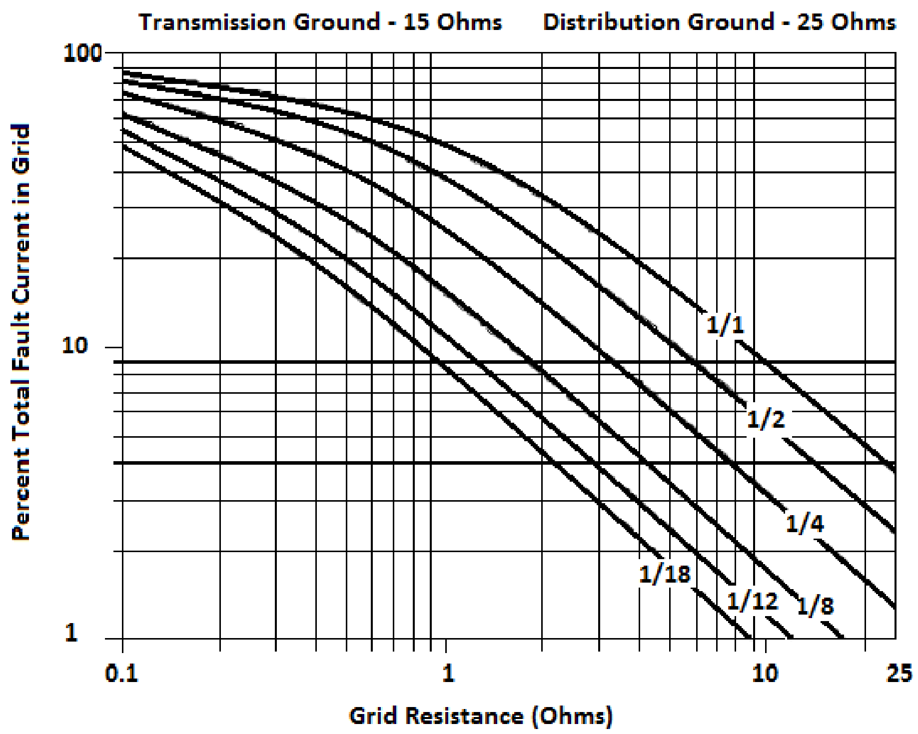
1. Location of the fault
2. Magnitude of substation ground grid impedance
3. Buried pipes and cables in the vicinity of or directly connected to the substation ground system

4. Overhead ground wires, neutrals, or other ground return paths

The most accurate method for determining the percentage of the total fault current that flows into the earth is to use a computer program such as EPRI's SMECC, *Substation Maximum Earth Current Computation*. This program and similar programs, however, require an involved data collection effort. For the purposes of this course, the graphical method will be used.

Two graphs are presented below to help understand how to use the split factor. Figure 2 is for 100 percent remote, zero percent local fault current contribution. This represents typical distribution substations with delta-wye grounded transformers, switching stations, and transmission stations with no local sources of zero-sequence current. The graph contains a number of curves representing various combinations of one transmission line with various feeders at the substation.

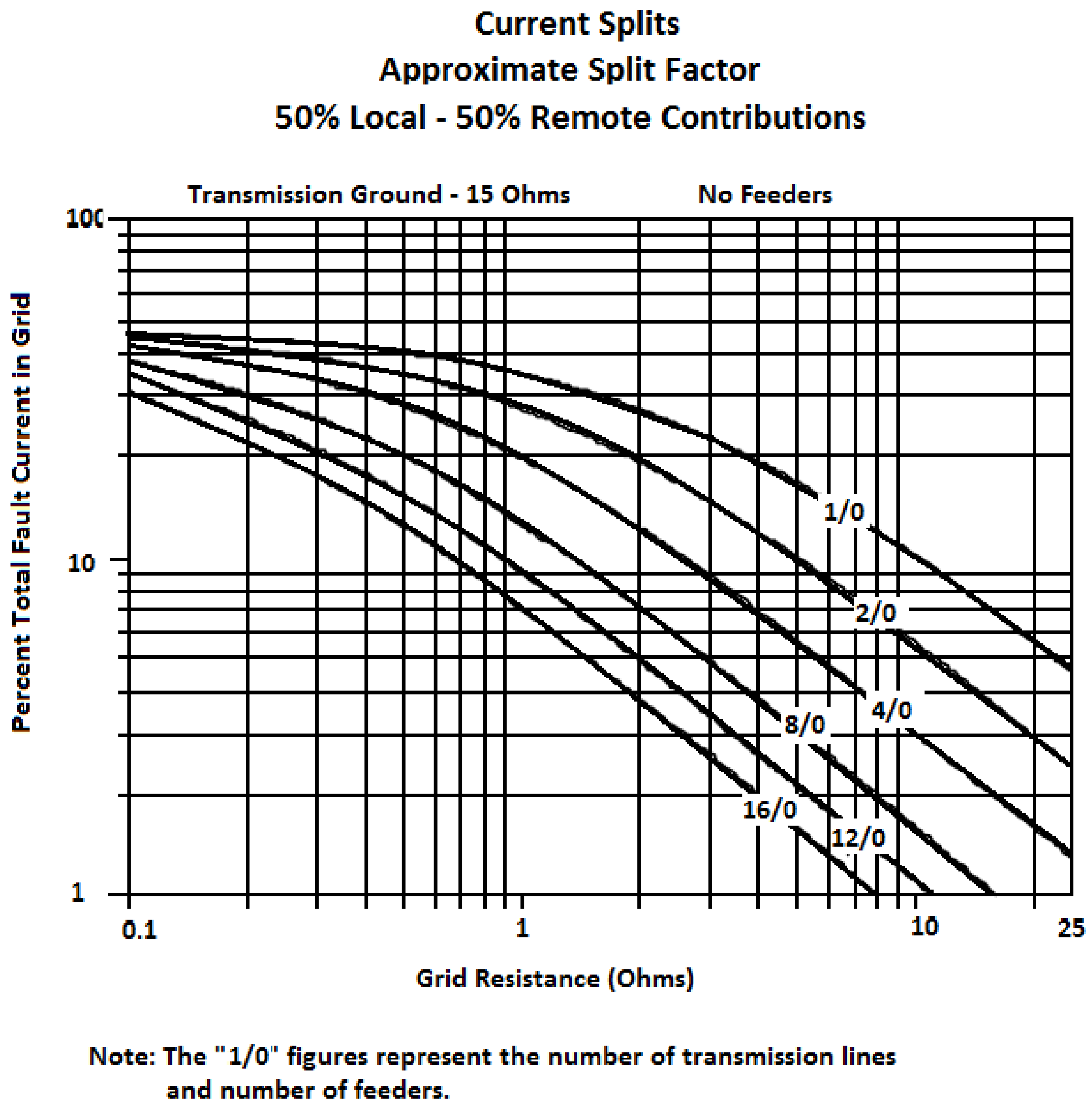
Current Splits
Approximate Split Factor
100% Remote
1-Transmission Line, Low Line Ground Resistance



Note: The "1/8" figures represent the number of transmission lines and number of feeders.

Figure 2

Figure 3 is for a 50 percent local, 50 percent remote fault current contribution. This represents typical transmission substations or generating stations with one transmission line and various feeders (feeders are considered transmission lines on this graph). These stations contain local sources of zero-sequence current such as autotransformers and grounded-wye generator step-up transformers. 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.



Current Splits
Approximate Split Factor
50% Local - 50% Remote Contributions

Note: The "1/0" figures represent the number of transmission lines and number of feeders.

Figure 3

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 use the graphs, the approximate tower impedance of the transmission lines and feeders should be known, and the value for the grid resistance has to be calculated. Since the design has not yet been started, an approximate value can be calculated by using,

$$\mathbf{R_g = \frac{\rho}{1.22} * \sqrt{\frac{\pi}{A}}}$$

Where:
R_g = Substation ground resistance, ohms.
ρ = Soil resistivity in ohm-m
A = Area occupied by the ground grid, in ft^2

Since the soil resistivity and the ground grid area are the two most important variables controlling the substation ground resistance, This equation yields a sufficiently accurate answer to be used for the X-coordinate on the graphs. Once the appropriate graph has been chosen with all the available information, the intersection of the substation ground resistance and the appropriate curve yields the value for the split factor on the Y-axis. Note that this value is given as a percentage and should be converted to decimal notation before using in an equation.

The Decrement Factor, D_f

The *decrement factor* accounts for the asymmetrical fault current wave shape during the early cycles of a fault as a result of the DC current offset. In general, the asymmetrical fault current includes the sub-transient, transient, and steady-state AC components, and the DC offset current component. Both the sub-transient and transient AC components and the DC offset decay exponentially, each having a different attenuation rate. However, in typical applications of this course, it is assumed that the AC component does not decay with time but remains at its initial value.

The decrement factor can be calculated using,

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

Where:
t_f = Time duration of fault in seconds
T_a = X/(ωR) = the DC offset time constant in seconds
ω = 2*π*f, where “f” is frequency (Hz)

For 60 Hz,

$$T_a = \frac{X}{(120 * \pi * R)}$$

The selection of the time duration of a fault "t_f" should reflect the fastest clearing time (relay plus breaker time) for transmission substations and worst-case backup clearing time for distribution and industrial substations. This conservative approach results in the highest "D_f".

The X/R ratio used in the calculation of the DC offset time constant, "T_a", is the system X/R ratio, inductive reactance to resistance, at the fault location for a given fault type. The X and R components of the system sub-transient fault impedance should be used to determine the X/R ratio. The X/R ratio is 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. This equation can be used to compute the decrement factor for specific X/R ratios and fault duration. Typical values of the decrement factor for various fault durations and X/R ratios are shown in Table 1.

Table 1

Typical Values of D_f

Fault Duration, T_f		Decrement Factor D_f			
Seconds	Cycles	X/R = 10	X/R = 20	X/R = 30	X/R = 40
0.00833	0.5	1.576	1.648	1.675	1.688
0.05	3	1.232	1.378	1.462	1.515
0.10	6	1.125	1.232	1.316	1.378
0.20	12	1.064	1.125	1.181	1.232
0.30	18	1.043	1.085	1.125	1.163
0.40	24	1.033	1.064	1.095	1.125
0.50	30	1.026	1.052	1.077	1.101
0.75	45	1.018	1.035	1.052	1.068
1.00	60	1.013	1.026	1.039	1.052

For relatively long fault durations, the effect of the DC offset current can be assumed to be more than compensated by the decay of the sub-transient component of AC current. A decrement factor of 1.0 can be used for fault durations significantly greater than 1 second.

Maximum Grid Current

During a system fault, the fault current will use the earth as a partial return path to the system neutral. The current that is injected into the earth during a fault results in a ground potential rise. Typically, only a fraction of the total fault current flows from the grounding system into the earth. This is due to the transfer of current onto metallic paths such as overhead static shields, water pipelines, etc.

Faults occurring within the substation generally do 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 substation has a grounded-wye transformer). The faults that produce the largest ground currents are usually line-to-ground faults occurring at some distance away from the substation. The maximum grid current is the current that flows through the grid to remote earth and is calculated by,

$$\mathbf{I_G = D_f * I_g}$$

Where:
I_G = Maximum grid current in amperes
D_f = Decrement factor for the entire duration of fault t_f, found for t_f, given in seconds
I_g = RMS symmetrical grid current in amperes

Asymmetrical Fault

The *asymmetrical fault current* includes the sub-transient, transient, and steady-state AC components, and the DC offset current component and can be defined as shown in,

$$\mathbf{I_F = D_f * I_f}$$

Where:
I_F = Effective asymmetrical fault current in amperes
I_f = RMS symmetrical ground fault current in amperes
D_f = Decrement factor

The DC offset in the fault current will cause the conductor to reach a higher temperature for the same fault conditions (fault current duration and magnitude). In addition, if present, DC offset could result in mechanical forces and absorbed energy being almost four times the value of an equivalent symmetric current case.

Chapter 3
Ground Conductor

The two most commonly used materials for grounding in the United States are copper and copper-clad steel.

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

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

Ground Conductor Sizing

The ground conductor for both the grid and equipment connections should be sized according to,

$$\mathbf{A_{kcmil} = I * \frac{197.4}{\sqrt{\left[\left(\frac{TCAP}{t_c * \alpha_r * \rho_t}\right) * \ln\left(\frac{K_o + T_m}{K_o + T_r}\right)\right]}}}$$

Where:
I = RMS fault current, in kA
A_{kcmil} = Area of conductor, kcmil
T_m = Maximum allowable temperature, degrees C
T_a = Ambient temperature, degrees C
T_r = Reference temperature for material constants, degrees C
α_o = Thermal coefficient of resistivity at 0C, 1/C
α_r = Thermal coefficient of resistivity at reference temperature T_r, 1/C
ρ_r = Resistivity of the ground conductor at reference temperature T_r, mW-cm
K_o = $1/\alpha_o$ or $(1/\alpha_r) – T_r$, degrees C
t_c = Fault current duration, seconds
TCAP = Thermal capacity per unit volume from Table 2, J/(cm^3*C)

Note that α_r and ρ_r are both to be found at the same reference temperature of "T_r", degrees Celsius. Table 2 provides data for "α_r" and "ρ_r" at 20C. The values in this equation are metric values.

The selection of the fault current, I, is different for the equipment ground connection and the ground grid conductors and is discussed in the next section.

Table 2

Material Constants Data

Description	Material Conductivity (%)	α_r Factor @20C (1/C)	K_o @0C (C)	Fusing Temperature T_m (C)	ρ_r @20C (uΩ-cm)	TCAP Thermal Capacity (J/cm^3-C)
Copper, Annealed soft-drawn	100	0.00393	234	1083	1.72	3.42
Copper, Commercial hard-drawn	97	0.00381	242	1084	1.78	3.42
Copper-clad Steel wire	40	0.00378	245	1084	4.40	3.85
Copper-clad Steel wire	30	0.00378	245	1084	5.80	3.85
Copper-clad Steel rod	20	0.00378	245	1084	8.62	3.85

The formula can be simplified to,

$$\mathbf{A_{cmil} = I * K_f * \sqrt{t_c}}$$

Where:

A_{kcmil} = Area of conductor in kcmil

I = RMS fault current in kA

t_c = Fault current duration in seconds

K_f = Constant from Table 3 for the material at various values of T_m (fusing temperature or limited conductor temperature) and using ambient temperature (T_a) of 40C.

Table 3
Material Constants Data

Description	Material Conductivity (%)	Fusing Temperature T_m (C)	Kf
Copper, Annealed soft-drawn	100	1083	7.00
Copper, Commercial hard-drawn	97	1084	7.06
Copper, Commercial hard-drawn	97	250	11.78
Copper-clad Steel wire	40	1084	10.45
Copper-clad Steel wire	30	1084	12.06
Copper-clad Steel rod	20	1084	14.64

Sizing Equipment Ground Conductor

In determining the size of the equipment ground conductors, use the total fault current since it has to flow through the equipment ground conductors before it can reach the ground grid and divide among various conductive and earth paths to reach the system neutral. Use the effective asymmetrical fault current, I_F, for I in the previous equations when sizing the equipment ground conductors.

Sizing Ground Grid Conductors

"I_G" can be substituted for "I" in the previous equation for the design of the grid to take advantage of the fact that not all the fault current flows through the earth and prevent overdesigning the grounding system. The current I_G should, however, reflect the worst fault type and location, the decrement factor, and any future system expansion. Another more conservative approach is to use "I_F" for "I".

The use of "I_F" will result in a larger conductor that will provide extra strength for installation, take into account the effects of corrosion, and provide some margin for unexpected future system expansion. It is best to be conservative and provide an adequate margin when sizing the ground grid conductors as a result of the expense involved in replacing or upgrading existing ground conductors at a later date.

Additional Conductor Sizing Factors

The designer should take precautions to ensure that the temperature of any conductor and connection in the grounding installation does not pose a danger to the safe operation of the substation. For instance:

- Typically, conductors and connections near flammable materials should be subject to more stringent temperature limitations.
- If the strength of hard-drawn copper is required for mechanical reasons, then it may be prudent not to exceed 250C to prevent annealing of the conductors.

Carefully examine the possible exposure to a corrosive environment. Even when the correct conductor size and the selected joining (connecting) method have satisfied all the test requirements of IEEE Std. 837, "Qualifying Permanent Connections Used in Substation Grounding," it may be prudent to choose a larger conductor size to compensate for some gradual reduction in the conductor cross section during the design life of the installation where the soil environment tends to promote corrosion.

Connections from Equipment and Structures to Ground Grid

Attention should be paid to the connections of substation structures, equipment frames, and neutrals to the ground grid to realize the benefits of an effective ground grid system. Conductors of adequate ampacity and mechanical strength should be used for the connections between:

- All ground electrodes, such as grounding grids, rodbeds, ground wells, and, where applicable, metal, water, or gas pipes, water well casings, etc.

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

Solid bare copper ground conductor or wire is usually employed for these ground connections. However, transformer tanks are sometimes used as part of a ground path for surge arresters on them. Similarly, most steel or aluminum structures may be used for the ground path if it can be established that their conductance, including that of any connections, is and can be maintained as equivalent to that of the conductor that would normally be installed. Where this practice is followed, any paint films that might otherwise introduce a highly resistive connection should be removed and a suitable joint compound applied or other effective means, such as jumpers across the connections, taken to prevent subsequent deterioration of the connection. Do not assume equal division of currents between multiple ground leads at cross-connections or similar junction points.

Extra ground connections should be considered at all critical locations (such as at equipment neutrals, surge arrester grounds, operating handles and ground mats, etc.) to ensure an effective grounding capability even when one conductor is broken or a connection is improperly made. Do not assume equal division of currents between multiple ground connections.

Securely attach the shortest possible length ground conductor to structures and/or equipment and form the conductor to conform to the foundation with minimum exposure to mechanical damage. Conductor sizes for any critical connection should not be smaller than 1/0 AWG to ensure mechanical adequacy.

Periodically inspect all accessible ground leads. Exothermic weld, brazed, or compression-type connectors can be used for underground connections. Compression connectors if used in grounding applications should be of a type that compresses the conductor and the connector into a tight homogenous mass, removing virtually all air. Use an oxide-inhibiting compound with all compression connectors to seal out air and moisture and prevent oxidation or corrosion in the connection.

Oxidation or corrosion in the connection can create hot spots that can shorten the life of the connection. With the connection below grade, there is no visual way of knowing when the connection has failed. A properly installed exothermic connection is a molecular connection that eliminates the oxidation and corrosion in the connection and reduces the opportunity for hot spots.

Chapter 4
Touch and Step Potentials

Underground fault conditions, the portion of fault current flowing between a substation ground grid and the surrounding earth, “I_G”, will result in potential gradients within and around the substation. Unless proper precautions are taken in design, the maximum gradients present can result in a potential hazard to a person in or near the substation. In addition to the voltage magnitude of the local gradients, such things as duration of the current flow, impedances in its path, body resistance, physical condition of the person, and probability of contact all enter into the safety considerations.

Tolerable Limits of Body Current

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. The threshold of perception for the human body is about one milliampere at 60 Hz. Currents of 1 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.

Higher currents (about 9 to 25 mA) can result in painful situations and affect the muscles so that the energized object is difficult if not impossible to release. Still higher currents can affect breathing and may cause fatalities if duration (usually on the order of minutes) is long enough. Further current increases (about 60 mA and above) can result in ventricular fibrillation of the heart. Currents above the level for ventricular fibrillation can cause heart paralysis, inhibition of breathing, and burns.

Since currents of a magnitude that exceed let-go level can affect breathing, they have to be avoided if the duration is likely to be long. Fortunately, in most situations in substations, the protective relays will prevent any fault from lasting that long. Therefore, it is usually those levels of current that can lead to ventricular fibrillation that form the basis for most potential gradient limitation efforts.

It is assumed that 99.5 percent of all persons can safely withstand, without ventricular fibrillation, the passage of a current with magnitude and duration determined by,

$$\mathbf{I_B = \frac{k}{\sqrt{t_S}}}$$

Where:
I_B = RMS magnitude of the current through the body in amperes
t_s = Duration of the current exposure in seconds
k = Constant related to electric shock energy,
For a person weighing 110 lbs, k = 0.116
For a person weighing 155 lbs, k = 0.157

The equation based on tests limited to a range of between 0.03 and 3.0 seconds and is not valid for very short or long durations. It indicates that much higher body currents can be allowed where fast operating protective devices can be relied upon to limit the fault duration. An engineering decision based on judgment is needed as to whether to use the clearing time of primary high-speed relays, or that of the backup protection, as the basis for calculation.

Typical Shock Situations
There are five basic situations involving a person and grounded facilities during a fault. They are,

1. Metal-to-Metal Touch Voltage, E_{mm},
2. Step Voltage, E_S,
3. Touch Voltage, E_T,
4. Mesh Voltage, E_M, and
5. Transferred Voltage, E_{trrd} (also known as GPR).

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

Tolerable Touch and Step Voltages

The tolerable touch and step voltages are the criteria that have to be met to ensure a safe design. The lower the maximum touch and step voltages, the more difficult it is to produce an adequate grid design. In most cases the tolerable touch voltage will be the limiting factor.

The equations for the maximum touch and step voltages are as follows:

$$\mathbf{E_{step} = (R_B + 2 * R_f) * I_B}$$

$$\mathbf{E_{touch}} = \left(\mathbf{R_B} + \frac{\mathbf{R_f}}{\mathbf{2}}\right) * \ \mathbf{I_B}$$

Where:
E_{step} = Step voltage in volts
E_{touch} = Touch voltage in volts
R_B = Resistance of the human body to electric current. R_B is generally estimated to be 1000 ohm for DC and 60 Hz AC current.
R_f = Ground resistance of one foot, which is calculated by,

$$\mathbf{R_f = C_S * 3 * \rho_s}$$

"C_s" is the surface layer derating factor based on the thickness of the protective surface layer spread above the earth grade at a substation. If no protective surface layer is used, then C_s = 1.

"ρ_s" is the resistivity of the protective surface layer used at the substation in ohm-m. If no protective surface layer is used, then $\rho_s = \rho$ = resistivity of homogenous soil. Substituting for I, R_B, and R_f, into the equations,

For body weight of 110 lbs,

$$E_{step110} = (1{,}000 + 6 * C_s * \ \rho_s) * \frac{0.116}{\sqrt{t_s}}$$

$$E_{touch110} = (1{,}000 + 1.5 * C_s * \ \rho_s) * \frac{0.116}{\sqrt{t_s}}$$

For body weight of 155 lbs,

$$E_{step155} = (1{,}000 + 6 * C_s * \ \rho_s) * \frac{0.157}{\sqrt{t_s}}$$

$$E_{touch155} = (1{,}000 + 1.5 * C_s * \rho_s) * \frac{0.157}{\sqrt{t_s}}$$

Determine “t_s”. The faster the clearing time of the fault, the less risk there is to personnel. 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. Given all of the above safety factors and using the assumption that not all of the worst-case conditions will be present at the time of the fault, the worst-case primary clearing time for the substation can be used. An extremely conservative design would use the backup clearing time because it ensures a greater safety margin.

Protective Surface Material and Reduction Factor

A thin layer of highly resistive protective surface material such as gravel spread above the earth grade at a substation can greatly reduce the available shock current at a substation. The surface material increases the contact resistance between the soil and the feet of people in the substation. The surface material is generally 3 to 6 inches in depth and extends 3 to 4 feet outside the substation fence. If the surface material does not extend outside the substation fence, then the touch voltage may become dangerously high.

The range of resistivity values for the surface material layer depends on many factors, some of which are kinds of stone, size, condition of stone (that is, clean or with fines), amount and type of moisture content, atmospheric contamination, etc. Table 4 indicates that the resistivity of the water with which the rock is wet has considerable influence on the measured resistivity of the surface material layer. Thus, surface material subjected to sea spray may have substantially lower resistivity than surface material utilized in arid environments. Table 4 gives typical resistivity values for different types of surface material measured by several different parties in different regions of the United States. These values are not valid for all types and sizes of stone in any given region. Perform tests to determine the resistivity of the stone typically used in the region’s substations.

Table 4

Typical Surface Material Resistivities

No	Description of Surface Material	Resistivity of Sample Ω-m	
		Dry	Wet
1	Crusher Run Granite with Fines (NC)	140 x 10^6	1,300 (Groundwater 45 Ω-m)
2	1-2/3 in. Crusher Run Granite (GA with Fines	4,000	1,200 (Rainwater 100 Ω-m
3	¾-1 in. Granite (CA) with Fines	-	6,513 (10 minutes after 45 Ω-m Water Drained)
4	#4 (1-2 in.) Washed Granite (GA)	1.5x10^6 to 4.5x10^6	5,000 (Rainwater, 100 Ω-m)
5	#3 (2-4 in.) Washed Granite (GA)	2.6x10^6 to 3x10^6	10,000 (Rainwater, 100 Ω-m)
6	Size Unknown, Washed Limestone	7x10^6	2,000-3,000 (Groundwater, 45 Ω -m)
7	Washed Granite, Similar to 3/4in. Gravel	2x10^6	10,000
8	Washed Granite, Similar to Pea Gravel	40x10^6	5,000
9	#57 (3/4 in.) Washed Granite (NC)	190x10^6	8,000 (Groundwater, 45 Ω -m)
10	Asphalt	2x10^6 to 30x10^6	10,000 – 6x10^6
11	Concrete	1x10^6 to 1x10^9	21 - 100

An analytical expression for the ground resistance of the foot on a thin layer of surface material can be obtained from,

$$C_S = 1 + \frac{4.88 * b}{\rho_s} * \sum_{n=1}^{\infty} \left(K^n * R_{m(2nh_s)}\right)$$

And,

$$K = \frac{\rho - \rho_s}{\rho + \rho_s}$$

Where:
C_s = Surface layer derating factor
K = Reflection factor between different material resistivities
ρs = Surface material resistivity in ohm-meters
ρ = Resistivity of the earth beneath the surface material in ohm-meters
hs = Thickness of the surface material in feet
b = Radius of the circular metallic disc representing the foot in feet
$R_{m(2nhs)}$ = Mutual ground resistance between the two similar, parallel, coaxial plates, separated by a distance ($2nh_s$), in an infinite medium of resistivity “ρs” in ohm-meters

Chapter 5
Design of a Substation Grounding System

The prevailing practice for a grounding system of most utilities both in the United States and other countries is the use of buried horizontal conductors in the form of a grid, supplemented by a number of vertical ground rods connected to this grid. Some of the reasons behind the system of vertical rods and horizontal conductors are that horizontal (grid) conductors are most effective in reducing the danger of high step and touch voltages on the earth surface. Vertical ground rods penetrating the lower resistivity soil are far more effective in dissipating fault currents whenever a two- or multi-layer soil is encountered and the upper soil layer has a higher resistivity than the lower soil layer. This is important because the resistivity of lower soil layers remains nearly constant with changing seasons while the upper soil layer resistivity may experience high resistivity conditions with seasonal changes due to the freezing or drying of the upper soil layer.

Several parameters define the geometry of the grid, but the area of the grounding system, the conductor spacing, and the depth of the ground grid have the most impact on the mesh voltage, while parameters such as the conductor diameter and the thickness of the surfacing material have less impact. The area of the grounding system is the single most important geometrical factor in determining the resistance of the grid. The larger the area grounded, the lower the grid resistance and, thus, the lower the GPR.

The grounding system grid shall consist of a network of bare conductors buried in the earth to provide for grounding connections to grounded neutrals, equipment ground terminals, equipment housings, and structures and to limit the maximum possible shock current during ground fault conditions to safe values. If the calculated mesh and step voltages of the grid design are below the maximum values for touch and step voltage, then the design is considered adequate. Personnel may still receive a shock during fault conditions, but that shock will not be sufficient to cause ventricular fibrillation.

The ground grid should encompass all of the area within the substation fence and extend at least 3.0 feet outside the substation fence. A perimeter grid conductor should be placed 3.0 feet outside and around the entire substation fence including the gates in any position. A perimeter grid conductor should also surround the substation equipment and structure cluster in cases where the fence is located far from the cluster.

A soil resistivity test will determine the soil resistivity profile and the soil model needed (that is, uniform or two-layer model). Estimates of the preliminary resistance of the grounding system in uniform soil can be determined using the equation in Chapter One. For the final design, more accurate estimates of the resistance may be desired. Computer analysis based on modeling the components of the grounding system in detail can compute the resistance with a high degree of accuracy, assuming the soil model is chosen correctly.

The fault current "$3I_0$" should be the maximum expected future fault current that will be conducted by any conductor in the grounding system, and the time "t_c" should reflect the maximum possible clearing time (including backup).

The tolerable touch and step voltages are determined by equations given in Chapter 4. The choice of time "t_s" is based on the judgment of the design engineer. Using the assumption that not all the worst-case conditions will be present at the time of the fault, the worst-case primary clearing time for the substation can be used for t_s. An extremely conservative design would use the backup clearing time for t_s.

The entire area inside the fence and including a minimum of 3.3 feet outside the fence needs to be covered with a minimum layer of 4 inches of protective surface material such as crushed rock (or approved equal) possessing a minimum resistivity of 3,000 ohm-meters wet or dry.

The ground grid consists of horizontal (grid) conductors placed in the ground to produce square mesh. This can be visualized as a checkerboard pattern. One row of horizontal conductors is equally spaced 10 to 50 feet apart. A second row of equally spaced horizontal conductors running perpendicular to the first row is spaced at a ratio of 1:1 to 1:3 of the first row's spacing. For example, if the first row spacing was 10 feet, the second row spacing could be between 10 to 30 feet). The crossover point for the first and second row of conductors should be securely bonded together. The purpose of the bonded connections is to ensure adequate control of surface potential, secure multiple paths for fault currents, minimize the voltage dorp in the grid, and provide a certain measure of redundancy in case of conductor failure. Grid conductors range in size from 2/0 AWG to 500 kcmil; the conductor diameter has negligible effect on the mesh voltage.

Grid conductors should be buried a minimum of 18 inches to 60 inches below final earth grade (excluding crushed rock covering) and may be plowed in or placed in trenches. In soils that are normally quite dry near the surface, deeper burial may be required to obtain desired values of grid resistance.

Vertical ground rods may be at the grid corners and at junction points along the perimeter. Ground rods may also be installed at major equipment, especially near surge arresters. In multi-layer or high-resistivity soils, it might be useful to use longer rods or rods installed at additional junction points. Vertical ground rods should be 5/8 inch diameter by at least 8.0-feet long copper or steel. Where used, they should be installed with tops 2 inches minimum below grade and bonded to the ground grid connectors. A good design practice is to space rods not closer than their length. An additional determinant is having enough rods so that their average fault current pickup would not exceed 300 amperes, assuming all ground system current entering the grid through the rods.

If the GPR of the preliminary design is below the tolerable touch voltage, no further analysis is necessary. The design needs only the refinements required to provide access to equipment grounds. The calculation of the mesh and step voltages for the grid as designed can be done using the approximate analysis techniques previously described for uniform soil.

If the computed mesh voltage is below the tolerable touch voltage, the design may be complete. If the computed mesh voltage is greater than the tolerable touch voltage, the preliminary design should be revised.

Both the computed touch and step voltages have to be below the tolerable voltages. If not, the preliminary design has to be revised. If either the step or touch tolerable limits are exceeded, revision of the grid design is required. These revisions may include smaller conductor spacing, additional ground rods, etc.

After satisfying the step and touch voltage requirements, additional grid and ground rods may be required. The additional grid conductors may be required if the site is irregular or if the grid design does not include conductors near equipment to be grounded. Additional ground rods may be required at the base of surge arresters, transformer neutrals, etc. Also review the final design to eliminate hazards due to transferred potential and hazards associated with special areas of concern.

Preliminary Design

The design criteria are the tolerable touch and step voltages. For a preliminary design, the grid will consist of uniform square or rectangular mesh. This is so the touch and step voltages calculated by the simplified design equations are valid for every location within the ground grid. Once a safe preliminary design has been achieved, then the ground grid may be modified so that the grid does not consist entirely of uniform square or rectangular mesh. Make sure that all grid modifications do not result in mesh that is larger than the one used in the preliminary design since it could result in unsafe touch and step voltages. Remember that additional ground conductors added to the preliminary design will result in a more conservative design, and fewer ground conductors than the preliminary design could result in an unsafe design.

Take the following steps to arrive at a preliminary design:

1. On a layout drawing of the substation site, draw in the largest square, rectangular, triangular, T-shaped, or L-shaped grids that will fit within the site;

2. Place grid conductors to produce square mesh of approximately 20 to 40 feet on a side.
3. Set the grid depth, h, equal to 18 inches.
4. Set the thickness of surface material equal to 4 inches.
5. Place ground rods around the perimeter of the substation.

As a general rule, place a ground rod at every other perimeter grid connection and at the corners of the substation. Since ground rods discharge most of their current through their lower portion, they are effective in controlling the large current densities (and associated large step and touch potentials) that are present in the perimeter conductors during fault conditions.

Calculate Design Mesh Voltage

Mesh voltage (a form of touch voltage) is taken as being from a grounded structure to the center of a rectangle of the substation grounding grid mesh. Mesh voltages represent the highest possible touch voltages that may be encountered within a substation's grounding system and thus represent a practical basis for designing a safe grounding system for within, and immediately outside, the substation fence area. The mesh voltage has to be less than the tolerable touch voltage for the grounding system to be safe.

However, the mesh voltage may not be the worst-case touch voltage if ground rods are located near the perimeter, or if the mesh spacing near the perimeter is small. In these cases, the touch voltage at the corner of the grid may exceed the corner mesh voltage. In a substation that utilizes a grid as part of the grounding system, it is theoretically possible to design and install the grid in such a way that the mesh voltage can be kept within desired limits.

The mesh voltage values are obtained as a product of the geometrical factor "K_m", a corrective factor "K_i" that accounts for some of the error introduced by the assumptions made in deriving K_m, the soil resistivity "ρ", and the average current per unit of effective buried length of the grounding system conductor (I_G/L_M),

$$\mathbf{E_m = \frac{3.28 * \rho * K_m * K_i * I_G}{L_M}}$$

Where:

ρ = Soil resistivity, ohm-m
K_m = Spacing factor for mesh voltage, simplified method
K_i = Correction factor for grid geometry, simplified method
Lc = Total length of grid conductor in feet
L_R = Total length of ground rods in feet
L_M = Effective length of Lc + L_R for mesh voltage in feet

Please note that several simplifying assumptions are made in deriving the equations for E_m and E_s.

I_G = Maximum grid current that flows between ground grid and surrounding earth (including DC offset) in amperes

The geometrical factor, K_m, is expressed by,

$$\mathbf{K_m = \frac{1}{(2*\pi)} * \left[\ln\left(\frac{D^2}{(16*h*d)} + \frac{(D+2*h)^2}{(8*D*d)} - \frac{h}{4*d}\right) + \frac{K_{ii}}{K_h} * \ln\left(\frac{8}{\pi*(2*n-1)}\right)\right]}$$

Where:
D = Spacing between parallel conductors in feet
d = Diameter of grid conductors in feet
h = Depth of ground grid conductors in feet
n = Geometric factor composed of factors n_a, n_b, n_c, and n_d
K_h = Corrective weighting factor that emphasizes the effects of grid depth, simplified method
K_{ii} = Corrective weighting factor that adjusts for the effects of inner conductors on the corner mesh, simplified method

For grids with ground rods along the perimeter, or for grids with ground rods in the grid corners as well as both along the perimeter and throughout the grid area, K_{ii} = 1. For grids with no ground rods or grids with only a few ground rods, none located in the corners or on the perimeter,

$$\mathbf{K_n = \frac{1}{(2*n)^{\frac{2}{n}}}}$$

$$\mathbf{K_h = \sqrt{(1 + \frac{h}{h_o}}}$$

Where,
h_o = Grid Reference Depth

The effective number of parallel conductors in a given grid, "n", can be made applicable both to rectangular or irregularly shaped grids that represent the number of parallel conductors of an equivalent rectangular grid,

$$\mathbf{n = n_a * n_b * n_c * n_d}$$

Where,

$$\mathbf{n_a = \frac{2 * L_C}{L_F}}$$

n_b = 1 for square grids
n_c=1 for square and rectangular grids
n_d = 1 for square, rectangular, and L-shaped grids

Otherwise,

$$\mathbf{n_b = \sqrt{\frac{L_p}{4 * \sqrt{A}}}}$$

$$\mathbf{n_c = \left[\frac{L_x * L_y}{A}\right]^{\frac{0.7 * A}{L_x * L_y}}}$$

$$\mathbf{n_d = \frac{D_m}{\sqrt{(L_x^2 + L_y^2)}}}$$

L_C = Total length of the conductor in the horizontal grid in feet
L_p = Peripheral length of the grid in feet
A = Area of the grid in ft^2
L_x = Maximum length of the grid in the x direction in feet
L_y = Maximum length of the grid in the y direction in feet
D_m = Maximum distance between any two points on the grid in feet
D = Spacing between parallel conductors in feet
d = Diameter of grid conductors in feet
h = Depth of ground grid conductors in meters

The irregularity factor, K_i, used in conjunction with the above-defined n is expressed by,

$$\mathbf{K_i = 0.644 + 0.148 * n}$$

For grids with no ground rods, or grids with only a few ground rods scattered throughout the grid but none located in the corners or along the perimeter of the grid, the effective buried length, L_M, is expressed by,

$$\mathbf{L_M = L_C + L_R}$$

Where:
L_R = Lc = Total length of grid conductor in feet
L_R = Total length of ground rods in feet
L_M = Effective length of Lc + L_R for mesh voltage in feet

For grids with ground rods in the corners, as well as along the perimeter and throughout the grid, the effective buried length, L_M, is expressed by,

$$\mathbf{L_M = L_C + \left[1.55 + 1.22\left(\frac{L_r}{\sqrt{L_x^2 + L_y^2}}\right)\right] * L_R}$$

Where:
L_r = Length of each ground rod in feet

Step Voltage (E_s)
Step voltages within a grid system designed for safe mesh voltages will be well within tolerable limits. This is because step voltages are usually smaller than touch voltages, and both feet are in series rather than parallel. Also, the body can tolerate higher currents through a foot-to-foot path since the current does not pass close to the heart. The step voltage has to be less than the tolerable step voltage for the ground system to be safe.

The step voltage values are obtained as a product of the geometrical factor "K_s", the corrective factor "K_i", the soil resistivity "ρ", and the average current per unit of buried length of grounding system conductor (I_G/L_S):

$$\mathbf{E_S = \frac{3.28 * \rho * K_s * K_i * I_G}{L_S}}$$

Where:
ρ = Soil resistivity, ohm-m
K_s = Spacing factor for step voltage, simplified method

K_i = Correction factor for grid geometry, simplified method
I_G = Maximum grid current that flows between ground grid and surrounding earth (including DC offset) in amperes
L_S = Effective buried conductor length in feet

For grids with or without ground rods, the effective buried conductor length, L_S, is expressed by,

$$\mathbf{L_S = 0.75 * L_C + 0.85 * L_R}$$

Where:
L_c = Total length of grid conductor in feet
L_R = Total length of ground rods in feet

The maximum step voltage is assumed to occur over a distance of 3.28 feet, beginning at and extending outside the perimeter conductor at the angle bisecting the most extreme corner of the grid. For the usual burial depth of 1.0' < h < 1.0', K_s is expressed by,

$$\mathbf{K_S = 1.05 * \left[\frac{1}{2 * h} + \frac{1}{D + h} + (\frac{1}{D} * (1 - 0.5^{(n-2)})\right]}$$

Where:
D = Spacing between parallel conductors in feet
h = Depth of ground grid conductors in feet
n = Geometric factor composed of factors n_a, n_b, n_c, and n_d

<u>Ground Potential Rise (GPR)</u>

In all the above situations for step, touch, and transferred voltage, the actual voltage potential encountered by the person involved is related to the ground potential rise of the grounding system above remote earth. This fact stresses the importance of keeping that value as low as possible. *Ground potential rise* is the maximum electrical potential that a substation grounding grid may attain relative to a distant grounding point assumed to be at the potential of remote earth. This voltage, GPR, is equal to the maximum grid current times the grid resistance,

$$\mathbf{V_{GPR} = I_G * R_g}$$

Where:
V_{GPR} = Ground potential rise in volts
I_G = Maximum grid current in amperes
R_g = Ground grid resistance in ohms, where,

$$\mathbf{R_g = \rho * \left[\frac{1}{L_T} + \frac{1}{\sqrt{20 * A}} * \left(1 + \frac{1}{\left(1 + h * \sqrt{\frac{20}{A}}\right)}\right) \right]}$$

Where:
h = Depth of the grid in feet
A = Area occupied by the ground grid in ft^2
L_T = Total buried length of conductors in feet
ρ= Soil resistivity in ohm-m

The equation shows that the larger the area covered by the grounding system and the greater the total length of the grounding conductor used, the lower will be the value of Rg for a given average earth resistivity. It also shows that a low earth resistivity is very important in keeping Rg low.

Earth resistivity varies with the temperature and moisture content of the soil and whether the soil is frozen or unfrozen. For a given location, the earth resistivity is usually not controlled by the substation designer, although, in cases of very high soil resistivity, special treatments are sometimes used to help lower the value of "ρ".

Whenever the product "I_gR_g" results in a voltage below the tolerable touch voltage there is not any danger of ventricular fibrillation to most humans from body contact in any of the cases discussed. If the product "I_gR_g" is in excess of allowable voltage values, then attention has to be given to elimination of possible exposure to transferred potentials and further investigation of touch and step potentials.

Design Modifications

If the calculated grid mesh and step voltages are much greater than the maximum touch and step voltages, then the preliminary design has to be modified. To reduce the grid mesh and step voltages, the following modifications can be tried:

1. Decrease the mesh size by increasing the number of parallel conductors in each direction.

2. Increase the thickness of the layer of surface rock. A practical limit to the depth of the rock may be 6 inches.

3. Limiting the total fault current, if feasible will decrease the GPR and all gradients in proportion. Other factors, however, will usually make this impractical. Moreover, if accomplished at the expense of greater fault clearing time, the danger may be increased rather than diminished.

Other effective measures can be taken to reduce the design mesh and step voltages. Their effects cannot be modeled using the simplified design equations and have to be modeled using a computer program such as EPRI SGSYS. These measures include the following:

1. Place additional parallel conductors around the perimeter of the grid to produce smaller perimeter mesh. The smaller mesh will reduce the mesh and step voltages at the perimeter of the grid. The resulting unequally sized mesh throughout the grid violates one of the assumptions of the simplified design equations.

2. Divert fault current to alternative paths. Diverting fault current is generally accomplished by ensuring that all power line overhead shield wires that enter the substation are connected to the ground grid. The calculated split factor assumes that all shield wires have already been connected to the grid. Using larger shield wires or shield wires of a higher conductivity may divert additional fault current. For very small substation sites with high soil resistivities, this may be the only method that will bring the grid design into conformance with the safety criteria.

3. If a two-layer soil model indicates that the bottom soil layer has a lower resistivity than the upper soil layer and lies deeper than 10 feet, use longer ground rods to reach the lower resistivity layer.

4. At a site with high-resistivity soil, drill a well and use it as a point of low resistance.

If all the above methods fail to obtain a grid design with safe mesh and step voltages, study and apply the following modifications where appropriate.

1. Supplementing the grid conductors with deeply placed electrodes. This is required where the earth in which the grid conductors are buried is of resistivity too high to economically achieve a satisfactory resistance to remote earth. Such a situation may occur because of the natural character of the earth. High earth resistivity may also be seasonal because of the earth’s drying out or becoming frozen. A decision on application of electrodes should necessarily be conservative because of the probabilistic nature of the problem. Seriously consider application of deep electrodes wherever relatively high resistivity in shallow earth will be experienced. Rods are the most commonly used electrodes. Other types of electrodes, such as ground wells, are also used.

2. Use of soil additives and treatments to increase the soil conductivity by reducing the resistivity of the soil.

3. Use of wire mats. It is feasible to combine both a surface material and fabricated mats made of wire mesh to equalize the gradient field near the surface. A typical wire mat might consist of copper-clad steel wires of No. 6 AWG, arranged in a 24 x 24 inch grid pattern, installed on the earth's surface and below the surface material, and bonded to the main grounding grid at multiple locations.

4. Wherever practical, use of a nearby deposit of low-resistivity material of sufficient volume to install an extra grid. This satellite grid, when sufficiently connected to the main grid, will lower the overall resistance and, thus, the ground potential rise of the grounding grid. The nearby low-resistivity material may be a clay deposit or it may be a part of some large structure, such as the concrete mass of a hydroelectric dam.

5. Barring access to certain areas, where practical, to reduce the probability of hazards to personnel.

Use of Computer Analysis in Grid Design

Several reasons justify the use of computer analysis in designing the grounding system:

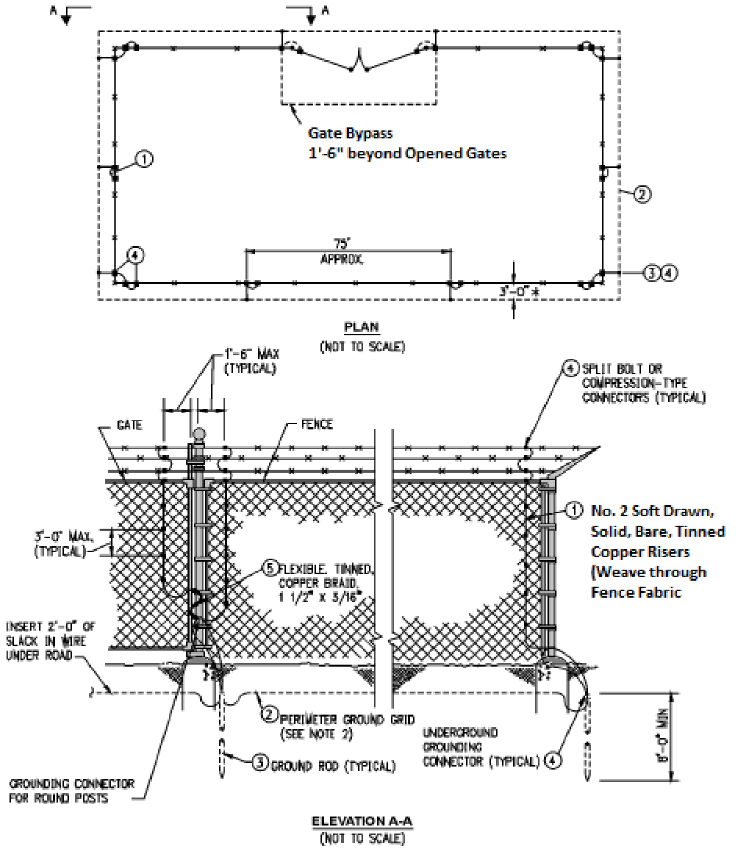
1. Parameters exceed those of the simplified design equation.
2. A two-layer or multi-layer soil model is preferred because of significant variations in soil resistivity.
3. Uneven grid conductor or ground rod spacing cannot be analyzed using the approximate methods presented in this chapter.
4. More flexibility in determining local danger points may be desired.
5. The presence of buried metallic structures or conductors not connected to the grounding system introduces complexity to the system.
6. The preliminary design can be optimized and analyzed.

Special Danger Points

The grounding of the substation fence is critical because the fence is generally accessible to the public. The substation grounding design should be such that the touch potential on both sides of the fence is within the calculated tolerable limit of touch potential.

The substation fence should be connected to the main ground grid by means of an outer grid conductor installed a minimum of 3 feet outside the substation fence as shown in Figure 4.

Typical Chain Link Fence Grounding



NOTES:

1 THE FENCE GROUND IS TO BE INTERCONNECTED WITH THE STATION GROUND BUS.

2. PERIMETER GROUND WIRE SHOULD BE CONTINUOUS CABLE CONNECTED TO FENCE POSTS, TO ALL GATE POSTS, AND TO ALL CORNERS.

3. WIRE TO BE LOOPED THROUGH GROUND ROD CLAMPS AND FENCE CLAMPS TO KEEP WIRE SPLICES TO A MINIMUM.

4. FOR OTHER REQUIREMENTS REFER TO S-6, RUS SPECIFICATIONS FOR GROUNDING IN STEAM-ELECTRIC GENERATING PLANTS AND ASSOCIATED STEP-UP SUBSTATIONS.

5. CONNECTIONS BETWEEN FENCE GROUND AND STATION GROUND BUS SHOULD BE AT INTERVALS SUCH AS TO LIMIT POTENTIAL GRADIENTS (STEP POTENTIALS) AND SHOULD GAVE ADEQUATE CURRENT-CARRYING CAPACITY FOR THE MAXIMUM FORESEEABLE GROUND FAULT CURRENT.

6. MINIMUM FENCE HEIGHT SHALL BE SEVEN FEET. THIS SHOULD NORMALLY CONSIST OF SIX FEET OF FABRIC AND A ONE-FOOT EXTENSION OF BARBED WIRE. RUS RECOMMENDS EIGHT FEET FOR THE FENCE HEIGHT; SEVEN FEET OF FABRIC AND A ONE-FOOT EXTENSION OF BARBED WIRE. WHERE LOCAL ORDINANCES PROHIBIT THE USE OF BARBED WIRE, THE FENCE FABRIC MUST BE INCREASED TO SEVEN FEET. BARBED WIRE SHOULD OVERHANG AWAY FROM THE SUBSTATION YARD.

Figure 4

Connections to the outer grid conductor should be made at all corner posts and at line post every 40 to 50 feet. The gateposts should be securely bonded to the adjacent fence as shown in Figure 4. It is recommended that all gates swing inward and be designed and installed to prevent an outward swing. If gates are installed with an outward swing, then the ground grid should extend a minimum of 3 feet past the maximum swing of the gate. The reasons to extend the ground grid to cover the swing of the gate are the same as the reason to install a ground conductor 3 feet outside the fence. The voltage above remote earth decreases rapidly as one leaves the substation grounding area. For example, if a person standing outside the substation grounding grid touches a fence or outward-swung gate under substation fault conditions, the resulting potential difference could be large enough to pose a serious danger.

Equipment operating handles are a special circumstance because of the higher probability for coincidence of adverse factors, namely, the presence of a person contacting grounded equipment and performing an operation that can lead to electrical breakdown. If the grounding system is designed conservatively for safe mesh potentials, then the operator should not be exposed to unsafe voltages. However, because of the uncertainty inherent in substation grounding design, a metal grounding platform (mat), connected to the operating handle should be placed where the operator should stand on it to operate the device regardless of whether the operating handle is insulated.

Considerations involved in the switch grounding platform ground conductor include the following:

1. Proper grounding calculations and grid design should result in acceptable touch and step potential voltages without the additional grounding platform grounding. However, since the operation of the switch places the operator directly at risk when a substation fault occurs, additional precautions are needed. This includes adding switch grounding platforms and a 3 to 6-inch layer of clean crushed rock that covers the entire area inside the substation fence and extends 3 to 4 feet outside the substation fence to reduce the risk of electric shock.

2. Switch grounding platform grounding is added to minimize the voltage between the switch operator's hands and feet in the event of a fault at the switch during manual operation.

3. The basic methods to minimize the hand-to-foot voltage at the switch handle include the following: Minimize the current that flows in the conductor that connects the equipment grasped by the hand and the surface that is stood on, and minimize the resistance of the electrical connection between the hands and feet.

The grounding platform should be connected to the operating handle by a copper cable that connects to the operating handle and the grounding platform as shown in Figure 5.

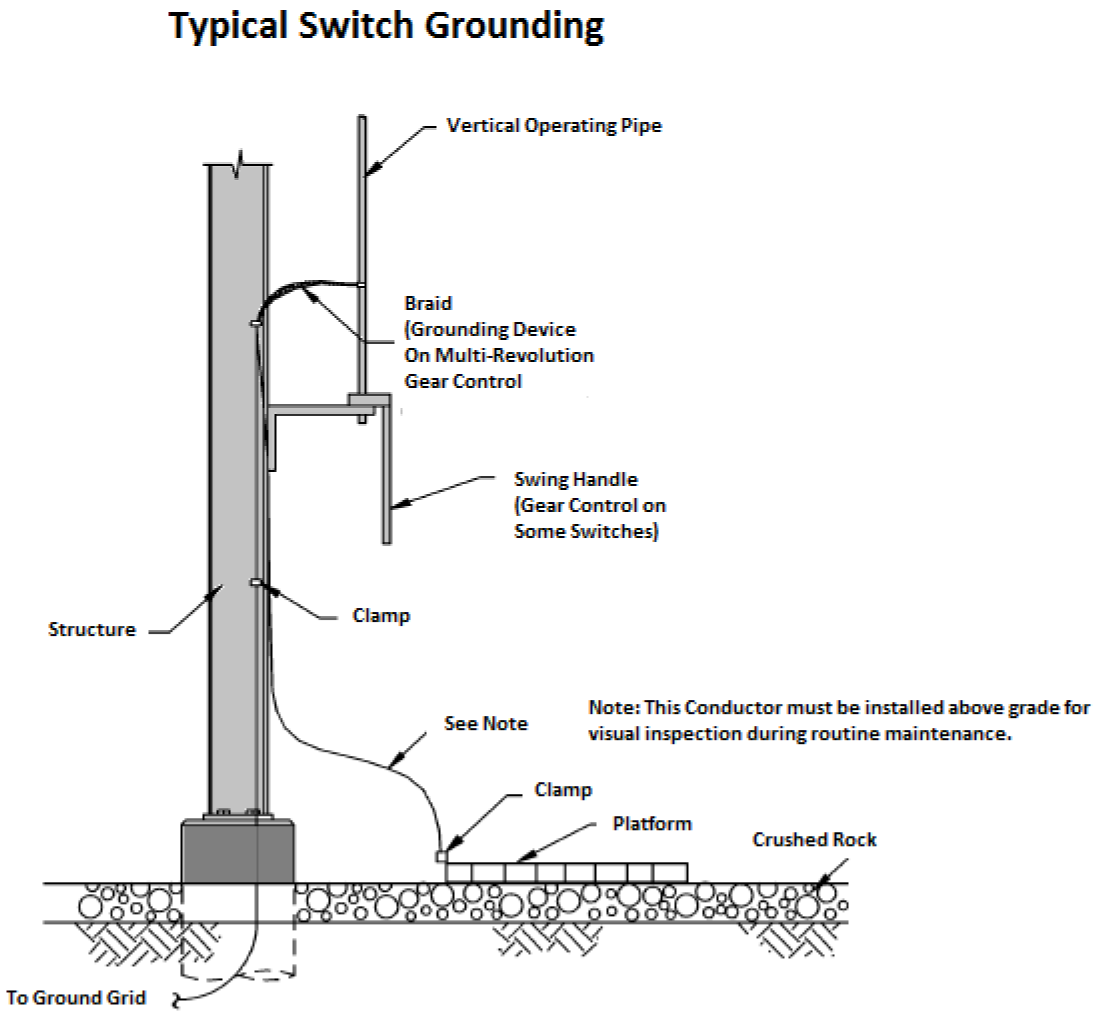


Figure 5

Figure 5 provides a grounding system for a switch operator operating the switch handle. With no other ground cable connection to the grounding platform, minimal current will flow through the operator’s body to the platform since it will be insulated from the earth and conductor because of the surface rock. The hand-to-foot voltage will be minimized and closely maintained with this connection. The grounding platform area needs to be kept clean of contamination and vegetation. If the grounding platform conductor to the switch handle breaks, then the contamination or vegetation touching the grounding platform can result in the grounding platform’s potential being close to that of the ground grid, which is a less safe situation.

The design engineer should be familiar with the application of switch handle grounding and operator platform grounding by utilizing the latest available standard and updates on this subject. The engineer also should develop a safety procedure checklist regarding all grounding aspects of the switch operator handle for the utility maintenance crew to follow before attempting to operate the switch.

Metallic Cable Sheaths

Metallic cable sheaths in power cable have to be effectively grounded to prevent dangerous voltages resulting from insulation failure, electrostatic and electromagnetic induction, flow of fault current in the sheath, and voltage rise during fault current flow in the substation ground system to which the sheaths are connected. Cable sheaths should be grounded at two or more locations: at cable terminations and at splices and taps. Control cable shields are not intended to carry significant current and thus should only be grounded at one end. Where any cable sheath may be exposed to excessive ground current flow, a parallel ground cable should be run and connected to both ends.

Surge Arresters

Surge arresters are designed to pass surge energy from lightning and switching transients to ground and so are frequently subjected to abnormal current flow to ground. They have to be reliably grounded to ensure protection of the equipment they are protecting and to minimize high potential gradients during operation. The surge arrester grounds should be connected as close as possible to the ground terminals of the apparatus to be protected and have as short and direct a path to earth as practical. Arrester leads should be as free from sharp bends as practical. The tanks of transformers and steel or aluminum structures may be considered as the path for grounding arresters, provided effective connections can be made and secure multiple paths are available. Where there can be any question regarding the adequacy of these paths, it is recommended that a separate copper conductor be used between the arrester ground terminal and the substation grounding grid.

Investigation of Transferred Voltage

Transferred voltage contact may be considered a special case of the “touch” contact. A potential hazard may result during a ground fault from the transfer of potentials between the ground grid areas and outside points by conductors such as communication circuits, low-voltage neutral wires, conduit, pipes, rails, metallic fences, etc. A person standing within the substation touches a conductor grounded at a remote point, or a person standing at a remote point touches a conductor connected to the substation grounding system. Here, the shock voltage may be essentially equal to the full voltage rise of the grounding system under fault conditions and not the fraction of this total that is encountered in the usual “step” or “touch” contacts.

It is impractical and often impossible to design a grounding system based on the transferred voltage. 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. Carefully examine the presence of any situations involving possible transferred voltage and take steps to eliminate or avoid them.

Effect of Sustained Ground Currents

After the grounding design has been established as safe for the maximum ground fault current at the appropriate clearing time, check step and touch voltages for sustained ground currents.

Sustained currents are those currents below the setting of protective relays that may flow for a long time. Currents produced through the body as a result of these long-duration currents should be below safe let-go values. 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.

Chapter 6
Corrosion

Corrosion is the deterioration of a metal by chemical or electrochemical reaction with its environment. The basic reason for corrosion problems in and around the substation grounding grid is electrochemical in nature.

The way in which corrosion affects underground structures varies depending on the mechanism and circumstances. In general, there are two types of corrosion. One is the general metal loss in which the entire surface of the metal exposed to the soil in a given area is corroded away. Typical of this is the general thinning of strands on a concentric neutral cable throughout the area. The second type of corrosion is localized or *pitting-type* corrosion. In this form, very local areas of metal are attacked while the metal immediately adjacent remains untouched. This type of corrosion can also be found on concentric neutral cables. It generally results in the breakage of many of the individual strands of the neutral, rendering it disconnected and either useless or significantly reduced.

The important difference between local pitting corrosion and general metal loss is that it takes very little metal loss of the local pitting type of corrosion to cause a complete loss of continuity in a neutral wire or to penetrate a pipe wall or lead sheath. Therefore, local pitting-type corrosion is more serious to the power industry. See Figure 6.

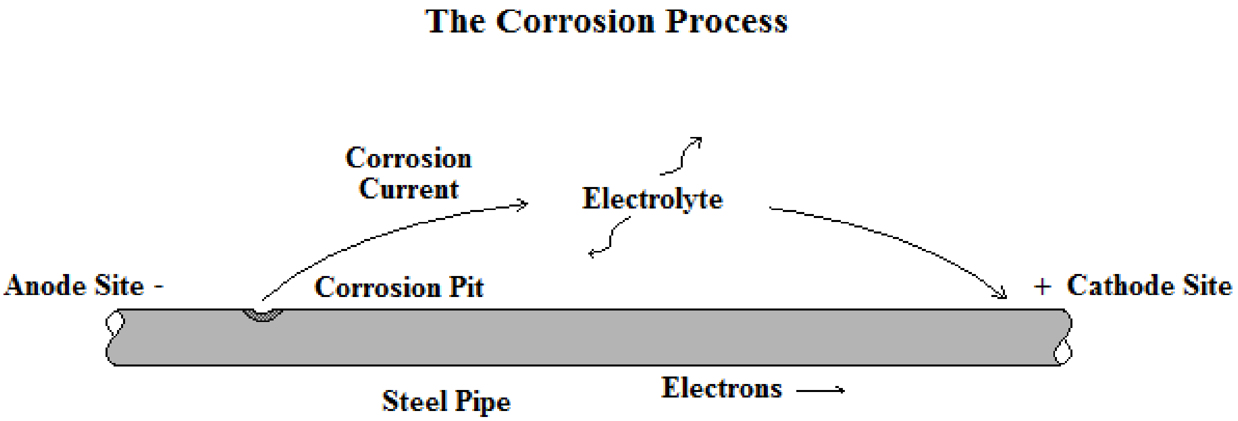


Figure 6

The substation grounding grid corrosion is caused by an electrochemical reaction in the soil environment called a *galvanic cell* or sometimes a “corrosion cell.” The galvanic cell is made up of three parts: the anode, the cathode, and the electrolyte. The environment that we are talking about (soil, in this example) is called the *electrolyte*. The electrolyte is defined as an ionic conductor. In other words, it transfers or allows the transfer of ions. The electrode at which chemical reduction occurs is called the *cathode* (positive current enters the cathode from the electrolyte). The electrode at which chemical oxidation (corrosion) occurs is called the *anode* (positive current leaves the anode and enters the electrolyte). It is necessary for the anode and the cathode to be connected together electrically to complete the corrosion cell. For a corrosion cell to function, there has to be an electrical potential between the anode and the cathode. This electrical potential can result from a number of conditions. Two of the most common corrosion cells encountered result from:

1. Dissimilar metals in the same environment

2. The same metal in dissimilar environments

1. Dissimilar Metals. When two dissimilar metals are placed in the same environment, there will be a difference in DC voltage because of the different activity levels that the metals occupy in the Electromotive Force (EMF) Series. In a typical substation, a voltage difference on the order of 1-volt will probably exist between a copper ground cable and galvanized steel structures, and a DC corrosion current will flow from the steel. The current will be limited by the resistance between the structures in accordance with Ohm's law and also by surface films, which may greatly reduce the current and the rate of corrosion. Another example of dissimilar metal corrosion would be an underground bare copper cable and a galvanized conduit buried in the ground inside a substation.

2. Dissimilar Environments. Differences in DC potential along the ground grid conductors or concentric neutrals can be caused by varying oxygen concentrations, different values of pH, or because the soil resistivity varies over a fairly wide range. In this case, areas effected by corrosion may be at random locations that would have to be located.

One element that is very important in its effect on underground corrosion is oxygen. Either through its presence or its absence, oxygen is one of the primary causes of metal deterioration underground. As a result of soil compaction during backfill, the type of soil, or the steel conduit being laid in the bottom of the trench, steel conduits often have less oxygen near the bottom of the pipe. Depending on the type of soil (sandy, clay, loam, etc.), the pipe may vary from anodic to cathodic. This generally does not occur in smaller substations, but should be a consideration in larger substations.

Preliminary Preventive Measures

It is important that certain preliminary data be obtained prior to final site selection so that corrosion problems can be avoided or minimized. This procedure ensures that design and/or material selection will minimize possible corrosion problems. The preliminary data should include the following items.

A soil resistivity survey at each proposed site is the necessary first step, since the economic choices of materials and designs will vary with soil resistivity. Once soil resistivities are known, decisions can be made regarding overhead or underground feeder construction, the use of jacketed cable, and anodes or other cathodic protection against corrosion. For soils of high resistivity (over 200 ohm-meter) where both grounding and cathodic protection are difficult to accomplish, semiconducting jacketed cable may be the most effective. One way to obtain this information would be using the four-pin method as mentioned in Chapter 1.

A pH survey of each substation site should also be a part of any corrosion evaluation. Soils seldom have a pH lower than 5 (acid) or greater than 8 (alkaline), where 7.0 is neutral. Soils with a pH of 5 and lower can contribute to severe corrosion and rapid deterioration of exposed metals. Acid soil conditions are usually limited to soils containing decomposed acidic plants and needles from coniferous trees. Soils with a pH of 8 and above can contain a high concentration of dissolved salts resulting in a low soil resistivity. Soils of this type are referred to as alkaline or calcareous. Alkaline soils are high in sodium and potassium, while calcareous soils are high in magnesium and calcium. Alkaline earth elements such as magnesium and calcium tend to form protective layers on ferrous metal surfaces and are considered favorable environments for metals.

Select materials to minimize dissimilar-metal corrosion effects due to buried copper and steel (or other metals) in the same environment. For example, the grounding system at any one substation location should consist wholly either of copper or steel. This is particularly important in corrosive soils such as those with low values of earth resistivity (less than 20 to 30 ohm-meter). No commonly used material can be wholly immune to possible corrosion damage. However, in the absence of a planned maintenance program to periodically determine the specific condition of ground grid conductors, the final choice of material should consider the available, proven historical records of the materials under consideration.

Where buried steel such as steel anchor assemblies, piping, and conduit is of necessity connected to the copper grounding grid for safety, the higher the ratio of steel-to-copper surface area, the less likely will be the adverse effects of corrosion of the steel. Where the copper grounding system is the only metal placed in the substation soil, be alert for possible interconnected steel in nearby line anchor assemblies, piping, wells, conduit, or oil or gas lines that may be inadvertently connected to the grounding system and subject to accelerated corrosion. If such conditions exist, cathodic protection of the interconnected steel may be necessary. For large substations, a rectifier-type cathodic protection scheme may be required.

Testing and Installation

Earth resistivity in undisturbed soil may be determined typically with a four-terminal ground tester and test electrodes. Avoid test locations close to parts of an existing ground mat or other buried metal.

Obtain soil samples at the approximate depth of the underground structures in the substation. These samples can usually be obtained with a soil auger. A pH reading can be taken immediately, or the soil can be stored in an airtight container such as a plastic bag and the readings taken at a later time. Lower pH values generally indicate more corrosive soils. These tests can be handled by a testing laboratory or done in house using commercially available soil testing kits.

Sacrificial anodes, where used, should be placed:

1. At locations of the lowest resistivity soil within or near the substation area.
2. At depths at least equal to those of the ground grid and/or other assemblies to be protected.
3. Ten to twenty feet away from the buried bare conductors or other assemblies, to the extent that space allows usual anode locations are at edges or corners of the ground grid, and at structures in low-resistivity locations near the substation. The connection from anode to the system neutral and station grid should be reliable and have low resistance. Compression fittings or exothermic welded connections are preferable to bolted connections or clamps.

Exothermic welding is preferred to clamps or bolted connections for dissimilar-metal (copper-to-steel) connections underground. For similar metal, copper-to-copper or steel-to-steel (galvanized) connections, suitable bolted or clamped connections with clamps of the same material should be satisfactory. Cover welds with mastic or other underground coating (such as used for pipelines) in very corrosive soils with resistivities in the range below 10 ohm-m. In most soils this is not considered necessary.

Estimating Corrosion Conditions from DC Potential Measurements

One frequently used indicator of corrosion or freedom from corrosion is the DC potential (voltage) measured from a copper–copper sulfate reference electrode or half-cell. This measurement is made as shown in Figure 7.

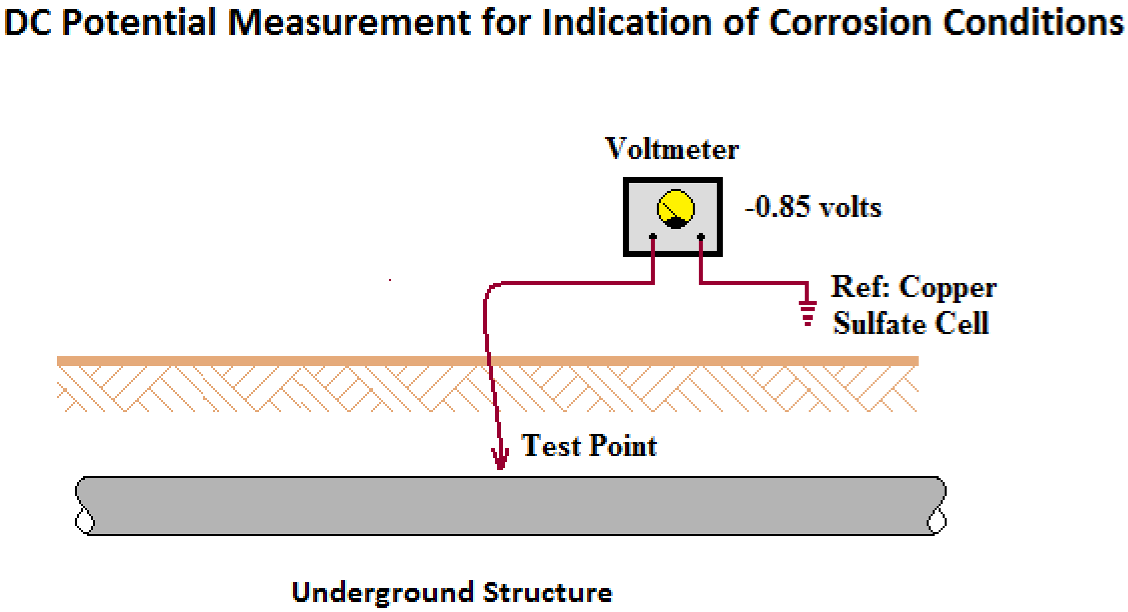


Figure 7

The copper–copper sulfate half-cell is a copper rod surrounded by a saturated solution of copper sulfate in water, with a porous plug to allow the solution to come in contact with the soil. The voltmeter usually is a potentiometer (null-type) voltmeter or a special high-resistance (10 megohms or higher) low-range voltmeter. However, a useful reading may also be possible with a 20,000 ohm-per-volt DC meter with a 2.5-volt range.

The variations in DC potential are small and often expressed in millivolts. Usually, the neutral is negative with respect to the copper–copper sulfate half-cell. Table 5 lists some typical potentials for metals and combinations of metals that may be present and connected to a substation ground grid.

Table 5

DC Potentials of Various Buried Metals

Buried Metal	Typical Potential Volts
Zinc	-1.1 or less

New Galvanized Steel	-1.1 or less
Steel fully protected against corrosion	-0.85 or less
Old buried Steel pipe	-0.65
Copper-grounded neutral with anchors and Steel piping connected	-0.50
All-Copper grounded neutral	-0.30

DC potential measurements indicate the effectiveness of anodes for cathodic protection. For example, anodes may be installed at a copper-grounded substation to relieve corrosion of anchor rods near the substation. If the anodes are effective, the station ground grid becomes more negative. The potential might be shifted from –0.55 volt to –0.75 volt. In a situation where original anchor rods have begun to fail after 15 years, such a change in potential should be adequate to ensure permanence of the newly installed anchors. In very corrosive soils (such that anchor rods might otherwise fail in five years or less), a shift to at least –0.85 volt may be needed for complete protection.

Very little is known about potentials of copper corroding in soil. However, copper corrosion has been observed in a neutral to moderately alkaline soil (pH 7.1 to 8.0) at potentials of –0.10 to +0.047 volt with reference to a copper–copper sulfate half-cell. If cathodic protection of copper is found to be necessary, a potential of –0.35 volt is suggested for purposes of design.

In distribution substations, underground exit feeders with bare concentric neutrals may be vulnerable to corrosion. They should be provided with cathodic protection if the possibility of corrosion is believed to exist. In addition to DC potentials, the measurements in Table 6 have significance in underground corrosion surveys. Earth resistivity measurements help to indicate the degree of corrosiveness of the soil. Low resistivity soils (lower than 15 to 20 ohm-m) are regarded as relatively corrosive to steel or copper. High resistivity, well-aerated soils such as sand and gravel may also be corrosive to copper. Locations of sudden change in earth resistivity, including roadside ditches where salt accumulates, are probable locations of corrosion.

Table 6

Soil Corrosiveness vs. Resistivity

Corrosiveness	Resistivity
Severely Corrosive	0-5 ohm-m
Very Corrosive	5-10 ohm-m
Corrosive	10-30 ohm-m

Moderately Corrosive	30-100 ohm-m
Slightly Corrosive	100-250 ohm-m
Less Corrosive	>250 ohm-m

Guy current measurements, at cable terminal poles and other guyed poles nearby, indicate locations of anchor rod corrosion and probable corrosion of other buried steel in the vicinity. Neutral-to-earth resistance measurements indicate the overall effectiveness of grounding. Multi-grounded electric distribution neutrals normally have a low resistance to earth.

Summary

This course covered electrical substation grounding. Grounding is concerned with safe grounding practices and design for outdoor AC substations for power frequencies in the range of 50 to 60 Hz. An effective substation grounding system typically consists of driven ground rods, buried interconnecting grounding cables or grid, equipment ground mats, and connecting cables. The course reviewed the parameters associated with designing an effective and safe ground grid.

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