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Guide
for
**SAFETY IN ALTERNATING-CURRENT
SUBSTATION GROUNDING**

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CONTENTS

Section	Page
1.00 PURPOSE AND SCOPE	5
2.00 THE BASIC PROBLEM IN SAFE GROUNDING	5
3.00 WHAT DOES IT TAKE TO MAKE AN ACCIDENT?	6
4.00 TOLERABLE LIMITS OF BODY CURRENT	6
Effects of Frequency, Magnitude, Duration, Reclosures, and Current Paths Through the Body	
5.00 IMPORTANCE OF HIGH-SPEED CLEARING OF FAULTS	8
6.00 TOLERABLE POTENTIAL DIFFERENCES — STEP, TOUCH AND TRANSFERRED VOLTAGES	8
7.00 DESIGN PROCEDURE	10
8.00 INVESTIGATION OF SOIL CHARACTERISTICS	10
Soil Type, Resistivity Measurements, Capacitance, Effects of Voltage Gradient, Chemical Content, Moisture, Temperature and Current Magnitude	
9.00 DETERMINATION OF MAXIMUM GROUND CURRENT	12
Procedure; Types of Ground Faults; Symmetrical Component of Ground Cur- rent at Time of Fault Initiation; Effect of Direct-Current Offset — The Decrement Factor; Effect of Future Changes; Effect of Station Ground Re- sistance; Overhead Ground Wire; Directly Buried Pipes and Cables	
10.00 PRELIMINARY DESIGN OF GROUNDING SYSTEM	16
Type of Ground System; Advantages of Grid; Preliminary Design of Grid; Connections to Grid; Ground Conductor Size; Ground Conductor Material; Conductor Length Required for Gradient Control; Effect of Irregularities — The Non-Uniformity Factor K_1	
11.00 CALCULATION OF RESISTANCE OF GROUNDING SYSTEM	22
12.00 CALCULATION OF MAXIMUM GRID POTENTIAL RISE	22
13.00 CALCULATION OF STEP VOLTAGES AT PERIPHERY	22
14.00 CALCULATION OF INTERNAL STEP AND TOUCH VOLTAGES	24
General; Effect of Sustained Ground Currents	
15.00 INVESTIGATION OF TRANSFERRED POTENTIALS	24
Communication Circuits; Rails; Low-Voltage Neutral Wires; Portable Equip- ment and Tools Supplied from Substation; Pipes; Auxiliary Buildings	
16.00 INVESTIGATION OF SPECIAL DANGER POINTS	25
Operating Handles; Fences; Cable Sheath Grounding; Lightning Arrester Grounding; Separate or Common Grounds	
17.00 CORRECTION OR REFINEMENT OF PRELIMINARY DESIGN	28
18.00 CONSTRUCTION OF GROUNDING SYSTEM	29
19.00 MEASUREMENT OF RESISTANCE OF GROUNDING SYSTEM AS CONSTRUCTED	29
20.00 FIELD SURVEY OF POTENTIAL CONTOURS AND STEP AND TOUCH VOLTAGES	32
21.00 RECALCULATION BASED ON FIELD MEASUREMENTS — REVISION OF DESIGN	33
22.00 CHECKING SAFETY OF EXISTING STATIONS	33
23.00 MODEL TESTS	33
24.00 USE OF ELECTRONIC COMPUTERS	33
25.00 PERIODIC CHECKS	33
26.00 CONCLUSIONS	33

Section	Page
APPENDIX I MATHEMATICAL ANALYSIS OF GRADIENT PROBLEM	35
APPENDIX II SAMPLE CALCULATION	39
APPENDIX III GROUNDING PRINCIPLES AND PRACTICE — FUNDAMENTAL CONSIDERATIONS ON GROUND CURRENTS By Reinhold Rudenberg. Reprinted from Electrical Engineering, January 1945. (Reference 16)	
Resistance of the Soil	43
Spherical Ground Electrodes	43
Rod and Wire Electrodes	46
Heating of the Ground	51
Linearly Extended Fields	53
Impulse Characteristics	58
Conclusions	61
APPENDIX IV GENERAL FUNDAMENTALS OF ELECTRICAL GROUNDING TECHNIQUE By Pierre Laurent. Trans- lation of Article in Bulletin de la Societe Francaise des Electriciens, July 1951. (Reference 28)	
Classification and Performance of Electrodes	62
Electrical Characteristics of the Earth	66
Review of Electrodes According to Shape	68
Multiple Electrodes — Interaction	79
Review of Some Special Problems	
Resistance and Gradients in Large Stations	84
Coupling Between Electrodes	85
Currents in Overhead Ground Wires	86
Discharge of Earth Currents from Buried Cable Sheaths	86
Earth Currents in Sheets of Water	87
Restricted Conductive Areas in Very Resistant Sites	87
High Conductivity Geological Faults	88
Use of Salts, Coke or Charcoal	88
Current Diverted Through Human Body	88
APPENDIX V MEASUREMENT OF GROUND POTENTIALS IN A 220 KV SUBSTATION By H. Langer. Translation of Article in Elektrotechnische Zeitschrift, Feb. 11, 1954. (Reference 38)	
Introduction	91
Statement of the Problem	91
Description of the Ground System	91
Ground System Layout	91
Procedure of Measurement and Instruments	92
Total Distributed Resistance of the Grounding System	94
Approximate Calculation of the Total Distributed Resistance from the Dis- tributed Resistances of the Components	95
Limits of Accuracy of Potential Measurements	96
Profile of Ground Potential Along Sections Through the Substation	97
Relief Map of Earth Potentials	98
Contact and Step Potentials in the Current-Loaded Grounding System	98
Summary	101
APPENDIX VI GROUNDING METHODS FOR HIGH-VOLTAGE STATIONS WITH GROUNDED NEUTRALS. By Walter Koch. Translation of Article in Elektrotechnische Zeitschrift, Feb. 1950 (Reference 54)	103
BIBLIOGRAPHY WITH ABSTRACTS	108
BIBLIOGRAPHY INDEX OF AUTHORS	136

GUIDE TO SAFETY IN ALTERNATING-CURRENT SUBSTATION GROUNDING

1.—PURPOSE AND SCOPE

The purpose of this Guide is:

1. To review grounding practices with especial reference to safety.
2. To establish, as a basis for design, the safe limits for potential differences which can exist in a station, under fault conditions, between points which can be contacted by the human body.
3. To provide a step by step guide for the design of practical grounding systems based on these limits.
4. To recommend test methods for obtaining data for the design of ground systems, and for verifying the adequacy of ground systems as constructed.
5. To develop mathematical methods as an aid in the understanding and solution of typical ground gradient problems.
6. To make available in English translation, some of the more pertinent and valuable foreign language articles.
7. To provide a comprehensive bibliography, with abstracts, of existing literature related to the subject, for the benefit of those seeking additional information not included herein.

This Guide, as a whole, is primarily concerned with alternating-current outdoor substation installations. A few sections are applicable to indoor portions of such stations or to stations which are wholly indoors.

Obviously, the same ground gradient problems which exist in a substation yard will not be present within a building, provided the floor either furnishes an effective insulation from earth potentials, or else is effectively equivalent to a conducting plate or close mesh grid, which is always at station ground potential; and provided also that the conducting parts of the building structure and fixtures are kept at station ground potential. However, even in the case of a wholly indoor substation, it may be necessary to consider some of the possible hazards mentioned herein from "perimeter gradients" (at building entrances), and from transferred potentials. This applies primarily, of course, to large capacity utility substations where the station ground system may rise to a high potential during a fault.

This Guide does not attempt to cover the many special grounding problems peculiar to direct current substations, which are discussed elsewhere in the literature.⁶⁶

Finally, this Guide makes no attempt to develop a quantitative analysis of the effects of lightning surges. To cover this fully would require another report of nearly equal size. Appendix III and the references, however, contain much information on this. At this point it will merely be stated that the greater im-

pedance offered to steep wave front surges will increase the drop in ground leads to the grid system, and decrease the effectiveness of the more distant parts of the grid. Offsetting this in large degree, is the fact that the body can apparently tolerate far greater current magnitude in the case of surges than in the case of 60 cycles.

As a practical matter, it is felt that ground systems designed as recommended herein will give a high degree of protection against steep wave front surges entering the station and passing to earth through its grounding system. Obviously, a man can be killed by a direct stroke inside the station, just as he can outside.

2.—THE BASIC PROBLEM IN SAFE GROUNDING

Under fault conditions, the flow of current to earth will result in gradients within and around a substation. Figure 1 shows this effect for a station with a simple rectangular ground grid in homogeneous soil.

Unless proper precautions are taken in design, the maximum gradients along the ground surfaces may be so great, under very adverse conditions, as to endanger a man walking there. Also, dangerous potential differences may sometimes exist, during a fault, between structures or equipment frames which are "grounded," and the nearby earth.

Unfortunately, accurate pre-calculation of these gradients and voltages is seldom practical. The geometry of the grounding system is often far more com-

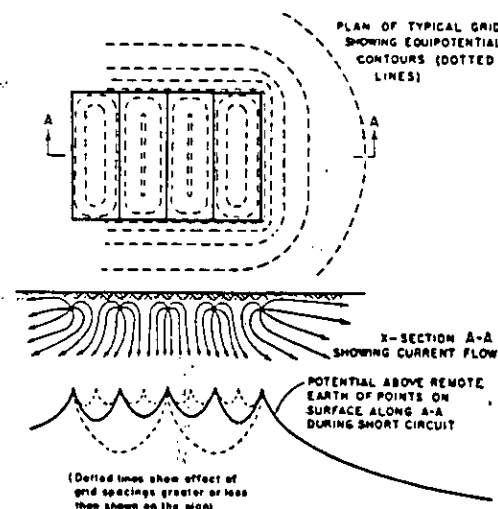


Figure 1. Currents and potentials in and around ground mat area

plex than that shown in Figure 1, and knowledge of subsurface soil characteristics may be very incomplete.

It should be emphasized that a low station ground resistance is not, in itself, a guarantee of safety.* There is no simple relation between the resistance of the ground system as a whole and the maximum shock current. A station of relatively low ground resistance may be dangerous under some circumstances. On the other hand, some stations with very high resistance are safe, or can be made safe, by careful design.

In addition to the magnitude of the local gradients, other factors enter into the safety problem. These include such things as duration of the shock, body resistance, physical condition of the individual, and probability of contact. These also are difficult to evaluate.

Some years ago, a great many people assumed that any object grounded, however crudely, could be safely touched. This misconception probably contributed to many tragic accidents in the past. Today, while there is a wider understanding of the problem, the many complexities and uncertainties mentioned above have tended to discourage any really scientific approach.

While it is true that the achievement of safety from ground-fault gradients may never become an exact science, much helpful information is available. A fuller use of this should, in some cases, permit a reduction of "ignorance factors", and in all cases give the designer a greater confidence in the safety of the station as designed.

3.—WHAT DOES IT TAKE TO MAKE AN ACCIDENT?

The logical first approach to the problem is to determine the circumstances which make electric shock accidents possible. Those of the type we are considering require coincidence of the following unfavorable factors:

1. Relatively high fault current to ground in relation to size of ground system and ground resistivity.
2. Soil resistivity and distribution of ground current flow such that high-potential gradients are possible at one or more points.
3. Presence of the individual at such a point, at such a time, and in such a position that his body bridges two points of high potential difference.
4. Absence of sufficient contact resistance or other series resistance to limit current through the body to a safe value under the above circumstances.
5. Duration of the fault and body contact, (and hence of the flow of current through the body) for a sufficient time to cause harm at the given current intensity.

The relative infrequency of accidents of the type

*The sole exception is the case where IR , the product of the maximum short-circuit current flowing in the ground system, and the resistance of the latter, represents a voltage low enough to be contacted safely.

being studied, as compared to accidents of other kinds, is due in no small part to the low probability of coincidence of all the unfavorable conditions required. Nevertheless, many fatalities due to gradients have occurred.

A little study will show that it is absolutely impossible, short of abandoning entirely the distribution of electric power, to prevent, at all times, in all places, and under all conditions, the presence of dangerous voltages. However, this fact does not relieve the engineer of the responsibility of seeking to lower this probability as much as he reasonably can. Fortunately, in most cases it can be reduced to an extremely low value by careful, intelligent design.²³

4.—TOLERABLE LIMITS OF BODY CURRENT

The hazards of the type under study depend, in the last analysis, on the frequency, magnitude, and duration of the current flowing through the vital areas of the body.

4.1—Frequency

In this report we are primarily concerned with the normal commercial frequencies of 50 or 60 cycles per second. Authorities generally agree that the body can tolerate slightly higher currents at 25 cycles per second, and perhaps even five times as much, at direct current, so conclusions drawn will be on the conservative side for these latter. Much information on special direct current grounding problems is contained in a 1938 report of the Conversion Substations Subcommittee. In the case of lightning surges, the human body seems able to tolerate very high currents, perhaps of the order of hundreds of amperes. Studies of the effect of both direct and oscillatory impulse currents are reported in the literature, the latter being much the more dangerous of the two.^{22, 23, 26.}

4.2—Magnitude

The effects of different current magnitudes will be considered first for duration of a few seconds or longer.

The threshold of perception is generally agreed to be at current flows of about one milliamperere.

Higher currents of the order of 9 to 25 milliamperes may be quite painful, and may result in lack of muscular control sufficient to make it difficult or impossible to release an energized object grasped by the hand.²⁴

For still greater currents, muscular contractions may make breathing difficult. Unlike the cases of respiratory inhibitions from the much larger currents mentioned later, the effects are not permanent, and disappear when the current is interrupted, unless, of course, the contraction is very severe and breathing is stopped, not for seconds but for minutes. Even such cases will often respond to resuscitation. Obviously we need not fear asphyxiation due to muscular contraction alone if modern relays or other protective devices can be counted upon to clear the shock current within a matter of a few seconds or less.

However, at still higher currents, death may occur due to a heart condition known as ventricular fibrillation. Such cases do not respond to resuscitation, and the skill and equipment to apply the only known remedy (a controlled countershock), in the small time during which it would be effective, is almost never available in the field. Hence the threshold of ventricular fibrillation is of major concern. Values given in the literature (where duration is not specified) vary from 50 milliamperes to 100 milliamperes. No good experimental basis was found for the first figure and it probably includes a safety factor. The figure of 100 milliamperes is based on the extensive experiments at Columbia University on animals having body and heart weights comparable to man, with maximum shock durations of 3 seconds.^{7, 9, 28, 70.}

It is not until still higher current values are reached that such things as stoppage of the heart, inhibition of respiration, or serious burning may occur and perhaps cause death or severe injury.

It will be seen that this report is greatly concerned with the threshold of fibrillation, for if shock currents can be kept below this value, deaths from this cause, and also deaths or injury from the causes which require still higher currents, will be avoided.

With regard to body currents below the fibrillation threshold, the report is concerned only with one combination of circumstances, namely a ground-gradient shock which might last some minutes (due to absence both of effective protective devices and effective means of rescue) and be of sufficient intensity to stop breathing by severe contraction of the chest muscles.

Because large ground gradients from faults are usually rather infrequent, and shocks from this cause still more so; and because both are usually of short duration, it would not be practical to design against shocks which are merely painful, and cause no injury.

It is not to be implied, however, that criteria developed for ground gradient potentials during fault are necessarily applicable to other situations where potentials are sustained and the probability of shock is higher.

4.3—Duration

All authorities agree that much higher currents can be tolerated without causing fibrillation if the duration is very short. Dalziel, analyzing the Columbia University tests, concludes that 99.5 percent of all men could withstand, without ventricular fibrillation, currents determined by the equation:³²

$$I_K t = 0.027 \quad (1)$$

$$\text{from which } I_K = \frac{0.165}{\sqrt{t}} \quad \text{amperes} \quad (2)$$

where: I_K is rms current through the body, in amperes
 t is time duration of shock, in seconds

0.027 is an empirically derived "energy constant"³³

* Since the body resistance involved can be assumed constant for practical purposes, this is equivalent to saying that fibrillation may be prevented by keeping the total watt-seconds of energy absorbed in the body during the shock below a given value (at least for shock duration within the range of 0.03 to 3.0 seconds covered by the experiments).

Note that the above equation results in values of 165 milliamperes for 1 second and 520 milliamperes for 0.1 second (6 cycles).

Equation (2) is based on tests limited to three-second durations. It is obviously not valid for very long durations, as some values of current can be tolerated indefinitely. On the basis of the Columbia University tests, Ferris, King, Spence and Williams suggested 100 milliamperes as the fibrillation threshold where shock duration is not specified. However, because the Columbia tests did not cover the longer shock durations, and because the possibility of asphyxiation from prolonged chest muscle contraction has not been ruled out, one might prefer to use a figure as low as 25 milliamperes or even the safe let-go values mentioned by Dalziel (men 9 milliamperes, women 6 milliamperes) in cases where shock potentials might persist for a few minutes or more without assurance of prompt rescue.³⁶

Equation (2) indicates that much higher currents can be allowed where fast operating protective devices can be relied upon to limit fault duration. A judgment decision is needed as to whether to use the clearing time of regular high-speed relays, or that of the back-up protection, as the basis for calculation. A case could be made for the former, due to the very low probability that relay malfunction will coincide with all other adverse factors necessary for an accident. However, even if calculations are based on the back-up relay time, a consideration of the time factor will show many situations to be safe which might otherwise seem dangerous.

4.4—Reclosures

A question may arise as to the effect of reclosure after a fault, which is so common under modern operating practice. A single "fast" automatic reclosure would usually result in a second shock initiated within a little less than a half-second from the start of the first, with little opportunity for the victim to free himself in the interval. With manual reclosure, where the interval would normally be from several seconds to a few minutes, there would be a greater possibility, but no assurance, that the victim could avoid another shock on reclosure.

The report on the Columbia University tests states that "Successive shocks have no cumulative effect on the susceptibility of the heart to fibrillation." Considered in its context, however, one would probably not be justified in applying this conclusion to intervals as short as most of those under discussion. This is because the conclusion is based in part on the finding that "heart action almost always returned to normal within 5 minutes of the application of current, provided fibrillation did not occur" (emphasis added.) The conclusion is also based on test shocks repeated "as many as ten times in a short interval;" but the length of this interval is not reported.

In the case of reclosing after a relatively short interval, an individual might receive a first shock which would not permanently injure him but would upset and disturb him temporarily. Then, if a second, per-

haps weaker, shock should occur before he has recovered his normal status, a fatality might result.

The limitations in present knowledge, therefore, suggests that perhaps some allowance should be made for reclosure shocks, but give no quantitative guide as to how this is to be done. In this dilemma, the designer, rather than ignoring this factor, may wish to make at least a rough allowance for it through some increase in the value of "t" used in Equation (2). He might, for example, assume that while the effect of two closely spaced shocks, of 0.1 second duration each, might be more severe than that of one such shock, it should be at least no more severe than is possible for a single shock of 0.2 second duration.

The need of more knowledge to permit better evaluation of this factor is apparent.

4.5—Current Paths Through Body

It should be remembered that the above discussion relates to paths such as those between the hand and one or both feet, where a major part of the current passes through parts of the body containing the vital organs, including the heart. It is generally agreed that current flowing from one foot to the other is far less dangerous. Loucks mentioned tests in Germany which confirmed the fact that much higher foot-to-foot than hand-to-foot currents were required to produce the same current in the heart region. He states that the ratio "could be as high as 25 to 1."⁴⁰

A good case could thus be made for permitting much higher values than those derived from Equation (2) where a path from one foot to the other is concerned. However, the following factors should be considered:

(a) A voltage between the two feet which is painful but not fatal might result in a fall which could result in current flowing through the chest area. This danger would depend largely on the duration of fault and the possibility of a successive fault, perhaps on reclosure.

(b) A person might be working or resting in a prone position when a fault occurred.

(c) Current between front and rear feet of quadrupeds would involve the chest area. Also the distance along the ground surface shunted, in the case of a large animal, could be about twice as great as for a man.

If trouble from these sources seems sufficiently remote, then the tolerable foot-to-foot current may be increased, perhaps even by a factor of ten or more, as compared to the hand-to-foot current computed from Equation (2). This has not been done, however, in the computations which follow.

It is apparent that the dangers from foot-to-foot contact are far less than from the other type. However, since deaths have occurred from the former, it is a hazard that should not be ignored.

5.—IMPORTANCE OF HIGH-SPEED CLEARING OF FAULTS

Too much emphasis cannot be given to high-speed

clearing of faults as a safety factor. It aids in two ways:

First, it is obvious that the probability of shock is greatly reduced by any reasonably fast type of fault clearing, in contrast to situations in which fault currents can persist for several minutes or possibly hours. (Most fatal accidents to humans from ground-fault gradients have occurred under the latter type of situation.)

Second, if such a coincidence should occur, both tests and experience show that the chance of severe injury or death is greatly lessened if the duration of current flow through the body is very brief.

6.—TOLERABLE POTENTIAL DIFFERENCES: "STEP," "TOUCH," AND "TRANSFERRED" VOLTAGES

Using the value of tolerable body current established by Equation (2), and the appropriate circuit constants, it is possible to calculate the tolerable potential difference between possible points of contact.

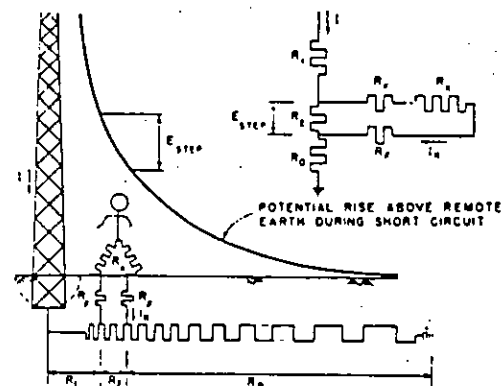


Figure 2. Step potentials near grounded structure

Figure 2 shows the equivalent circuit for a "step" or foot-to-foot contact. Here the potential difference shunted by the body is limited to the maximum value between two accessible points on the ground separated by the distance of one pace, which will be assumed to be one meter.*

Figure 3 shows the equivalent circuit for a "touch" or hand-to-both-feet contact. Here the problem is somewhat more complex. If the object touched were grounded immediately below it, the maximum earth potential difference intercepted would be that which could occur over a distance along the ground equal to the normal maximum horizontal reach, again approximately one meter. Unfortunately, objects touched

* For convenience, all units in these calculations will be in the meter-kilogram-second system. Resistivity will be expressed in ohm-meters, that is to say, in ohms per meter of current path length for a cross-sectional area of current path of one square meter. A cube of conducting material one meter on a side having a resistivity of one ohm-meter will have a resistance between opposite faces of one ohm. One ohm-meter is equal to 100 ohm-centimeters.

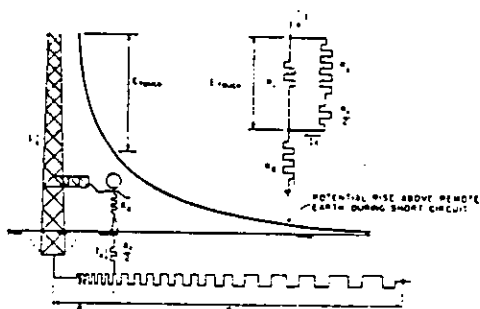


Figure 3. Touch potentials near grounded structure

may be grounded more remotely, and this fact must be taken into account. One example of this is the "mesh voltage" type of touch contact which will be defined later in Section 10.7.

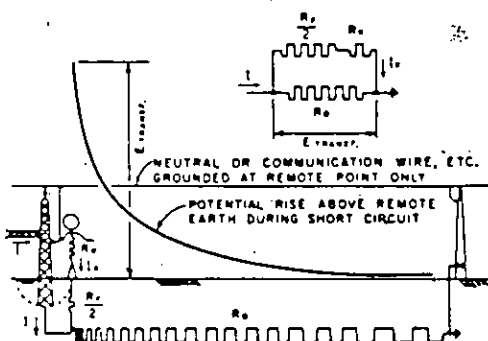


Figure 4. Example of hazard from transferred potential

Figure 4 shows an example of "transferred" potential contact, (which may be considered as a special case of the "touch" contact). A person standing within the station area touches a conductor grounded at a remote point; or a person standing at a remote point touches a conductor connected to the station ground mat. Here the shock voltage may be essentially equal to the full voltage rise of the ground mat under fault conditions and not the fraction of this total which is encountered in the usual "step" or "touch" contacts.

Circuit constants include the resistance of the ground electrode system (R_1 plus R_2 plus R_0 in Figure 2; R_1 plus R_0 in Figure 3; and R_0 in Figure 4); the contact resistance of the hand (for touch contacts); the resistance of the shoes; the resistance R_p of the ground immediately under each foot; and the body resistance R_b .

Hand contact resistance may be very low and will be assumed as equal to zero. Resistance of the shoes is uncertain, and for damp leather may be very small. It will also be assumed to be zero.

Resistance of the ground just beneath the feet, however, may affect appreciably the value of the body current, a fact which may be most helpful in some

difficult situations. The foot can be considered equivalent to a superficial circular plate electrode with a radius of about eight centimeters, and the ground resistance can be calculated in terms of the resistivity ρ_s (in ohm-meters) of the soil near the surface. It has been determined that the resistance of the two feet in series (step contact) is approximately $6 \rho_s$ ohms, and the resistance of the two feet in parallel (touch contact) is approximately $1.5 \rho_s$ ohms. For practical purposes, therefore, the resistance R_p in ohms for each foot can be assumed to be $3 \rho_s$; 2, 10, 20, 30, 50, 60.

The proper value to use for body resistance (including skin resistance, and the internal resistance of the body) is much more difficult to establish. Various authorities suggest figures from 500 up to a few thousand ohms.

Dalziel conducted tests in which skin and contact resistances were minimized by immersing the arm to the elbow and standing in 10 inches of salt water. Results on both 60 cycles per second and direct current, with the current limited to 10 milliamperes, gave values from 400 to 600 ohms, and 500 ohms is believed reasonable, for accident electric shock cases, for the internal resistance of the body between major extremities. This same author conducted tests on hundreds of volunteers to determine reasonably safe let-go currents and voltages. Statistical methods were employed to reduce the data. The let-go current or voltage which 99.5 percent of a large group can release was taken as a reasonably safe value for a large sample of normal healthy men. Tests were made with hands wet and feet standing in salt water to simulate very adverse conditions for receiving an electric shock. The values obtained using 60 cycles per second for men were: current 9.0 milliamperes; corresponding voltages, hand-to-hand 21.0 volts, hand-to-feet 10.2 volts. Hence, the alternating current resistance, hand-to-hand, equals $21.0/0.009$ or 2330 ohms; the resistance hand-to-feet equals $10.2/0.009$ or 1130 ohms.

Laurent uses 3000 ohms in his sample calculations as typical of the usual body and skin resistance for 50 cycles per second.

If one wished to be very conservative, he might use in the calculations, a body and skin resistance of 500 ohms, which would provide a large safety factor under all ordinary conditions. (If this assumption were to be made, it would be necessary to substitute the figure 82.5 for the figure 165 where the latter appears in Equations (3), (4), (18), and (19).)

However, it is felt that a value of 1000 ohms is more reasonable for the purposes of this Guide. This conclusion is based on the tests just described; on the extreme improbability that all the many factors involved in shock severity would have their most adverse values at the exact instant of the shock (see Section 3); and the desire to avoid an unreasonable compounding of safety factors.

A figure of 1000 ohms has therefore been used, in the calculations which follow, to represent the resistance of the body from a hand to both feet, and also the resistance from one foot to the other.

Very high voltages or currents decrease the resistance by damaging the skin at the point of contact, but since the purpose of this paper is to avoid shocks of this magnitude, this fact is not pertinent to the present discussion.

Tolerable potential differences between any two points of contact can be calculated in terms of the circuit constants and the allowable body current. By the Helmholtz equivalent source theorem (Thevenin theorem), the body current between these two points will be equal to that which the pre-existing voltage would cause to flow through the body resistance, in series with the external network connecting the points of contact. Strictly speaking, this latter network may include two paths in parallel, the direct path through the ground, and a parallel path through the point of circuit fault.

However, a simplified approach is fully adequate. Since it is necessary to limit the body current to some value in milliamperes, and since the fault currents which are of concern are expressed in hundreds, or probably thousands of amperes, we can neglect any change in the pre-existing voltage by reason of the current diverted through the body. We can thus assume that the full potential difference existing prior to contact will still be present to force current through the path which includes the body.

Substituting appropriate circuit constants, and the expression for the tolerable current from Equation (2), the tolerable potential differences between two points which may be contacted simultaneously become:

$$E_{step} = (R_K + 2R_F) (I_K) \\ = (1000 + 6\rho_s) (0.165) \\ = \frac{165 + \rho_s}{\sqrt{t}} \quad \text{volts} \quad (3)$$

$$E_{touch} = (R_K + \frac{R_F}{2}) (I_K) \\ = (1000 + 1.5\rho_s) (0.165) \\ = \frac{165 + 0.25\rho_s}{\sqrt{t}} \quad \text{volts} \quad (4)$$

Where E_{step} is the tolerable potential difference between any two points on the ground surface which can be touched simultaneously by the feet.

E_{touch} is the tolerable potential difference between any point on the ground where a man may stand and any point which can be touched simultaneously by either hand.

Some utilities establish more or less arbitrary voltage limits, e.g., 150 volts, for step and touch potentials due to fault gradients. From the above it would appear that a 150-volt limit should be adequate, neglecting the foot-to-ground resistance, for duration of shock not exceeding 1.2 seconds.

A fixed, relatively low voltage limit of this type for fault gradients, however, may be very difficult to achieve under some conditions. Consideration of foot-to-ground resistance and high-speed clearing of faults may then be most helpful in achieving safety at reasonable cost.

7.—DESIGN PROCEDURE

With tolerable step and touch voltage limits thus determined, one can design and construct the ground system for a substation, using a step-by-step procedure as follows:

1. Investigation of soil characteristics.
2. Determination of maximum ground current.
3. Preliminary design of grounding system.
4. Calculation of resistance of grounding system.
5. Calculation of maximum-grid potential rise.
6. Calculation of step voltages at periphery.
7. Calculation of internal step and touch voltages.
8. Investigation of transferred potentials and special danger points.
9. Correction or refinement of preliminary design as indicated by 6, 7, and 8.
10. Construction of grounding system.
11. Field measurement of resistance of grounding system as constructed, and perhaps, of step and touch voltages.
12. Review of 5, 6, 7, and 8 based on actual measurements.
13. Modification of ground system or addition of screens and barriers, etc. if and as indicated by 12.

An example of the application of this procedure to a practical case is included as Appendix II.

Appropriate parts of the above procedure can be used in checking the safety of existing stations, and applying corrective measures if required.

8.—INVESTIGATION OF SOIL CHARACTERISTICS

8.1—Soil Type

Investigation of a station site will normally include at least a determination of the general soil composition, often to a reasonable depth by means of borings. Some general idea will usually be obtained also as to its homogeneity.

The literature gives many tables showing ranges of resistivity for various soils and rocks. Table I from Rudenberg has the advantage of extreme simplicity. More detailed classifications are available in the references.^{1, 2, 16, 28, 43.}

TABLE I
Average Resistivity of the Ground

Type of Ground	Resistivity in ohm-meters
Wet organic soil	10
Moist soil	10 ²
Dry soil	10 ³
Bed rock	10 ⁴

8.2—Resistivity Measurements

Estimates based on soil classification will permit only a crude approximation of the resistivity. Electrical resistivity tests are therefore very desirable. These should preferably be made at a number of places within the site, and with different probe spacings, to get an indication of any important variations of resistivity with location or depth. The number of such readings taken will normally be greater where these variations are large; especially if some resistivity readings are so high as to suggest a serious safety problem.

Where resistivity varies appreciably with depth, it is often desirable to use a range of probe spacings sufficient so that a fairly accurate estimate for still greater spacing can be found by extrapolation.⁶⁵

The method of measurement in general use is based on Equation (5) below, described by Dr. F. Wenner of the U. S. Bureau of Standards. Two current electrodes and two intermediate potential electrodes, each of small dimensions, are placed in the earth at equal distances apart in a straight line to a depth "B." The voltage between the two potential electrodes is then measured and divided by the current between the two current electrodes to give a value of mutual resistance "R". Instruments in common use make the division automatically and are direct reading in ohms.^{67, 71, 72, 73}

Then:

$$\rho = \frac{4\pi AR}{1 + \frac{2A}{\sqrt{A^2 + 4B^2}} - \frac{2A}{\sqrt{4A^2 + 4B^2}}} \quad (5)$$

Where: ρ is the resistivity of the soil in ohm-meters.

R is the resistance in ohms resulting from dividing the voltage between the potential probes by the current flowing between the current electrodes.

A is the distance between adjacent electrodes in meters.

B is the depth of the electrodes in meters.

If "B" is small compared to "A," as in the case of probes penetrating the ground a short distance only, the above equation can be simplified as follows:

$$\rho = 2\pi AR \quad (6)$$

(A modification of the above method which gives greater sensitivity for very large probe spacings is described by L. G. Palmer. See abstract of Reference 71.)

The derivation of the above equations is based on the assumption that the soil resistivity is uniform. More frequently than not, however, the apparent resistivity, as measured by the above method, will vary somewhat with the probe spacing. This usually indicates a soil resistivity which varies with depth, since the test current flows mainly near the surface for small probe spacings, whereas more of it flows deeper for large spacings.

It is customary to assume, in such cases, that the apparent resistivity measured for a given probe spacing "A" represents the "average" resistivity of the soil to a depth "A." This assumption is not rigorously exact, but is acceptable for most practical purposes.

More exact theoretical approaches to situations where resistivity varies markedly with depth are suggested by Sunde, and in some of the books on geophysical prospecting to which he refers. For example, it is often possible, from readings taken with a wide range of probe spacings, to deduce a stratification of the earth into two or more layers of appropriate thickness which will account for the actual test variations.⁵⁵

Instruments suitable for ground-resistance measurements, which are designed for four terminal measurements, and have a suitable range can also be used for measurement of soil resistivity.

Resistivity measurement records should include temperature data and information as to the dry or moist condition of the soil at the time the resistivity is measured. All data available on buried conductors known or suspected to be in the area studied should be recorded.

Buried conductors, in contact with the soil, can, of course, invalidate readings made by the method described, if they are close enough to alter the test current flow pattern appreciably. For this reason, resistivity measurements of this kind have little value in an area where grid conductors are already installed, (except perhaps for shallow-depth measurements near the center of a large mesh rectangle). In such situations, measurements are sometimes made a short distance outside the grid, with the probes so located as to minimize the effect of the grid conductors on the current flow pattern. Though not conclusive as to conditions inside the grid, such readings may be better than nothing, especially if there is reason to believe that the soil in the area is reasonably homogeneous.

In addition to the field measurement method mentioned, it is possible to measure resistivity of soil samples in the laboratory, either by the same four-electrode method (if probe spacing is small relative to dimensions of sample), or by measuring the resistance between opposite conducting faces of a container of known length and cross-sectional area. The disadvantages of this method are the difficulties of obtaining enough representative samples and of maintaining the same conditions of moisture and compaction as for the soil in place.

8.3—Capacitance

The typical ground electrode or grid can be represented schematically as in Figure 5. The soil acts both as a conductor, of resistivity ρ , and as a dielectric, with a dielectric constant "K." "Leakage" current will flow in parallel with charging current in proportions determined by these constants. If the soil is homogeneous, the geometry, including the current paths and, of course, the location of equipotential surfaces, is identical for both. However, except for high frequencies in combination with very high resistivity

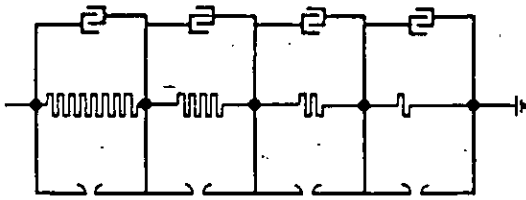


Figure 5. Schematic representation of ground electrode or system

Ground behaves essentially as a pure resistance at commercial frequency and with common values of resistivity. Very high frequencies or steep wave fronts, with very high soil resistivities, tend to make charging current flowing in ground capacitance relatively more important. For very high voltages, soil may not be able to sustain resulting high gradients and arcs will form, starting at electrode surface and progressing outward into ground, thus increasing effective electrode dimensions until soil can withstand remaining gradients.

ties, the charging current is negligible in comparison to the "leakage" current, and the ground can be treated as a pure resistance.

8.4—Effect of Voltage Gradient

This resistance is not affected by the voltage gradient, unless the latter exceeds a critical value. This value will vary with the nature of the soil, but it is of the order of some kilovolts per centimeter. If exceeded, arcs will start at the electrode surface and progress into the ground so as to increase the effective size of the electrode, until the gradients beyond are reduced to values which the soil can withstand. This condition is represented by the gaps in Figure 5. Since the station ground system will normally be designed to keep gradients well below these critical values, the resistance and resistivity can be assumed to be unaffected by voltage.

8.5—Effect of Chemical Content

It is well known that the resistivity of soils varies widely with composition and the amount and type of soluble salts, acids, or alkali which they may contain. (Appendix III and Appendix IV).

8.6—Effect of Moisture

The resistivity of soil rises abruptly when the moisture content falls below about 22 percent by weight. Hence, wherever feasible, the electrode system should be buried deep enough to insure contact with permanently moist earth. Where this is not feasible, greater dependence will usually be placed on a well-distributed system of vertical rods bonded to the grid and reaching deeper layers. Gravel or crushed-rock coverings, usually about three or four inches in depth, such as are often used in substation yards, are helpful in retarding evaporation of moisture and thus limiting the drying out of the top layer during prolonged dry weather periods. (This surface covering of high-resistivity material is also valuable in reducing shock currents, as noted elsewhere).^{5, 6.}

8.7—Effect of Temperature

The resistivity of soils rises abruptly when the temperature falls below 32°F. Hence the electrode system should extend below the frost line wherever feasible.⁸

For increasing temperatures above 32°F, the resistivity will decrease. However, in unusual cases of prolonged heavy current, the boiling point of water may be reached in the vicinity of an electrode, so that drying of the soil and high resistivity may result. Such conditions, however, are seldom encountered in actual substation installations.

8.8—Effect of Current Magnitude

It is important to know whether resistance and resistivity measurements made in the usual manner with very small currents are valid under short-circuit conditions. Tests which have been made show that these measurements are valid, on the presumption that the high currents are not of sufficient magnitude to result in extremely high voltage gradients, or of sufficient duration to bake out the ground around the electrode.^{10, 11.}

9.—DETERMINATION OF MAXIMUM GROUND-FAULT CURRENT

9.1—Procedure

The following steps are involved in determining the correct value of ground-fault current for use in station grounding system design calculations:

(a) Determine which of the possible types of ground fault will result in the greatest flow of current between the ground grid and surrounding earth and hence the greatest rise in ground grid potential and largest local gradients in the substation area. (See Figure 6)

(b) Determine, by computation or network analyzer study, the maximum symmetrical rms value I'' of this ground-fault current flowing between station ground grid and surrounding earth at the instant of fault initiation.

(c) Apply a correction factor, where appropriate, to allow for the effect of direct current offset and alternating current and direct current decrements (See Table II).

(d) Apply a correction factor, where appropriate, to allow for future increase in fault currents due to expansion of the system.

9.2—Types of Ground Faults

The first step (a), should offer no difficulty if a simplified diagram is made, equivalent to those in Figure 6, to represent the actual situation. The diagram should include any overhead ground wires which are connected to the station ground system or transformer neutrals.

9.3—Symmetrical Component of Ground Current at Time of Fault Initiation

In step (b), the maximum symmetrical rms value I'' of ground-fault current may be determined in the conventional manner, using the following equation:

$$I'' = \frac{3E}{3R + 3R_f + (R_1 + R_2 + R_0) + j(X''_1 + X_2 + X_0)} \text{ amperes} \quad (7)$$

In most cases, however, the effect of the resistance terms in the above equation is negligible for practical purposes, and the following simplified equation is sufficiently accurate and more convenient:

$$I'' = \frac{3E}{X''_1 + X''_2 + X''_0} \text{ amperes} \quad (8)$$

In the above equations:

I'' = Symmetrical rms value of ground-fault current, at instant of fault initiation, in amperes.

E = Phase-to-neutral potential, in-volts.

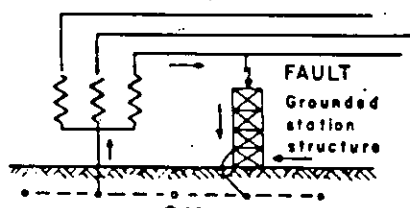
R = Estimated resistance to earth of local station ground system, in ohms.

R_f = Estimated minimum resistance of the fault itself, in ohms.

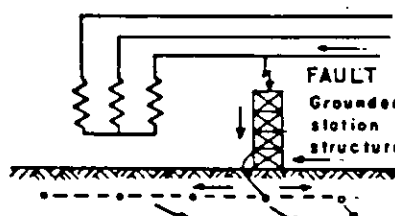
R_1 = Positive-sequence resistance, ohms per phase.

R_2 = Negative-sequence resistance, ohms per phase.

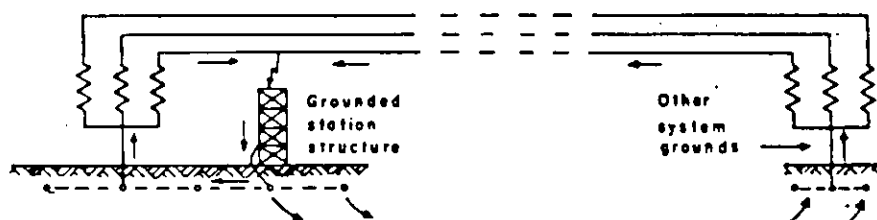
R_0 = Zero-sequence resistance, ohms per phase.



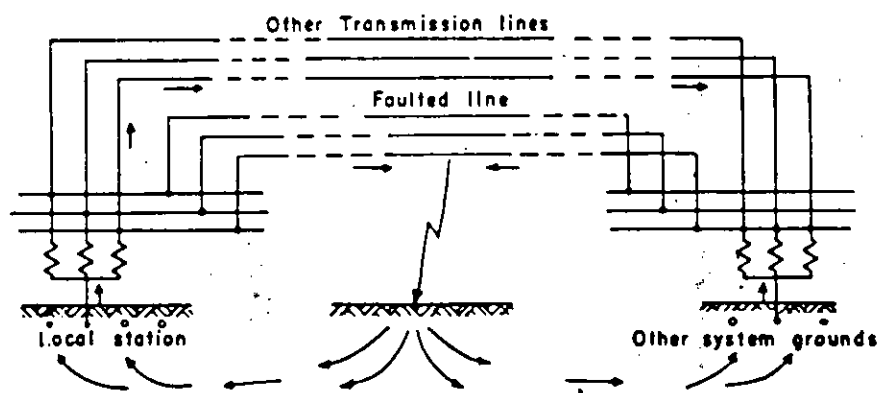
Case 1—Fault within local station. Local neutral ground only. Fault current follows metallic path provided by ground grid. No appreciable current flow in earth.



Case 2—Fault within local station. Neutral grounded at remote location only. Total fault current flows from station ground grid to earth.



Case 3—Fault in station. System grounded at local station and also at other points. Fault current returns to local neutral through local grid and to remote neutrals through the earth. Latter is the component of concern in study of danger voltages.



Case 4—Fault on line outside station. System grounded at local station, and also at other points. Portion of fault current returning from earth to ground grid at local station determines grid potential rise and gradients there.

Figure 6. Cases 1, 2 and 3 show faults within local station. Case 4 shows fault on line outside local station.

X''_1 = Direct-axis positive-sequence reactance (sub-transient) ohms per phase.

X_2 = Negative-sequence reactance, ohms per phase.

X_0 = Zero-sequence reactance, ohms per phase.

The values R_1 , R_2 , R_0 , X''_1 , X_2 , and X_0 are taken looking into the system from the point of fault. Computations are made in such a way as to exclude any currents which do not flow between the local ground system and earth (see cases 1, 3 and 4 of Figure 6).

9.4—Effect of Direct Current Offset—The "Decrement Factor"

With regard to step (c), it must be remembered that, in general, short circuits occur at random with respect to the voltage wave. Moreover, the shock contact may exist at the moment the fault is first initiated. Hence, to allow for the most severe condition, it is necessary to assume a 100 percent offset asymmetrical wave of ground-fault current for the duration of the shock.

Since the experimental data on the fibrillation threshold is based on symmetrical sine waves of constant amplitude, it is necessary to determine an rms value of a simple sine wave current, I , which is equivalent to the more complex asymmetrical fault current wave. This value I can be determined as follows:

$$I = \sqrt{\frac{1}{T} \int_0^T i_F^2 dt} = DI'' \quad (9)$$

where:

$$D = \frac{1}{I''} \sqrt{\frac{1}{T} \int_0^T i_F^2 dt} \quad (10)$$

In the above equations:

I = Adjusted rms value of ground-fault current, in amperes for use in calculations.

T = Time duration of fault (and hence of shock), in seconds.

t = Time after fault initiation, in seconds.

i_F = rms value of ground-fault current at time of t seconds after fault initiation.

D = A multiplying factor, hereinafter called "decrement factor" to allow for effect of direct-current offset, and attenuation of alternating-current and direct-current transient components of fault current.

The value of the integral above depends on the rate of attenuation of both alternating current and direct current components, and a rigorous solution is quite complex. The problem is in fact quite similar to that encountered in circuit breaker application. This latter problem has been met by American Standard C37.5 which has established a simplified method to determine the rms values of current, at various times after fault initiation, through the use of multiplying factors. For example, the American Standard multiplying factor at the end of the first half cycle is 1.6;

and it becomes successively 1.4, 1.2, 1.1, and 1.0 at times equal to 1, 2, 3, and 4 cycles respectively.

A similar simplified approach seems equally appropriate in the present case. When applied to the solution of Equation (10) it results in decrement factors as given in Table II below:

TABLE II

Shock and Fault Duration		Decrement Factor
T	D	
Second	Cycles (60 Cycle Alternating Current)	
0.08	1/2	1.65
0.1	6	1.25
0.25	15	1.10
0.5 or more	30 or more	1.00

For intermediate values of fault duration, decrement factors may be obtained by linear interpolation.

For closely spaced successive shocks (as from reclosures) one should use decrement factor corresponding to the duration of the shortest single shock, even if the time "t" used elsewhere in the calculations is based on the sum of the individual shock durations. (See Section 4.4.)

It will be apparent that the decrement factors given above must not be confused with the American Standard multiplying factors. The decrement factors are used to determine the effective current during a given time interval after inception of a fault, whereas the American Standard multiplying factors are used to determine the rms current at the end of this interval. Because of the decay of alternating-current and direct current transient components with time, the decrement factors are slightly higher than the American Standard factors for short fault and shock durations.

For relatively long durations, the effect of the direct current component can be assumed to be more than offset by the alternating current decrement from the maximum symmetrical value I'' at the inception of the fault. A decrement factor of 1.0 is therefore indicated for fault durations of 30 cycles or more.

It is realized that both the direct current and alternating current transient components of fault currents are dependent upon the ratio of reactance to resistance (X/R ratio) of the circuit. The method of derivation of decrement factors disregards resistance in the fault path and hence will result in computed current values somewhat higher than actual values. However, the error will be on the side of safety. Circumstances of the present problem do not warrant the complexities of a more rigorous approach.

9.5—Effect of Future Changes

With regard to step (d), it should be noted that it is a common experience for maximum fault currents at a given location to increase as system capacity is added or new interconnections are made. If no margin for this is provided in the original ground system design,

the latter might become unsafe without the fact being realized. Moreover, any additions necessary to meet changed conditions will usually be much less convenient and more expensive to install later than if included in the original construction. Thus it is usually prudent to allow a margin for system growth. This allowance can be made by decreasing the value of system impedance used in the calculations; or simply by multiplying the value of calculated fault current by an appropriate factor.

9.6—Effect of Station Ground Resistance

In the great majority of cases it is sufficient to derive the ground-fault current as in Equation (8) on the basis of system reactance values alone, neglecting the system resistance, the station ground resistance, and the resistance at the fault. The error thus introduced is usually small, and is always on the side of safety.

However, there may be unusual cases where the predicted station ground resistance is so large, in relation to system reactance, that it is worthwhile to take it into account by using the more exact Equation (7).

This poses a problem, since, if the station ground system is not yet designed, its resistance is not known. Station ground-grid resistance depends on ground-grid design, and ground-grid design depends on ground current, which is what we are trying to determine. Fortunately, the vicious circle can be broken for practical purposes. The station resistance, once the resistivity has been determined or estimated, depends primarily on the area to be occupied by the ground grid. This is usually known approximately in the early design stages. Resistance can then be estimated by use of the following approximation:

$$R = \frac{\rho}{4r} \quad (11)$$

where:

- R is station ground resistance in ohms.
- ρ is average ground resistivity in ohm-meters.
- r is radius of a circle having the same area as that occupied by the ground grid.

For greater refinement, a trial value can be assumed for the total length of buried conductor to be used in the grid. The more accurate Equation (20) can then be used in lieu of Equation (11) to derive a value for station ground resistance.

9.7—Effect of Fault Resistance

If the fault is an insulation breakdown within the local station, the only safe assumption is that the resistance of the fault be assumed zero. (Figure (6), Cases 1, 2, or 3.)

In the case of a fault outside of the local station area, on a line connected to the station bus (Figure (6), Case 4), it is permissible, if a conservative minimum value of fault resistance R_f can be assigned, to use this in the ground-fault current calculations. This is done

by multiplying R_f by 3 and adding it to the other resistance terms as indicated in the denominator of Equation (7). One should, however, be able to assure himself that a fault resistance at least as great as the value of R_f used will be maintained under all conditions; otherwise, it will be prudent to neglect the fault resistance in this case also. Any error from neglecting R_f will, of course, be on the side of safety.

9.8—Overhead Ground Wire

High-voltage transmission lines are commonly provided with overhead ground wires, either throughout their length or for short distances from each substation. They may be insulated from the substation ground mat (to prevent galvanic corrosion of steel tower footings, or to lessen short-circuit duty on circuit breakers); or they may be tied solidly to the ground system of the substation.

Where transmission line overhead ground wires are to be connected to the station ground, they may divert a substantial proportion of the ground currents away from the station ground grid. Where this situation exists, therefore, one may take advantage of it in the ground grid design.

Since the ground current will divide in the inverse ratio of the input resistance of the overhead wires and the station ground resistance, it is necessary to establish at least approximate values for these.

Rudenberg, Laurent, and others provide some assistances in the computation of the former quantity in Appendixes III and IV and in the bibliography references 45, 61, 62, 65, and 69.

The station ground resistance can be determined approximately by the method suggested in the previous section.

It should be realized that connecting the station ground to overhead ground wires and through them to transmission-line towers will usually have the overall effect of increasing the hazard at tower bases, while lessening it at the substation. This is due to the fact that each of the nearby towers will share in each voltage rise of the substation ground mat whatever the cause, instead of being affected only by a local insulation failure or flashover at one of the towers. On the other hand, when such a tower fault does occur, the effect of the connected station ground system should decrease the magnitude of gradients near the tower bases.

9.9—Directly Buried Pipes and Cables

Buried cables with their sheaths or armor in effective contact with the ground and buried metallic pipes will have a somewhat similar effect where they are bonded to the station ground system, but extend beyond its perimeter.

By conducting part of the ground current away from the station before it enters the ground, the potential rise of the grid during fault, and the local gradients

in the station are somewhat lessened. As discussed later, however, external hazards may sometimes be introduced.^{7, 16}

Because of the complexities and uncertainties in the pattern of current flow, the effect is often difficult to calculate. Some guides to the computation of the input impedance of such current paths leaving the substation are supplied by Rudenberg and Laurent in Appendixes III and IV. From these values one can calculate approximately the division of ground current between these paths, the station ground system, and any overhead ground wires which are present and connected.

10.—PRELIMINARY DESIGN OF GROUNDING SYSTEM

10.1—Type of Ground System

In the discussion which follows, it is assumed that the basic ground system will take the form of a grid of horizontally buried conductors. The AIEE Application Guide on Methods of Substation Grounding (1954) reported that such a practice was followed by most utilities.⁴¹

10.2—Advantages of Grid

This wide use of the grid is due to the following advantages:

(a) In systems where the maximum ground current may be very high, it is seldom possible to obtain a ground resistance so low as to insure that the total rise of the grounding system potential will not reach values unsafe for human contact. This being the case, the hazard can be corrected only by control of local potentials. A grid is usually the most practical way to do this.

(b) In a station of any size, no ordinary single electrode is adequate to provide needed conductivity and current-carrying capacity. However, when several of these are connected to each other, and to structures, machine frames, and circuit neutrals which are to be grounded, the result is necessarily a grid, regardless of original objectives. If this grounding network is buried in soil of reasonably good conductivity, this network alone may often provide an excellent grounding system in itself. That is to say, a design using multiple electrodes may require a connecting network which is in itself so effective that the original electrodes may be superfluous.*

For this reason, some utilities depend on the use of a grid alone. However, ground rods are relatively low in material and installation cost, and are of particular value if the resistivity of the upper layer of soil in which the grid is buried is of much higher resistivity

* Laurent illustrates this with the example of four 10-foot ground rods set at the corners of a 20-foot square, and interconnected with cable in a cross. Resistance of the four rods alone will be about 0.10 Ω ; that of the buried connection cables alone as electrodes will be about 0.11 Ω ; and the over-all resistance will be about 0.08 Ω ; in other words, even in this relatively small "grid," driving the rods reduced the resistance by less than 30 percent from what would be obtained by the minimum connecting cable alone. Examples computed by Schwarz for typical large stations showed gains of the order of only 2 to 5 percent for grids with rods, as compared to grids alone. ^{24, 42}

than that of the soil beneath, or if it may become so because of drying out or freezing.

10.3—Preliminary Design of Grid

Practical design of a grid will usually start with an inspection of the layout plan for equipment and structures.

A continuous cable should surround the grid perimeter, to enclose as much ground as practical and to avoid current concentration and hence high gradients at projecting ground cable ends.

Within the grid, cables should be laid in parallel lines, and preferably at reasonably uniform spacing. They should obviously be located, where practical, along rows of structures or equipment to facilitate the making of ground connections.

The preliminary design should be adjusted so that the total length of buried conductor, including cross-connections and rods, is at least equal to that computed by Equation (19) in order to keep local potential differences within acceptable limits:

Without over-emphasizing the point, it should be noted that very frequent cross-connections, especially as in a square mesh, represent a somewhat inefficient use of the ground conductor. A conductor is obviously a little less effective in the region where it crosses the area already occupied by another conductor than it would be in an area by itself. Some cross connections, however, are desirable to provide multiple paths, especially from such points as transformer neutral connections, to minimize potential drops in the grid itself, and as further assurance of continuity in case of mechanical damage to a grid conductor.

A typical grid system for a switching station or substation might comprise 4/0 bare-stranded copper cable buried 12 to 18 inches below grade and spaced in a grid pattern of about 10 by 20 feet. (Other conductor sizes, burial depths and grid conductor spacings, however, are frequently used). At each junction of 4/0 cable, the cables would be securely bonded together and there might also be connected a driven copper-covered steel rod approximately $\frac{3}{8}$ -inch diameter and approximately 8 feet long. In very high resistance soils it might be desirable to drive the rods deeper. (Lengths approaching 100 feet are of record). A typical grid system usually extends over the entire substation yard, and sometimes beyond the fence which surrounds the building and equipment.

Areas of the grid near high concentrations of fault currents, such as at neutral-grounding connections should have reinforced wire sizes where necessary to handle adequately the most severe condition, taking into account both fault current and fault duration.

10.4—Connections to Grid

Conductors of adequate capacity and mechanical ruggedness should be used for the connection to the grid of (a) all non-current-carrying metallic parts

which might accidentally become energized, such as metal structures, building steel, transformer tanks, metal housings and guards, oil circuit breakers, machine frames, etc.; (b) electrodes such as ground rods, well casings, water pipes, etc.; and (c) lightning arresters, coupling capacitors, and where appropriate, transformer and machine winding neutrals, power and lighting secondary circuits, and other electric circuits as desired. It is also desirable in most cases to ground the secondaries of potential and current transformers, except that grounds on such circuits should be restricted to a single point on each circuit to avoid "sneak" currents which may have a serious effect on relay and meter performance.

Copper cables or straps are usually employed for these ground connections. However, transformer tanks are often used as part of the ground path for lightning arresters mounted thereon. Similarly, steel structures may be used as part of the path to ground if it can be established that the conductivity, including that of any joints, is and can be maintained as equivalent to the copper conductor that would otherwise be required. Studies by some utilities have led to their successful use of steel structures as part of the path to the ground mat from overhead ground wires, lightning arresters, etc. Where this practice is followed, any paint films which might otherwise introduce a high-resistance joint should be removed and a suitable joint compound applied or other effective means taken to prevent subsequent deterioration of the joint from oxidation. Aluminum structures, where used, can normally provide an excellent ground current path from equipment mounted thereon.

Connections between the various ground leads and the cable grid, and connections within the cable grid are usually clamp-type or brazed. Ordinary soldered connections are to be avoided because of possible failure under high fault currents or due to galvanic corrosion; however, "Siflos" silver-soldered connections are often used to advantage.

10.5—Ground Conductor Size

Each element of the ground system (including grid proper, connecting ground leads and electrodes) should be so designed that it will

(a) Resist fusing and deterioration of electric joints under the most adverse combination of fault current magnitude and fault duration to which it might be subjected.

(b) Be mechanically rugged to a high degree, especially in locations exposed to physical damage.

(c) Have sufficient conductivity so that it will not contribute substantially to dangerous local potential differences.

Methods of meeting these requirements are discussed in order below.

Adequacy of a copper conductor and its joints against fusing can be determined from Table III, or from the following equation developed by Onderdonk, upon which the table is based.⁴¹

$$I = A \sqrt{\frac{\log_{10} \left(\frac{T_m - T_a}{234 + T_a} + 1 \right)}{33 S}} \quad (12)$$

where:

- I is current, in amperes.
- A is copper cross-section, in circular mils.
- S is time, in seconds, during which current I is applied.
- T_m is maximum allowable temperature, in degrees Centigrade.
- T_a is ambient temperature, in degrees Centigrade.

The following assumptions may normally be made in applying the above equation:

- Ambient temperature of 40 degrees Centigrade.
- All heat retained in conductor due to short time duration.
- Melting point of copper, 1083 degrees C.
- Allowable temperature, brazed joints 450 degrees C.
- Allowable temperature, bolted joints 250 degrees C.

While the earlier AIEE Grounding Guide based its recommended sizes on 30 seconds, many utilities feel, probably correctly, that this is far more conservative than necessary for systems using modern protective devices.⁴¹

The designer should be free to base design on his own system conditions, though the safety factor, for reasons stated later, should not be made too small. One approach which seems reasonable is to assume a time of 4 seconds, that is to say, the same duration as is used for the short-time rating of switchgear.

In the case of portable temporary ground leads, such as are used to ground buses for protection of personnel during maintenance, it may be found that more is gained in safety by reducing the weight of the leads, than is lost by reducing the safety factor; hence, in this case an assumed duration closer to actual fault time may be appropriate.

Current values used in calculations should take into account the probability that the maximum fault currents will increase over the years as the system grows. It would obviously be most inconvenient to reinforce all ground leads in a station at a later date.

TABLE III

Minimum Copper Conductor Sizes to Avoid Fusing

Time Duration of Fault	Circular Mils per Ampere		
	Cable Only	With Brazed Joints	With Bolted Joints
30 seconds	40	50	65
4 seconds	14	20	24
1 second	7	10	12
0.5 second	5	6.5	8.5

An all-aluminum conductor having a conductance equivalent to a given copper conductor will also have an approximately equal short-time current-carrying capacity. This follows from the fact that, for equivalent direct current conductance, the temperature coefficients, specific heats, and densities of copper and aluminum, respectively, are such as to cause their respective melting points to be reached in approximately the same length of time.

The fusing time of copperweld is somewhat longer than that of a copper conductor of the same direct-current conductance, the steel inner core providing a heat reservoir for the heat generated in the copper.

The size of wire required where lightning may impinge directly upon it is considerably greater than that required to conduct the lightning surge through it. There are a few records of 2/0 copper wire having been severed by lightning impinging directly, but these are rare. However, it has been stated that there is no record of wire larger than No. 10 copper having been melted due to the direct passage of lightning current through it. Thus the problem is largely one of mechanical protection and mechanical forces. The Code for Protection Against Lightning, American Standard C5, specifies minimum sizes for these conducting cables, and lists for copper cable not less than No. 2 wire. Thus the cable size selected for fault current should be more than adequate for conducting lightning currents.

Mechanical ruggedness will set a practical minimum conductor size. The earlier AIEE Grounding Guide, in effect, recommended minimum sizes of 1/0 and 2/0 copper for brazed and bolted joints respectively. It further stated that "a large segment of the industry has set the 4/0 copper as a minimum for mechanical reasons." On the other hand, many utilities have successfully used smaller sizes (down to No. 3 AWG in at least one case) with no appreciable mechanical trouble.¹⁴

While it seems proper for each designer to establish minimum sizes in the light of his own local conditions, the need of mechanical ruggedness still needs emphasis. It is obviously impractical to observe or inspect buried portions of the ground system, and open circuits, even in exposed locations, could escape detection in many cases. It is partly for this reason that a policy is often followed of providing duplicate ground leads to different points on the grid from such important points as transformer and generator neutrals.

The third requirement of conductor size, namely that its conductivity be sufficient so that it will not itself contribute substantially to dangerous potentials, is usually assumed to have been met when the other two criteria previously discussed are satisfied. (See discussion of voltage drop in the ground system, in the section on "Effect of Irregularities.")

The effect of diameter on the resistance of the ground electrode formed by the buried conductor, and on the local gradients, has not been mentioned as a factor determining conductor size. Increase in diameter

has a favorable effect in reducing both, other things being equal. However, the effect is small, the touch voltage varying approximately in proportion to the logarithm of the reciprocal of the diameter.

Some utilities prefer to use grid conductors somewhat smaller than has been customary with the industry as a whole, but to space them closer together.

Equations (16) and (17) in Section 10.7 provide interesting evidence in support of this approach. It will be seen that, if given grid spacing "D" is cut in half, a conductor diameter "d" of only one quarter of the original value is sufficient to maintain the same value of K_m and *other things equal*, the same value of danger potential E_{mesh} . This would result in a conductor with one-sixteenth the cross-sectional area and twice the total length, i.e., with one-eighth the total weight.

Actually, cutting the spacing D in half and thereby doubling the length L would decrease i , the average current per unit length, by a factor of 2, while increasing the irregularity factor K_i by a lesser degree. The net result would be some decrease in the danger potential E_{mesh} , along with the saving in grid material mentioned above.

Obviously, installation costs and mechanical ruggedness requirements will set practical limits to the use of closer mesh and smaller wire.

Close design of the grid in lieu of using arbitrarily large sizes will require more study of each part as to its ability to carry the fault current which may be introduced from any of the possible sources. It may often be desirable to connect ground leads to junction points on the grid where current can flow into the grid in four directions. Exactly equal division of current by the four paths should not, however, be assumed unless grid geometry supports such an assumption.

10.6—Ground Conductor Material

Copper is by far the most common metal used for ground-grid conductors, at least in the United States. Copper clad steel is usually used for grounding rods, and sometimes for grid conductors. Copper, in addition to its high conductivity, has the advantage of freedom from underground corrosion, since it is cathodic with respect to other metals likely to be buried in the vicinity. Thus there can be confidence that the integrity of the underground grid will be maintained over the years, so long as conductors are of adequate size and not subjected to mechanical injury.

Unfortunately, however, a grid of copper (or copper-clad steel) forms galvanic cells with buried steel pipe and conduit, lead cable sheaths, etc., with which it is connected; and is therefore likely to hasten the corrosion of the latter. Some utilities have tried tinning the buried copper to reduce the potential of the galvanic cell. This reduces the potential with respect to zinc and steel about 50 percent and eliminates the potential with respect to lead, tin being slightly sacrificial to lead. Other methods used to avoid or minimize underground corrosion include insulating of the

sacrificial metal surfaces with plastic tape, asphalt compound, or both; routing of buried metallic elements so that copper conductors will cross pipes, etc. made of other metals as nearly as possible at right angles, and then applying insulating coatings to one metal or the other where they are in near proximity; use of non-metallic pipes and conduit; and cathodic protection.

Many utilities have reported the successful use of steel as material for ground-grid conductors and for ground rods. This eliminates the adverse effect of the grid on other buried conductors, which is mentioned in the previous paragraph. With such a design, however, the protection of the grid itself requires attention. This is usually accomplished through some form of cathodic protection, often in combination with galvanizing of the steel, or use of corrosion resistant steel.^{28, 41, 42}

Less frequently, aluminum has been used for ground grids. In such cases the relatively high purity electric conductor grade is more satisfactory than most alloys. Use of aluminum, like use of steel, avoids contributing to the corrosion of underground pipes, etc. However, the aluminum itself may corrode in certain soils. Alternating-current corrosion of aluminum may also be a problem under some conditions. Hence, aluminum should only be used after full investigation of the circumstances.

The subject of underground corrosion and cathodic protection is complex. Many studies have been and are being made, and much has been published. A detailed discussion of the problem, however, is beyond the scope of this present Guide.

10.7—Conductor Length Required for Gradient Control

An equation can be developed to permit a rough calculation of the buried grid conductor necessary to keep the touch voltages inside the grid perimeter within safe limits.

Touch voltages, rather than step or transfer voltages, are used as the basis for this computation because:

(a) Step voltages encountered in practical installations are usually smaller than touch voltages; ground resistances beneath the two feet are in series rather than in parallel, and are thus more effective in limiting body current; also, the body can tolerate higher currents through a foot-to-foot path.

(b) Transfer voltages are more difficult to limit and usually require isolation or other special treatment.

Touch voltages from a grounded structure to the center of a rectangle of grid mesh are used, rather than touch voltages at a horizontal distance of one meter from the grid wire, since there are so many possibilities that an object touched, while standing at a distance of more than one meter, may be connected directly or indirectly to the grid. This special case of touch voltage will be referred to as "mesh

voltage." It will, in general, have a greater value than the touch voltage at a distance of one meter from the grid wire.

Laurent points out (Appendix III) that for the usual range of conductor size, burial depth and spacing, local values will be of the following order:²⁸

$$E_{step} = 0.1 \text{ to } 0.15 \text{ } \rho i \quad (13)$$

$$E_{touch} = 0.6 \text{ to } 0.8 \text{ } \rho i \quad (14)$$

$$E_{mesh} = \rho i \quad (15)$$

where:

E_{step} = Step voltage over a horizontal distance of one meter, in volts.

E_{touch} = Touch voltage at a horizontal distance of one meter* from grid conductor, in volts.

E_{mesh} = Potential difference, in volts, from grid conductor to ground surface at center of a grid mesh.

ρ = Resistivity in ohm-meters.

i = Current, in amperes per meter of buried conductor, flowing into the ground.

Laurent warns that these values are approximate only. This is because they are based on average ranges (for French practice) of conductor diameter, depth of burial, and grid-conductor spacing. This approximation is possible because these quantities are within the logarithm of the more exact equations, and hence can vary over a fairly wide range without changing greatly the value of the step, touch, and mesh voltages. (This is in contrast to variations in ρ and i which change these danger voltages in direct proportion).

The above approximations were adopted as such in the 1958 AIEE report on voltage gradients, subject to the following:

(a) It was suggested that each designer might check the approximations for applicability to his own usual design practices by means of the more exact equations included in the report. (These are also in Appendix I of this Guide).

(b) An irregularity factor should be used to allow for non-uniformity in the flow of ground current per unit length of buried conductor.^{43, 44}

Actually, with regard to paragraph (a) above, it requires but a few minutes to apply the equations of Appendix I so as to take into account the conductor diameter and depth of burial which the designer expects to use on a specific design, together with approximate trial values for the number and spacing of the parallel grid conductors. (A recheck can also be quickly made if the number and spacing proposed in the final design—after solving Equation (19) below—differ substantially from these trial values).

With regard to paragraph (b) above, analyses which have been made of the model tests by Koch and others (Figure 8) should provide practical guid-

* E_{touch} is here defined in a special sense. Elsewhere the more general definition in Section 6 will apply unless otherwise specified.

ance for approximate evaluation of the irregularity in current flow from different parts of the grid.

Therefore, in lieu of Equation (15), one may write:

$$E_{mesh} = K_m K_1 \rho \frac{I}{L} \quad (16)$$

where: K_m is a coefficient which takes into account the effect of number, n , spacing, D , diameter, d , and depth of burial, h , of the grid conductors. Its value in terms of these factors, as derived in Appendix I, is as follows:

$$K_m = \frac{1}{2\pi} \ln \frac{D^2}{16hd} + \frac{1}{\pi} \ln \left(\frac{3}{4} \right) \left(\frac{5}{6} \right) \left(\frac{7}{8} \right) \dots \text{etc.} \quad (17)$$

the number of factors in parenthesis in the second term above being two less than the number of parallel conductors in the basic grid, excluding cross connections.

K_1 is an irregularity correction factor, to allow for non-uniformity of ground-current flow from different parts of grid. See Figure 8 and discussion below for method of determination.

ρ is the average resistivity of the ground in ohm-meters.

I is the maximum total rms current, in amperes, flowing between ground grid and earth, as adjusted to allow for decrement and future system growth.

L is the total length of buried conductor, in meters.

If the value for E_{mesh} given by Equation (16) is equated to the maximum tolerable value given by Equation (4), we get:

$$\frac{K_m K_1 \rho I}{L} = \frac{165 + 0.25 \rho_s}{\sqrt{t}} \quad (18)$$

Hence, by solving for "L", the approximate length of buried conductor required to keep the mesh voltage within safe limits can be found:

$$L = \frac{K_m K_1 \rho I \sqrt{t}}{165 + 0.25 \rho_s} \quad (19)$$

where:

ρ_s = resistivity of ground immediately beneath the feet, in ohm-meters. It may take into account surface treatment (e.g. crushed-rock layers) having different resistivity than natural ground.

t = maximum duration of shock, in seconds.

Other factors are as defined above for Equation (16).

In addition to the horizontal grid conductors proper, current may enter the ground through ground rods, deep well casings, metal foundation pilings, etc., where these exist. It would probably be reasonable to add the sum of the lengths of these to that of the grid conductors. While such an addition is far from rigorous, it should give a closer approximation than if such vertical electrode elements were to be ignored.

The proper value to be used for K_1 will vary from about 1.2 to 2 or even more, depending on the geometry of the grid. See Section 10.8 below.³⁴

Cases may occur where the conductor length derived from Equation (19) is too great to be feasible economically. In such situations, the use of expedients mentioned later, with a somewhat less extensive grid, may be considered.

Where soil resistivity and total ground current are very low, the figure derived from Equation (19) may give too small a total length of conductor to properly connect all objects to be grounded, in which case, more conductor than that needed merely for gradient control will obviously be required.

10.8—Effect of Irregularities—The "Non-Uniformity Factor" K_1

Much of the information in the literature deals with more or less idealized conditions, such as soil of uniform resistivity, or symmetrical grids composed of square or rectangular meshes of uniform size. Even for these idealized conditions, the current per unit length of conductor which flows from the mat will vary, being higher at the sides than in the center, and higher yet at the corners. Voltage gradients will vary accordingly.

To make the problem more difficult, practical installations seldom conform to this idealized uniform resistivity and geometry. This does not mean, however, that the problem is hopeless. It does mean that a good conception is needed of the factors causing irregularities and how they operate. It will then be possible to apply a correction factor, which, though not precise, will usually be adequate for practical purposes.

Much helpful information on this question can be gained from the reports by Koch (Appendix VI) and Armstrong on tests of scale models in water tanks.^{36, 34}

Koch has plotted, for various grid configurations, the mesh center voltages above remote earth as percentages of the total voltage rise, IR , of the grid, (Appendix VI). Since we are now more interested in local potential differences, the figures reported by Koch have each been subtracted from 100 percent and replotted in Figure 7 as the potential differences between the grid and the various mesh centers, again as percentages of the total grid voltage rise IR . Figure (7) illustrates quite clearly the effects of both the fineness of the grid mesh, and of various irregularities.

However, what is also needed is a quantitative relationship of the mesh potential, in each case to ρ , I , and L ; that is to say, something that will help in evaluating the irregularity factor K_1 in Equations (16), (19) and (21) of this Guide.

Unfortunately, Koch did not report the grid resistance, current, or water resistivities for his various tests. It was therefore necessary to compute the

resistance of each grid used, so that the total voltage rise IR could be expressed as a function of ρ , L , and L . These resistances were therefore computed using Schwarz's method and were checked (agreement within about 6 percent)-using that of Laurent.^{42, 43}

By multiplying these computed values for the total voltage IR , by each of the respective percentages from Figure 7, coefficients have been derived and plotted in Figure 8. These coefficients are, in fact, the product of coefficients K_m and K_i for Equation (18) and thus when multiplied by $\frac{\rho I}{L}$ give the actual

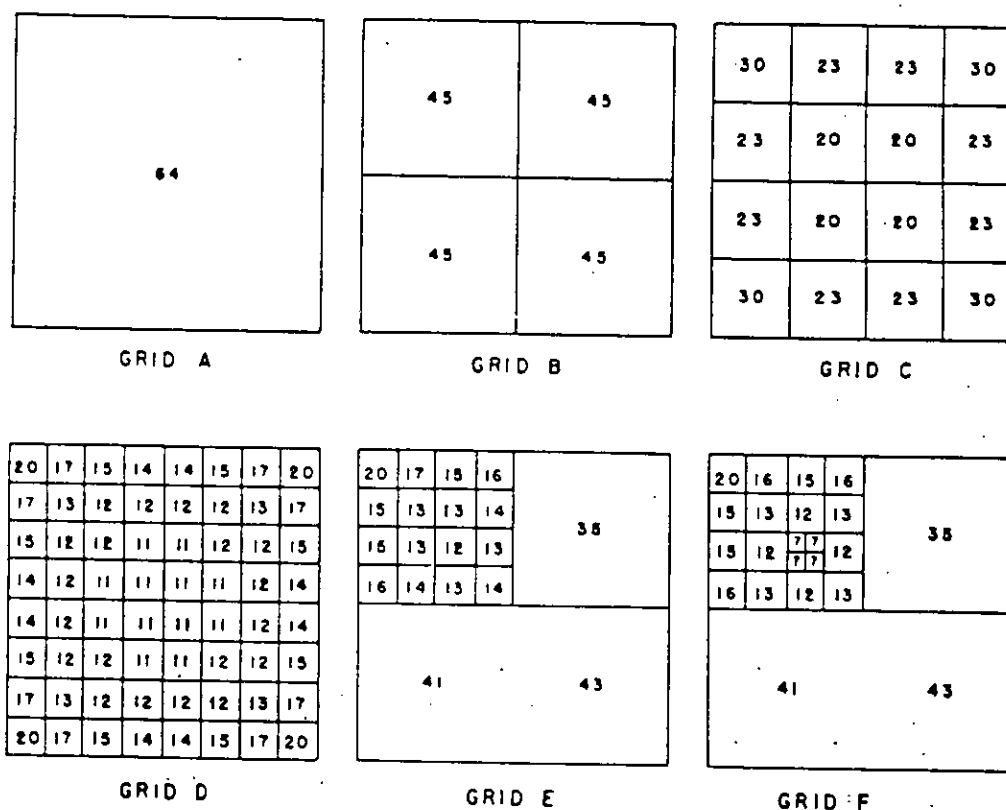
mesh potential in volts.

It is interesting to note that the test results reported by Armstrong on a nine mesh grid are entirely consistent with the results of the test by Koch,

though only the value of mesh potential at the center of one side is available.⁴⁴

The coefficients for grids C and D agree fairly well with the approximation of Equation (15), that $E_{mesh} \approx \rho i$ with K_m times K_i being approximately unity so far as the major portions of the yard are concerned. They also confirm the necessity, mentioned elsewhere, of using a factor K_i to take into account the higher gradients at corners or at projections from the periphery.

So far as internal gradients are concerned, these can be kept within tolerable limits by keeping the general mesh spacing throughout the station reasonably uniform and sufficiently close so that the mesh potentials, even at the corners, are within acceptable limits. A study of Figure 8, however, suggests an



Figures in diagrams above are mesh voltages expressed as a percentage of total grid potential rise IR . They are based on Koch tests (Appendix VI).

GRID	A	B	C	D	E	F
TOTAL GRID CONDUCTOR LENGTH "L" IN METERS	55.2	82.8	138.0	248.4	117.3	120.7
RESISTANCE "R" IN OHMS PER OHM-METER OF RESISTIVITY	0.0518	0.0467	0.0419	0.0382	0.0434	0.0430

Lengths and resistances are for full-scale equivalents of model grids tested by Koch.

Figure 7. Effect of mesh spacing on mesh voltages

alternate possibility of using a somewhat wider mesh over most of the area and correcting the situation near the corners by using a closer mesh there only.

Figure 8 is of value in showing why computations made on the assumption of fairly uniform distribution of grid conductors [Equations (16) and (19)], require revision in cases where conductor spacing is very irregular. It will be seen that grid E, though it has 42 percent more conductor than the uniformly spaced grid B, has a maximum mesh potential which is 25 percent higher in terms of $\frac{\rho I}{L}$ than is the case for grid B.*

Another factor which may threaten accuracy of results is non-uniformity of soil resistivity. Resistivity may vary in many ways. If surface layers have better conductivity than deeper layers, more of the current will then be channeled in these upper layers than would be predicted on a basis of uniform resistivity. The opposite will be true if the deeper layer are more conducting, especially if the ground system makes effective contact with them (e.g., by well-distributed ground rods). Resistivity at any given level may also vary horizontally over the yard areas.

If the resistivity used in calculations is somewhere near the effective average for the station, the local variations will in part be self-compensating since, while heavier ground currents will tend to flow in areas of low resistivity, the lower resistivity will result in a lesser voltage drop per foot for a given current density. On the other hand, local abrupt changes in resistivity along the path of current flow may result in unexpectedly high local gradients. 11, 23, 49, 53, 59, 71.

In general, some upward adjustment of the K_1 factor is appropriate wherever any large variation in soil resistivity is known or suspected. Considerable assistance in the study of problems of non-uniform resistivity is provided by Rudenberg and Laurent in Appendixes III and IV, and Reference 11.

Most studies of the grounding problem assume a uniform potential throughout the station ground grid itself. This implies that the longitudinal voltage drop in the grid conductors is negligible as compared to that in the ground and external circuit, an assumption usually accurate enough for practical purposes. However, to the extent that there may be potential differences between different parts of the grid itself, somewhat more current will tend to flow from the higher potential sections and less from the others. The higher potential section will, of course, be where the metallic path followed by the fault current is attached to the grid, that is, the ground wire from a machine frame subjected to insulation failure, or a star neutral ground connection. Since these connections are more likely to be in the central part rather than on the rim of the grid, this effect, and the normal tendency

of the ground current to be denser near the rim, tend to be compensating in some degree.

11.—CALCULATION OF RESISTANCE OF GROUNDING SYSTEM

Precalculation of the resistance of the ground grid, based on the preliminary design, may next be approached. (High accuracy is not usually to be expected, especially where soil data are incomplete or soil homogeneity is lacking).

Methods available include those proposed by Gross and his associates, by Schwarz, and Rudenberg.^{34, 42, 44, 52, 59, 65.}

A very simple method employed by Laurent and Niemann uses a modification of the circular plate electrode formula, Equation (11), adding a second term, as follows:

$$R = \frac{\rho}{4r} + \frac{\rho}{L} \quad (20)$$

Here "r" is the radius in meters of a circular plate having the same area as that occupied by the grid; "L" is the total length of buried conductor in meters; and ρ is the resistivity in ohm-meters.

The second term recognizes the fact that the resistance of a grid is more than that of a solid plate, and that this difference decreases as the length of conductor increases, becoming zero as the solid plate condition is reached when $L = \infty$.^{28, 30**}

12.—CALCULATION OF MAXIMUM GRID POTENTIAL RISE

The approximate resistance of the mat as a whole having been calculated, the maximum rise in potential above remote earth will be $E = IR$, where I is the maximum short-circuit current in the grid, and R is the ground-grid resistance. For very low values of resistance and short-circuit current, this voltage may itself be less than the value determined from Equation (4), and hence be small enough to be contacted safely. If so, the investigation may stop here, subject to verification of the grid resistance value after construction.

More frequently, the total potential rise IR will itself be in excess of a safe value, so investigation of local potentials will be in order.

13.—CALCULATION OF STEP VOLTAGES AT PERIPHERY

Within the grid, step and touch voltages can be decreased (at a price) to any desired value by decreasing the mesh interval of the grid. They can be made zero in the theoretical limiting case of the solid plate.

The situation is different in the zone immediately

* Absolute value of mesh voltages for a given fault current, however, is slightly less for grid E, since I/L is 30 percent less.

** If the equation is multiplied by I to get the total potential rise, then the term $\frac{\rho I}{L}$ can be considered to represent the voltage drop between the conductor and the ground surface areas within the mesh.²⁸

outside the grid periphery, where the problem could exist even for a theoretical solid plate. This problem may be serious in small stations where the grid can cover only a limited area. Fortunately, a station can usually be designed to eliminate the possibility of touch contacts beyond the ground system periphery, and the limitations on step potentials are less exacting.

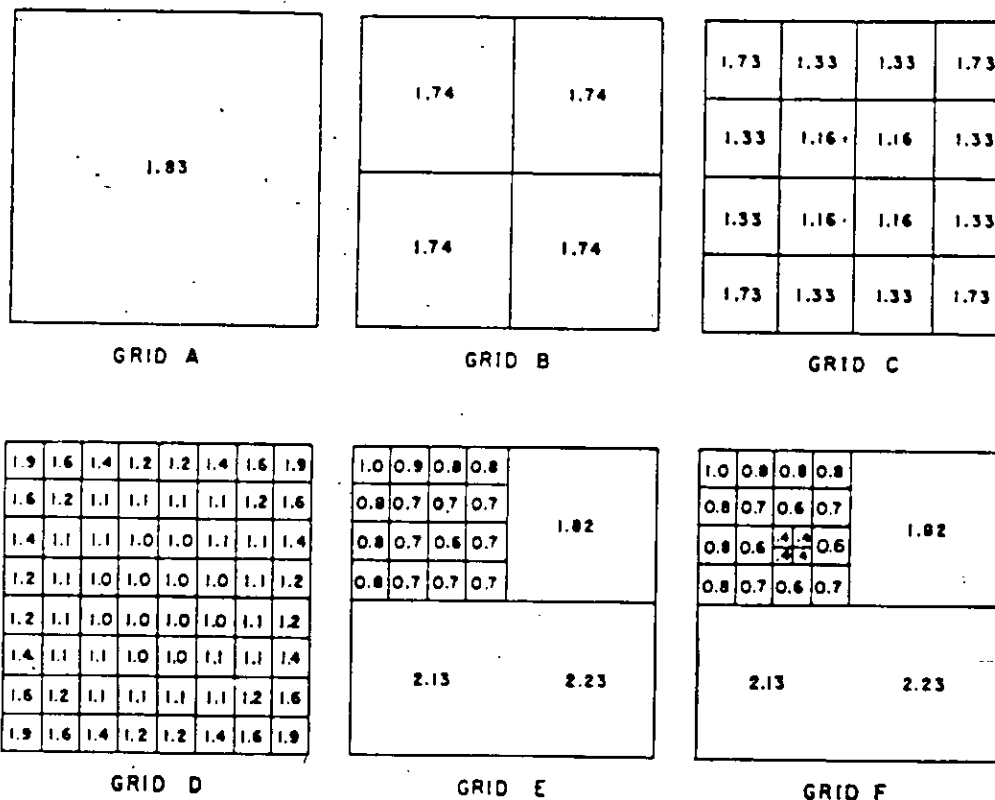
As stated previously, Laurent has suggested that the step potential will usually have a value of 0.10 to 0.15 ρ_i

for normal conductor size, spacing and depth of burial (the latter apparently assumed to be approximately one meter). Niemann uses 0.1 to 0.2 ρ_i .^{28, 30}

A coefficient of 0.2 was suggested in the 1958 AIEE report.³⁴

However, subsequent studies of differing designs and test data have shown many cases where the coefficients may be considerably higher than this.

Therefore, here, as in the case of mesh potentials,



Figures in diagrams above the products of coefficients $K_m \times K_i$ determined from Koch experimental data (Appendix VI).

GRID	A	B	C	D	E	F
MAXIMUM VALUE $K_m \times K_i$ AS RECORDED ABOVE	1.83	1.74	1.73	1.90	2.23	2.23
COEFFICIENT K_m COMPUTED BY METHOD OF APPENDIX I	1.82	1.50	1.18	0.86	1.50	1.50
COEFF. $K_i = \frac{K_m \times K_i}{K_m}$	1.00	1.16	1.47	2.21	1.49	1.49

It may be noted that the values of K_i for grids A, B, C, and D conform closely to the empirical curve $K_i = 0.65 + 0.172 n$ where n is the number of parallel grid conductors in one direction, i.e., excluding cross connections.

Figure 8. Determination of coefficients K_m and K_i for use in the equation: $E_{\text{mesh}} = K_m K_i \rho \frac{I}{L}$

it seems preferable to take advantage of the equations of Appendix I, which take into account the actual burial depth and spacing. It is also desirable to select an estimated irregularity factor K_1 on the basis of the general grid geometry.

The more accurate equation for step voltage then becomes:

$$E_{step} = K_1 K_2 \rho \frac{I}{L} \quad (21)$$

where:

K_2 is a coefficient which takes into account the effect of the number n , the spacing D , and the depth of burial h of the grid conductors. Its value in terms of these, as derived in Appendix I, is as follows:

$$K_2 = \frac{1}{\pi} \left[\frac{1}{2h} + \frac{1}{D+h} + \frac{1}{2d} + \frac{1}{3d} \dots \text{etc.} \right] \quad (22)$$

the total number of terms within the brackets being equal to the number of the parallel conductors in the basic grid, excluding cross connections.

K_1 , ρ , I , and L are as previously defined for Equation (16), Section 10.7.

A value of about 1.2 to 1.3 for K_1 is proposed by Niemann. This would probably be insufficient to cover corners of most grids. More conservative values can be assumed, especially if there are long narrow projections of the grid periphery. Ground-current density and surface gradients will, of course, tend to be higher at projecting corners of the grid periphery and lower than average at re-entrant corners. (Consideration of the analogy of a capacitor electrode in a homogeneous dielectric will make this clear.) According to Laurent, the external gradient near the corner of a square grid can be about twice as great as at the same distance from the middle of one side, if the network has a very fine mesh, this ratio decreasing to about 1.5 as the number of meshes is decreased. While Koch reported no measurements outside the grid periphery, Figure 8, derived from his tests, does give an indication of the degree of irregularity in large and small mesh grids.

An upward adjustment of K_1 can be made where appropriate to cover anomalies in ground resistivity.

Because step potentials are inherently less dangerous than other types, extreme precision is not too important. As French points out, if internal potentials are kept within tolerable limits, and if surface resistivity is comparable inside and outside the fence, then periphery step potentials are seldom a problem, especially since higher step potentials are usually permissible.²⁸

If, however, safety within the yard is achieved only with the assistance of a high-resistivity surface layer, such as crushed rock, which does not extend outside the fence, then step potentials may also be troublesome, especially near corners and projections. Extension

of the gravel layer, beyond the fence line, use of the "potential ramps" discussed in Appendix VI, and elimination of sharp projections are among the possible remedial measures where this condition exists.^{28, 30, 34, 35}

14.—CALCULATION OF INTERNAL STEP AND TOUCH VOLTAGES

14.1—General

If total length of buried conductor equals the value computed in Equation (19), the step and touch voltages within the grid perimeter should, in general, be within tolerable limits. Note, however, that if crushed rock is used over the surface of the station within the fence only, credit cannot be taken for its higher resistivity in figuring tolerable touch voltages on the outside of the fence. Also where conductor size, spacing, and depth of burial are not within the usual range of values, or where major irregularities exist in the geometry of the grid, or where important anomalies are suspected in ground resistivity, then more detailed investigation of all or part of the station area may be in order. The material in the appendix and in the various references may then be helpful, or it may be decided to add an additional safety factor to cover doubtful situations.

14.2—Effect of Sustained Ground Currents

Once the grounding design has been established as safe for the maximum ground-fault current at the appropriate clearing time, it will only be necessary to check step and touch voltages for sustained ground currents. Currents below the setting of the protective relays may flow for extended periods and should, therefore, be checked for causing body currents of less than safe let-go values. Fault currents between these two extremes will hardly require special consideration since the usual time characteristic of protective relays will only permit passage of fault currents of essentially lower ($I^2 \times T$) values than the maximum fault current. These lower currents of longer duration may thus be expected to produce body currents considerably below the threshold of fibrillation, even if somewhat above let-go threshold.

15.—INVESTIGATIONS OF TRANSFERRED POTENTIALS

A serious hazard may result during a fault from the transfer of potentials between the ground grid areas and outside points, by conductors such as communication and signal circuits, low-voltage neutral wires, conduit, pipes, rails, metallic fences, etc. The danger is usually from contacts of the "touch" type. The importance of the problem results from the very high magnitude of potential difference which is often possible. This may approach the full value of the ground grid potential rise under short-circuit conditions, in contrast to the relatively small portion of this which can normally be encountered in the usual "step" and "touch" contacts within the ground grid area.

15.1—Communication Circuits

For communications circuits, schemes have been

developed involving protective devices and insulating and neutralizing transformers to safeguard personnel and communications terminal equipment. These will not be discussed here except to emphasize the importance of adequate insulation and isolation from accidental contact of any of these devices and their wiring which may reach a high voltage with respect to local ground. This is often overlooked.

15.2—Rails

Rails entering the station, when connected either intentionally or otherwise to the ground grid, can theoretically create a hazard at a remote point by transferring there the grid potential rise during a fault. Similarly, if grounded remotely, a hazard can be introduced into the station area. Where considered serious, these hazards can be removed by insulating joints where the rails leave the ground grid area. A second set of insulating joints beyond the first would provide against the shunting of a single set by a metal car or the soil itself, and also reduce the somewhat remote hazard of accident from potential differences across a joint itself.

15.3—Low-Voltage Neutral Wires

Hazards are possible where low-voltage feeders or secondary circuits, serving points outside the station area, have their neutrals connected to the station ground. When the potential of the station ground grid rises as the result of ground-fault current flow, all, or a large part, of this potential rise may then appear at remote points as a danger voltage between this "grounded" neutral wire and the adjacent earth; moreover, where other connections to earth are also provided, the flow of fault current through these may, under unfavorable conditions, create gradient hazards at points remote from the station.

To avoid these difficulties, the low-voltage neutral may be isolated from ground at the station itself; always provided, however, that this does not result in slowing down the clearing time for low-voltage faults to the point where the total hazard is increased rather than diminished. If the low-voltage neutral is isolated from the station ground, it then becomes necessary to avoid hazards at the station due to the introduction, via the neutral wire, of remote earth potential. This implies that this neutral, in and near the station, should be treated as a "live" conductor. It should be insulated from the station ground system by insulation adequate to withstand the maximum ground-grid potential rise; and it should be located so as to minimize the danger of being contacted by personnel.

15.4—Portable Equipment and Tools Supplied from Substation

Similar hazards need to be considered in the case of portable mining, excavating or material handling equipment, or portable tools, which are supplied electrically from the substation and are used outside of the area of the grid where the mesh potential is held within safe limits. Such loads are often supplied by temporary pole lines or long portable cables. An example is often seen when an addition to an existing station is being constructed.

From what has been said in the previous section, it is apparent that a hazardous transferred potential might appear between a machine frame and the nearby earth during a fault, if the neutral or grounding wire to the machine is also connected to the substation ground. To avoid this, it is common to isolate the supply circuits, in cases such as these, from the substation ground; to ground the neutrals and machine frames to earth at the site of the work; and to make sure that the maximum fault current to the local ground is limited to a low value which will not itself cause gradient hazards.

15.5—Pipes

Water piping should always be tied to the station ground system, preferably at several points, to avoid hazards within the station area. The same is generally true of gas piping and other conductors such as cable sheaths or armor which are in more or less direct contact with the soil. Where these systems are very extensive, they may aid greatly toward reduction of the station ground grid resistance. To the extent that they carry ground current, the surface equipotential contours will be distorted outward where pipes leave the ground-grid area. The extent to which such a pipe or other buried conductor will transfer a potential outward from the station will vary inversely with the square root of its longitudinal impedance and directly with the square root of its leakage resistance per unit length. In soils of low resistivity, these potentials will not be transferred far. Where thought desirable to stop them at the grid boundary, insulating sections can be inserted. However, these should be of the order of thirty feet in length to avoid shunting by the adjacent soil. See Appendixes III and IV.

15.6—Auxiliary Buildings

Auxiliary buildings, including employee homes, can be treated as part of the substation, for grounding purposes, or as separate installations, depending on circumstances. If relatively close, and especially if linked directly to the substation by such things as water pipes, cable sheaths, phone lines, etc., it is appropriate to treat such buildings and their immediate area as part of the substation, including them within the ground grid and applying the same safety criteria. If more remote, and if such conducting links are lacking, it may be decided to treat such buildings as separate units with their own local safety grounds. If served electrically from the substation, they should then have their own distribution transformers of a type to provide adequate insulation against transfer of the substation ground-grid potential rise. Secondary neutrals would, in this case, be connected to the local ground at the auxiliary buildings only.

16.—INVESTIGATION OF SPECIAL DANGER POINTS

16.1—Operating Handles

Equipment operating handles deserve especial attention because of the higher probability for coincidence of adverse factors. For example, hand operation of equipment such as a disconnecting switch requires

the presence of the operator near a grounded structure at a point where opening in error of an energized circuit can sometimes result in an arc to the structure, or perhaps mechanical failure and electric breakdown of a switch insulator. A large percentage of fatal accidents from voltage gradients are in fact associated with operating handles.

It is relatively easy to protect against these hazards when the operating handle is within a reasonably extensive substation ground-grid area. If the grounding system has been designed conservatively and in line with principles here described, touch and step voltages near the operating handle, as elsewhere in the station area, should be within safe limits. If, however, conditions render accurate calculation especially difficult, one may wish to add an additional safety factor by using closer mesh, or higher resistance surfacing such as crushed rock, or both in this special danger area.

Grid F of Figure 7 shows the manner in which higher safety factors can be provided if desired at especially important places, such as switch handles, without appreciably affecting gradients elsewhere.

Much more difficult is the case of an isolated switch or switches such as a line sectionalizing switch where a permanent mat of large size is impractical. Methods used to meet this problem vary greatly, and include insulated platforms; metal platforms connected to handle and ground system; buried plates, grids or ground loops; portable grids connected to handle and ground system; use of insulating handle, etc.

It is true that more than one type of satisfactory solution is possible. It has also been shown by calculation and tests that many arrangements which might appear safe at first glance would be extremely dangerous should there ever be an insulation breakdown to the operating mechanism or structure.

One should guard against the fallacy that a cluster of ground rods or even a buried loop will necessarily insure safety by establishing the ground where a man stands at the same potential as the handle. It will not. Current leaving a buried conductor flows in part upward toward the surface. Associated with this upward flow through the resistivity of the ground is a potential drop, which may be a few volts, a few hundred volts, or perhaps many thousands of volts, depending on conditions.*

One utility checked, in a model tank, a design in which the operating mechanism was grounded to a cluster of three driven rods. Touch potentials of the order of half the normal line-to-neutral operating voltages were measured! The solution was a portable steel mat which could be rolled up and carried in a

* For instance, assume a simple loop 6 feet in diameter buried 18 inches deep, ρ equal to 200 ohm-meters, and system conditions such that the maximum short-circuit current flowing to ground from the loop is 300 amperes. Since $L = 6$ meters approximately, then $i = 50$ amperes per meter.

If we take Laurent's assumption that the potential difference between the grid and ground at the mesh center is of the order of $5i$, then the voltage between the operating handle, and the ground beneath the operator's feet will be of the order of 10,000 volts. (A more accurate computation would be possible but this will be sufficient to illustrate the point).

line truck and then spread on the ground and bonded to the handle when a switch was to be operated. The three ground rods were retained to insure fast relay action, as high step potentials will still exist at the boundaries of the mat during a fault.

Another utility using a buried counterpoise in conjunction with six driven ground rods, computed, by the methods outlined in this report, that touch potentials of the order of thousands of volts were possible. The solution adopted was to use three $\frac{1}{4}$ -inch thick perforated aluminum plates** joined in an L-shaped configuration. These are laid on the ground around the corner of the structure where the operating handle is mounted. The plates are then covered with a 6-inch depth of crushed rock. The perforations are to prevent pools of water collecting in the rock, and to help moisture to penetrate to the natural soil below the plates. The crushed rock serves several purposes. Since it is of high resistivity, even when wet, essentially all short-circuit current will flow down through the earth rather than up through the rock; the rock will be a high resistance in the path of any short circuit which might flow through the body; it will discourage growth of weeds or sod which would have a low resistance; it will help conserve moisture in the soil beneath; it will discourage theft of the electrode; and it will delineate for the operator the area where he can safely stand. The stranded aluminum counterpoise and the galvanized steel ground rods of the original design have been retained to insure fast relay action. Also, by occupying a much larger ground area than the plate itself, it decreases the over-all resistance, the potential rise of the plate, and the step potentials at its boundaries, though the latter may still be high.

In a situation of this kind, it is normally impractical to protect the man as he steps in or out of the protected area, whether the latter be plate, grid or insulating platform. Here, however, there is hazard only in the case of local breakdown, as remote line faults will not load the local ground. The chance that a local insulation failure will occur by pure coincidence as the man steps on the platform or grid is doubtless so remote it can be ignored. The best that can be done to protect him if he steps off after a breakdown, is to insure that relays are reasonably fast, to minimize shock duration, and that possible shock voltages are limited to those from step contacts rather than the more lethal touch contacts.

16.2—Fences

Fence grounding is of major importance because the more dangerous "touch" contacts are involved, because the outside of the fence is usually accessible to the general public, and because the fence may occupy a position on the periphery of the ground grid area where surface potential gradients are the highest. Past utility practices have been quite varied, but a few facts are clear:

**Copper and copperweld are avoided in this application to prevent galvanic corrosion of the transmission tower grillage footings. In circumstances where the aluminum might corrode, use of galvanized steel plates (with protective anode if necessary), would be indicated.

Two different general philosophies of fence grounding have been followed:

- (a) Inclusion of the fence within the ground grid area, and
- (b) Placement of the fence outside the ground grid area, either with or without close electric coupling between fence and the adjacent earth along its length, but with no electric tie between fence and main station grid.

Inclusion of the fence within the ground grid area increases the size of the area and thereby reduces, often substantially, the ground grid resistance, and hence the maximum ground grid voltage rise as well. While the fence now takes part fully in this rise, this is not of concern if internal and perimeter gradients of the grid are kept within acceptable limits.

Under this first philosophy, the perimeter conductor of the grid will normally either follow the fence line, or parallel it at a short distance (about 18 inches to 4 or 5 feet) outside. In either case, the perimeter ground conductor and fence should be bonded electrically at frequent intervals.

Placement of the ground conductor directly on the fence line permits the latter to be located on the property line if desired, without obtaining an easement to place a ground conductor on adjacent property. On the other hand, placement of the ground conductor a short distance outside the fence line will decrease somewhat the possible touch potential to which a person outside the fence could be subjected. Whether or not this difference is important will depend on circumstances.

(Note that, contrary to a misconception sometimes encountered, the ground surface above a conductor does not assume the potential of the conductor. Some current leaving the conductor will flow upward, causing a potential drop between the two points determined by the current density, soil resistivity, and depth of burial.)

Assume conditions as in Example 1 the end of Appendix I. If the fence lies one meter inside the perimeter conductor, and a man standing one meter outside the fence and above this conductor touches the fence, he will encounter a voltage of about 0.569 pi , the vertical difference of potential between the grid conductor (tied to the fence) and the ground surface immediately above the conductor where the man is standing.

Assume next that the fence is above the conductor, and the man, as before, is one meter outside. Here, if he touches the fence, he will encounter a potential difference made up of a vertical component as before, plus a horizontal component along one meter of ground surface, resulting in a total potential difference of 0.924 pi , or about 60 percent more than for the previous arrangement.

Locating the perimeter conductor one meter outside of the fence line instead of directly under the fence increases the touch potential for a man standing inside

the fence but only about 11 percent (0.797 pi against 0.718 pi).

If the second philosophy on fences is to be followed, i.e., if the fence and any associated grounds are not to be coupled in any way to the main ground (except through the soil), then three factors require consideration:

- (a) Is the falling of an energized line on the fence a danger which must be considered?
- (b) May hazardous potentials exist at the fence during other types of faults because the fence line crosses the normal equipotential contours?
- (c) Can complete metallic isolation of fence and station ground grid be assured at all times in practice?

In regard to the first point, construction of transmission lines over private fences is commonplace and gives no undue concern. The number of lines crossing a substation fence may be greater, but they are also under closer observation; also spans are often shorter and dead-ended at one or both ends. Hence this danger can be largely discounted. If one is to design against this danger, then very close coupling of the fence to adjacent ground throughout its length is necessary, and touch potentials inside and out must be reduced to acceptable limits for short-circuit currents of essentially the same maximum value as for the station. Isolation from the main station grid, which would otherwise dissipate a part of this current, will make this more difficult.

In regard to the second point, fences will seldom follow exactly the normal equipotential lines which result from fault current flowing in the station grid. If coupling of the fence to ground is left to chance, the fence might, under some circumstances, assume the potential of a point on the ground where the coupling was relatively good, and attain thereby a high voltage in relation to the adjacent ground surface at other points. Voltage and currents involved here are less than would result from the fall of an energized line, but may be sufficient in all but the simplest cases to warrant close coupling of the fence to ground, preferably by a buried conductor along its full length and frequently bonded to it.

In regard to the third point, a disadvantage of isolating the fence from the main grid (aside from sacrificing improvement of station grid resistance) is the chance of inadvertent electric connection between the grid and the fence areas. Telephone, signal, or distribution circuits from the station to a gate house, water pipes, etc., could transfer main grid potentials and introduce dangerous local potential differences during faults. If the fence itself is not tightly coupled to the nearby ground by its own adequate ground system, then any such inadvertent connections to the main grid could create a hazard along its entire length under fault conditions.

16.3—Cable Sheath Grounding

Metallic cable sheaths, unless effectively grounded, may attain dangerous voltages to earth. These voltages

may result from insulation failure, charges due to electrostatic induction, and flow of currents in the sheath, or from the voltage rise during faults discharging to the station ground system to which the sheaths are connected. Where low-resistance connections are available, grounding supplemented by bonding together all cable sheaths in a manhole, usually affords an excellent kind of protection. According to questionnaire on substation grounding practices in 1954, ninety-four percent of those reporting connected metallic cable sheaths to ground, on both three-conductor and single-conductor power cables. To reduce sheath currents on single-conductor cables, the majority grounded one end of the sheaths only when the length was not excessive. On long cables, normal cable practices were indicated, using bonding transformers, cross bonding, insulated joints, and so forth. Twelve percent of those reporting indicated grounding through primary cells or similar devices for cathodic protection. The effects of fault currents on the conditions to be encountered with any of these grounding arrangements can only be determined by careful analysis for each specific case.⁴¹

16.4—Lightning Arrester Grounding

Lightning arresters must always be provided with a reliable low-resistance ground connection. They should be connected as close as possible to the terminals of the apparatus to be protected and have as short and direct a path to earth as practicable. While many utilities provide separate ground leads from arresters mounted on metal structures, studies by others have shown that the steel mounting structures normally used, because of the large cross-section of their members, provide a higher conductivity path than a copper cable of the usual size. On this basis, some utilities use the steel mounting structure as the lightning arrester ground path. It is, of course, important in such cases to insure adequate electric connection from the structure to both arrester ground lead and ground grid; and also to be sure that the steel cross-sectional area is adequate for conductivity, and that no high resistance is introduced into joints from paint films, rust, etc. Aluminum structures, where used, can obviously provide a ground path of high conductivity and current-carrying capacity. American Standards for Power Transformers require copper-faced ground pads near the base for grounding the transformer bank. The Standards also provide for a ground pad at the top of the tank for fastening a copper ground lead from the lightning arrester when it is mounted on the transformer. The tank plate between the welded-on ground pads provides a higher conductivity path than a separate cable and when this arrangement is used, it makes a reliable low resistance ground connection.

16.5—Separate or Common Grounds

Separate grounds within the station area were formerly a source of danger, but are little used at present. The practice was based on the assumption that, by keeping "system" grounds separate from "safety" grounds, the short-circuit current due to line faults would not flow in the latter, and the resulting voltage rise of the safety grounds would be avoided. In practice, however, this had many disadvantages. First, re-

sistance of both safety and system grounds was greater than would be the case for the two connected together. Second, high currents could still flow in the safety ground in the event of insulation failures in the station. Third, it usually failed to achieve its objective, because of the inability to avoid a high degree of coupling between electrodes in the same area. Fourth, to the extent that decoupling was possible, potentials, often dangerous, were made possible between nearby "grounded" points.

17.—CORRECTION OR REFINEMENT OF PRELIMINARY DESIGN

If calculations, based on the preliminary design, indicate that dangerous potential differences can exist within the station, the following possible remedies should be studied, and applied where appropriate:

(a) Decrease in total grid resistance will decrease the maximum ground grid potential rise and hence the maximum transferred potential. The most effective way to decrease ground resistance is by increasing the area occupied by the grid. Deep driven rods or wells may be used if the available area is limited. Decrease in station resistance may or may not decrease appreciably the local gradients, depending on the method used.

(b) Improvement of gradient control. By employing closer spacing of grid conductors, the condition of the continuous plate can be approached more closely. Dangerous potentials within the station can thus be eliminated at a cost. The problem at the perimeter may be more difficult, especially at a small station where earth resistivity is high. However, it is usually possible, by burying the grid perimeter ground conductor outside the fence line, to insure that the steeper gradients immediately outside this grid perimeter do not contribute to the more dangerous touch contacts. A theoretically possible, though seldom used, method of controlling perimeter gradients and step potentials is to bury two or more parallel conductors around the perimeter at successively greater depths as distance from the station is increased.^{27, 33, 34}

(c) Addition of a relatively high resistance surface layer (e.g., crushed rock) to increase the resistance in series with the body. The value of this in reducing shock currents is not always fully realized. Tests by Bodier at a station in France showed that the river gravel used as yard surfacing when moistened had a resistivity of 5000 ohm-meters. A layer 4 to 6 inches thick decreased the "danger factor" (ratio of body to short-circuit current) by a ratio of 10 to 1, as compared to the natural moist ground. Tests by Langer in Germany compared body currents when touching a hydrant while standing on "wet coarse gravel" of 6000 ohm-meter resistivity with body currents while standing on "dry" sod. The current in the case of "dry" sod was of the order of 20 times the value for "wet coarse gravel"! Tests reported by Elek provide further confirmation of these benefits.^{27, 33, 34}

In basing calculations on the use of a layer of clean crushed rock or gravel, consideration should be given to the possibility that insulation may become impaired

in part through filling of voids by compression of the lower ballast layers into the soil beneath, by material from subsequent excavations, if not carefully removed, and in some areas, by settlement of airborne dust.

(d) Diverting of part of the fault current to other paths, e.g., by connecting overhead ground wires of transmission lines. In connection with the latter, the effect on fault gradients near tower footings should be weighed, however.

(e) Limiting of short-circuit current flowing in the ground mat to lower values. If feasible, this will, of course, decrease the total rise in ground-mat voltage 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.

(f) Barring of access to limited areas where it may be impractical to eliminate possibility of excessive potential differences during fault.

Using one or more of the above expedients where necessary, designs can be completed for construction purposes. These should be reasonably liberal, as grounding facilities can usually be installed more cheaply if all go in as part of the general construction job, without the necessity of making additions later.

18.—CONSTRUCTION OF GROUNDING SYSTEM

The next step, of course, is the actual construction of the grid as designed.

The method, or combination of methods chosen, will depend on a number of factors, such as size of job, type of soil, size of conductor, depth of burial, availability of equipment, cost of labor, and any restrictions due to nearby existing structures or energized buses.

Where conditions are favorable, the cheapest and quickest method of installing grid conductors is to plow them in. A special narrow plow is used. The plow may be either attached to, or drawn by, a tractor or four-wheel-drive truck, if there is sufficient maneuvering room. It may also be drawn by a winch placed at the edge of the yard.

The conductor may be laid on the ground in front of the plow, or a reel of conductor may be mounted on the tractor or truck, or else on a sled pulled ahead of the plow. The conductor is then fed into the ground along the blade of the plow to the bottom of the cut. Another method is to attach the end of the conductor to the bottom of the plow blade, and pull it along the bottom of the cut as the plow progresses. In this case, care should be taken to insure that the conductor does not work its way upward through the broken soil.

The cross connections are plowed in at slightly less depth to avoid damage to previously laid conductors. The points of crossing, or points where ground rods are to be installed, are then uncovered, and connections are made by the usual methods, such as brazing or clamping.

With adequate equipment, and in the absence of heavy rock, this method is suitable for all of the conductor sizes and burial depths normally used. In cases where plowing in is not practical, the conductor can, of course, be placed in hand-dug, or machine-dug trenches.

The ground system will normally be installed after the yard has been graded and all deep excavations have been back-filled and compacted, but before any surfacing is applied.

It has been shown that the insulating value of clean crushed rock or gravel is an aid to safety under ground-fault conditions. Therefore, when any excavation is necessary after a rock surfacing has been applied, care should be taken to avoid mixing the lower resistivity soil from the excavation with the surrounding rock surfacing material.

19.—MEASUREMENT OF RESISTANCE OF GROUNDING SYSTEM AS CONSTRUCTED

As has already been indicated, only approximate results can usually be expected from a precalculation of station ground resistance. A careful measurement of the resistance of the installation as constructed is therefore desirable.

It is not inferred that extreme precision is always possible in measurement, but results should be more dependable than calculated values, and adequate for their purposes, provided care is used to select methods which will avoid gross errors.

The basic measurement normally used consists essentially of passing a current through the station ground via a ground electrode or probe remote from the station, and measuring the voltage produced between the station ground and the surface of the ground at a remote area. The term "remote" implies very large probe spacings since the probes are considered to be placed in locations where the earth current density approaches zero.

In homogeneous soil, the pattern of current flow, and the values of potentials and gradients for any ground electrode or system approximates that of an equivalent superficial hemispherical electrode (of the same ground resistance) at points where the distance from the center of the electrode or grounding system is large as compared to its dimensions. In such cases, the curves for a hemisphere as shown in Figure 9 will apply. The density of the earth current, even from a large station grid, and the resulting gradient on the earth's surface, will become negligible at probe separations of the order of 1000 to 2000 feet.²⁰

For measuring resistance, the current source is connected between the station ground mat and a current probe located at a distance of several hundred feet from the station. The potential-measuring circuit is then connected between the station ground mat and a potential probe, measurements being made at various locations of the probe outside the station. This probe may be moved toward the current probe in equal incre-

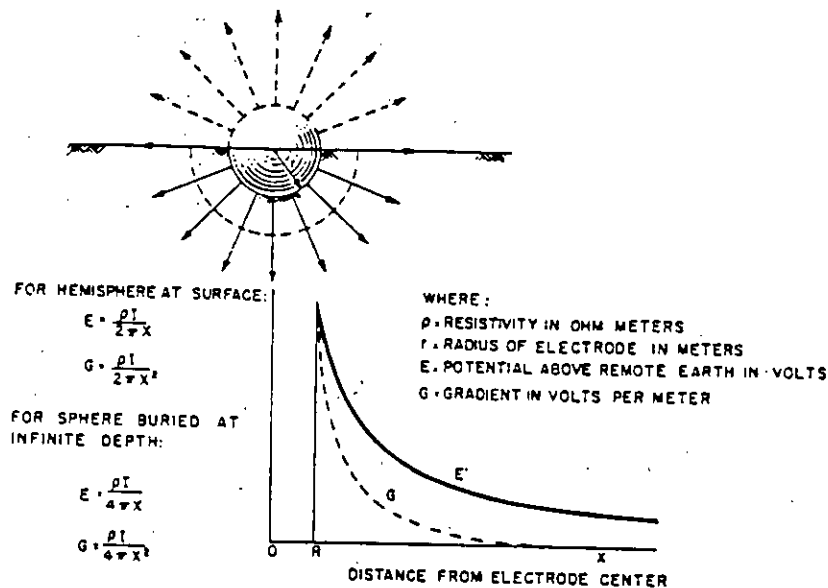


Figure 9. Radial flow of current from buried spherical electrode, or hemispherical electrode at ground surface.

ments of distance, starting near the station, and the resistance readings obtained at the various locations may be plotted against distance from the station. The resulting graph should resemble Curve A of Figure 10. From zero to P_1 the voltage per ampere of test current rises, but the voltage gradient decreases, becoming

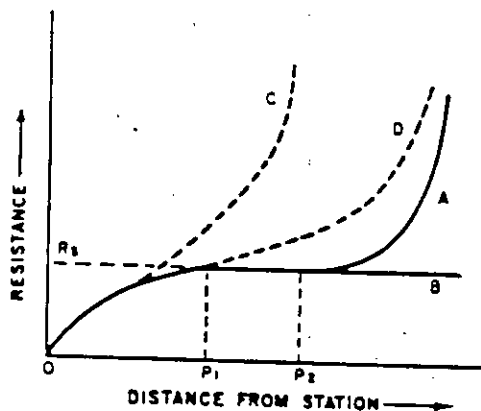


Figure 10. Typical curves of resistance values

- Measured in direction from station same as that of current probe with latter at sufficient distance.
- Same as A, except measured in opposite direction.
- Same as A, except current probe distance insufficient.
- Same as A, but showing error due to a mutual coupling between potential and current circuits comparable with station resistance.

practically zero at P_1 . At P_2 the effect of current converging on the current test probe becomes apparent and a rising voltage gradient is observed as the current probe is approached. The horizontal portion of the graph represents a zone where the effect of current convergence toward the ends of the current circuit is negligible. This zone is outside the "area of influence" of both the station and test grounds; R_s , the resistance measured on the flat portion, is the station ground resistance.

Simple direct-current measurements can be made with voltmeter and ammeter but this method is subject to errors due to polarization voltages set up by the passage of direct current from ground electrodes to earth.

Alternating-current tests with voltmeter and ammeter are feasible but may present difficulties due to the effects of residual voltages under normal operating conditions. Circuits can be devised for balancing out residual voltages if they are reasonably steady, and if the content of harmonics is small; or if large test currents are available, the residuals may be made negligible by comparison. In some instances, simultaneous measurements of the residual current and voltage are possible, using these quantities directly to measure the station ground resistance.

Special instruments often used for ground-resistance measurements comprise a hand-cranked or motor-driven direct-current generator with a current reverser, a synchronized (mechanical) rectifier, and a crossed-coil movement that directly indicates the ratio of test voltage to test current on a scale calibrated in ohms. The circuit is so designed that the readings are not affected by residual voltages.

Measurement problems sometimes encountered include:

(a) Inadequate Current Probe Spacing. Curve C of Figure 10 shows the effect of inadequate separation between the current probe and the station ground. No part has a zero slope to indicate the station resistance. This difficulty arises because current flowing from the station ground does not diverge sufficiently to allow the current density, and hence the voltage gradient, to approach zero, before beginning to converge toward the current probe. The areas of influence of the station ground and the current probe are said to overlap. In this situation the remedy, of course, is to locate the current probe farther from the station and to repeat the measurements. Separations of from 1000 to 2000 feet are usually adequate even for the largest stations. If such separations cannot be achieved, or in the rare cases where they do not permit finding the point of zero slope, a fair approximation can be obtained from a reading with the potential probe at about two-thirds the distance of the current electrode, measuring from the center of the ground system.

It is sometimes thought that the difficulty demonstrated by Curve C is due to high current-probe resistance, and attempts are made to reduce this resistance, for example, by wetting the area around the probe with salt water. This step is based on the idea that when the probe resistance is high, the voltage gradients remote from the probe are also high. Treatment of the local area around the probe is not a solution, however, since the current distribution in remote areas is not appreciably altered by local treatment at the probe, and the voltage gradients in these areas are thus essentially unchanged. When such curves are obtained, an increase in probe spacing is required.

(b) Mutual Coupling Between Current and Potential Circuits. When ground-resistance measurements are being made at large stations with resistance below 0.5 ohm, graphs similar to that of Curve D of Figure 10 are sometimes obtained. The curve starts to rise in the usual manner for increasing values of distance from the station. It then rises as a straight line until the potential probe is moved into the area of influence of the current probe and the typical sharp upward rise results. Since there is no region of zero slope, the station ground resistance is not indicated, and increasing the probe spacing does not remove the difficulty.

The linear rise in the center of the curve is caused by mutual coupling between the current and potential circuits. Each of these circuits is a single wire with earth return and the mutual coupling between them is expressed as an impedance coefficient of the form:

$$Z_{pc} = A + jBf \log_{10} \frac{C \sqrt{\rho/f}}{d_{pc}} \text{ ohms per unit length} \quad (23)$$

where: f = test-current frequency, in cycles per second

ρ = earth resistivity, in ohm-meters

d_{pc} = average distance between current and potential circuits, in meters, when these are located in the same direction from the station.

A, B, C are constants.

Thus, in addition to the voltage drop across the

station ground resistance to be measured, an error equal to Z_{pc} times the test current appears in the potential circuit. This error voltage is a function of frequency; indeed, if an instrument of the hand-cranked generator type, without speed control, is used, the instrument reading may rise noticeably as cranking speed is increased.

For a test-current frequency of 60 cycles per second, an earth resistivity of 50 ohm-meters, and a lead separation of 1 meter,

$$Z_{pc} = .002 + j.02 \text{ ohms per 100 feet of potential lead length} \quad (24)$$

This error becomes significant when the station resistance is low and the physical size of the ground mat is large enough to require long test leads.

Since the term involving lead separation is a logarithm, it is impractical to increase the lead separation sufficiently to eliminate the error. If the potential lead is laid out in a direction from the station different from that of the current lead, however, the effect of mutual coupling can be eliminated. The angle between the leads should preferably be at least 90 degrees, although angles as small as 60 degrees have been found adequate in some instances where larger angles were impractical because of the location of the station.

When this technique is used, a curve of the type illustrated in Curve B of Figure 10 is obtained. No turn-up is found after the straight portion is reached, since the potential probe never enters the area of influence of the current probe. A minor difficulty arises in this method in determining whether the current probe spacing is adequate. With inadequate spacing, the curve will still contain a flat portion, but the indicated resistance value will be too low.

The following measurement sequence has been found to constitute a satisfactory method of avoiding errors from incorrect spacing:

Two suitable directions at least 90 degrees apart having been selected, the potential lead is laid in one direction and a probe is placed 800 to 1000 feet from the station fence.

The current lead is laid in the other direction and a reading is taken with the current probe located at the same distance as the potential probe. The current probe is then moved out in 100-foot steps until the same reading is obtained at three successive locations.

The current probe having been left in the last foregoing position, the potential probe is moved out in 100-foot steps until three consecutive readings are obtained without a change in value. These last readings then represent the true value of station ground resistance.

Communication circuits entering a station may sometimes be convenient for use as current and potential circuits since grounds often can be put on these circuits at remote stations or exchanges, thus insuring adequate probe spacings. This method is particularly useful when placing of local probes is difficult because of the character of the surrounding terrain. If this technique

is used, it is essential that the circuits follow different directions from the station to the temporary ground locations, to avoid mutual coupling errors. If the circuits are in cable, the sheaths must be isolated from the station ground and from any grounds within its zone of influence; otherwise the indicated resistance value will be too low.

(c) **Extraneous Grounds.** The effect of connections to grounds outside the station is sometimes highly significant, and may be difficult to measure accurately. The station ground layout should preferably be so designed that all such grounds can be temporarily disconnected from the main ground networks for purposes of measurement.

The value of ground resistance measured, with all outside grounds disconnected, gives some idea of the effectiveness of the grounding arrangement for lightning surge currents, since outside grounds are usually too distant to be effective at surge frequencies. If a repeat measurement with the outside grounds again connected shows little or no change in the resistance value, the effect of these grounds can also be neglected for power-frequency calculations. If noticeable reduction in resistance is indicated, the effect must be taken into account in determining the performance of the grounding arrangement during fault conditions.

The difficulty in determining the effect of extraneous grounds lies in evaluating the reactance associated with them, if they are located at significant distances from the station. If the measurement has been made at power frequency, using the voltmeter-ammeter method, no problem exists, since the total impedance will have been measured. Earth resistance instruments of the hand-cranked generator type, however, are virtually unaffected by the reactive component of the impedance, and therefore measure only the resistance of the grounding system.

If the extraneous ground consists of a connection to a single remote ground electrode, its effect can be established by making a separate measurement to determine the resistance, and then calculating the reactance by the usual methods for calculating the impedance of earth-return circuits. If the outside grounds include multi-grounded distribution neutrals or transmission-line sky-wire, methods are available for calculating the amount of current diverted by these circuits from the station ground networks, and hence the voltage rise due to current through the measured station ground resistance can be found.^{25, 43, 46, 49}

If the effect of outside ground connections is large, and if an accurate knowledge of it is important, the feasibility of making tests at power frequency should be considered, since the assumptions required for the calculations necessarily introduce errors.

20.—FIELD SURVEY OF POTENTIAL CONTOURS AND STEP AND TOUCH VOLTAGES

The best assurance that a station is safe would come from actual field tests of step and touch voltages with

a heavy current load on the ground mat. Because of the expense, few utilities are likely to make these tests as a regular routine practice. If, however, gross discrepancies between calculated and measured resistance, or known anomalies in the ground resistivities throw doubt on the calculated step and touch potentials, then such tests may be considered. This is especially true where the computed values are close to tolerable limits, and further improvement of the ground to provide a larger safety factor would be difficult or costly.

In such situations, it may be worthwhile to load the ground mat with a test current (preferably of the order of about 100 amperes) and actually take measurements of potential gradients at selected locations throughout the station and around its perimeter. The basic method for such gradient measurements involves passing a test current through the station ground, via a remote current electrode, as in station ground resistance measurements, and measuring the resulting touch and step potentials. To obtain the potentials existing under actual fault conditions, the test values are multiplied by the ratio of actual ground-fault current to test current.

Since the potentials of interest are those existing at the surface of the earth, the potential probe used is of a type which makes a surface contact. The relatively high contact resistances involved generally rule out the use of instruments designed for ground resistance measurements, since they operate over a limited range of potential probe resistance. It is usually necessary, therefore, to use a voltmeter-ammeter method, with a high-impedance voltmeter, and with test currents high enough to overcome the effects of residual ground currents.

Several methods of measuring and recording potentials may be used. Using a high-impedance voltmeter, e.g., a vacuum-tube meter, profiles and contours of open-circuit contact potentials may be plotted for the entire station. By assuming suitably conservative values of body-and-foot-to-ground resistances, and safe body current, the maximum safe value of open-circuit contact voltage can be determined and hazardous touch and step potentials can be located on the potential map.

Langer (Appendix V) and Bodier have described measurement techniques in which the effect of actual contact and body resistances are simulated. The operator wears rubber gloves and rubber-soled boots equipped with metallic-mesh contact surfaces. Voltages between these metal contact surfaces are measured by a vacuum-tube voltmeter shunted by a resistance equal to an assumed value of body resistance, and current is measured by a milliammeter. The ratio of shock current to total ground current is thus determined.^{27, 34}

By including foot-to-earth contact resistances as a part of the test procedure, the effect of variations in surface conductivity is taken into account. Thus, the additional safety factor provided by surface coverings of crushed stone, pavement, etc., is included in the test results.

21.—RECALCULATION BASED ON FIELD MEASUREMENTS—REVISION OF DESIGN

With the figure for measured resistance available, the maximum ground-mat potential rise can be recalculated. If substantially different from that based on the computed resistance, the precautions taken against transferred potentials may need review.

The measured resistance does not provide a direct means of rechecking the computed step and touch potentials as these are derived from the resistivity. However, if the difference between the computed and measured station grid resistance is very large, the resistance or resistivity figures may come under suspicion, the latter being, in general, less reliable. Each case will have to be judged on its merits to determine whether the discrepancy is such as to warrant further investigation or additional measurement of the resistivities, employment of larger safety factors, or direct measurement of danger potentials or shock currents as described above.

22.—CHECKING SAFETY OF EXISTING STATIONS

Previous sections of this Guide have contained suggestions for design of new stations so as to eliminate or minimize ground gradient hazard. French has pointed out a way by which these same methods can be extended to provide a quick and simple check, whereby those stations which are definitely safe can be distinguished from those which are either unsafe or marginal, and hence require more detailed study.⁴³

By rearranging Equation No. (19), it will be seen that a station should be safe, as regards internal gradients, if:

$$\frac{K_m K_1 \rho I \sqrt{t}}{L} - 0.25 \rho_s < 165 \quad (25)$$

By adopting sufficiently conservative values for the various terms, the engineer can usually reassure himself quite quickly in regard to most stations on his system, and be able to devote his detailed attention to the problem cases.

An example supplied by French, (while valid only for grid spacings of twelve feet or more and values of K_m times K_1 and t equal to, or less than those he has chosen), is nevertheless of interest. If the product of K_m multiplied by K_1 is taken as 1.25, and if the fault clearing time is not more than 30 cycles (0.5 second), then, if

$$i = \frac{I}{L}$$

it follows from Equation (25) that:

$$1.25 \rho_1 - 0.353 \rho_s < 233 \quad (26)$$

If the soil is homogeneous to the surface, then $\rho_s = \rho$ and the above requirement for safety becomes:

$$(i - 0.283) \rho < 187 \quad (27)$$

If the surface is gravel or crushed stone and there is reasonable assurance that it will remain in good condition, a conservative value of 3000 ohm-meters for wet stone can be used for surface resistivity. Substituting this value, the requirement for safety becomes:

$$\rho_1 < 1035 \quad (28)$$

Obviously, similar equations can readily be worked out for other values of K_m , K_1 , and t .

Step and transferred potentials remain to be checked. However, it can be shown that, for the grid spacing of twelve feet or more assumed by French, and with normal burial depths, stations which meet the above requirements will generally be safe from the standpoint of perimeter step potentials, if there are no especially sharp projections of the grid perimeter.

Note, however, that if the yard is covered with crushed rock to the fence only and not beyond, credit for the higher surface resistivity cannot be taken either for the perimeter step potential or the touch potential at the fence.

23.—MODEL TESTS

Test data from actual stations is often difficult to apply to the general problem, because of lack of controlled conditions, special local circumstances and variations in soil resistivity at the site.

Scale model tests, therefore, have sometimes been employed to determine ground resistance and potential gradient patterns of grounding arrangements. The usual method is to place a model of the grounding system in a body of water large enough to minimize boundary effects, and to measure voltages in the water with a vacuum-tube voltmeter. By the use of appropriate scale factors, the results can be applied to various conditions of fault current and earth resistivity.

These methods have proved useful in determining the relative characteristics of various grounding arrangements. Their usefulness in studying potential gradients in extensive grounding layouts is limited by the fact that rather large water volumes are required to permit detailed mapping of potentials.^{20, 26, 34}

24.—USE OF ELECTRONIC COMPUTERS

Computers have been used to develop some of the data of this Guide, as well as some of those in the references regarding computation of station resistance.

Computers make it feasible to compare many alternate combinations of grid conductor spacing, diameter, and burial depth for any given station, permitting selection of the one which gives lowest cost with safety.

Ultimately, computers may make feasible more refined methods of handling irregularities of grid geometry and soil resistivity in ground grid calculations.

25.—PERIODIC CHECKS

Some utilities like to recheck station ground resistance at monthly intervals for a few years to determine seasonal variation and effect of soil stabilization after completion of construction. It is also well to review the ground system from time to time for possible changes in system conditions which may affect the maximum value of ground current, as well as extensions to the station itself which may affect the max-

imum current, the station ground resistance, or local potential differences.

26.—CONCLUSIONS

Frequency of accidents from ground-fault gradients has been limited by low probability of coincidence of all the adverse factors required. Nevertheless, one fatal accident which could be prevented is too many.

Precise calculation in this field is seldom attainable. Field measurements of local potentials, when the ground system is loaded with relatively high test current, are quite conclusive, but too expensive for routine application.

It is hoped, however, that the material here presented may help engineers to avoid both the more dangerous situations, on the one hand, and extreme over-design on the other.

The following factors should again be emphasized:

Prompt clearing of faults is a major element of safety.

Low station ground resistance is no guarantee of safety, unless it is so low that the maximum fault current flowing through it cannot raise the ground system voltage to a lethal value. In all other cases, gradients should be studied.

APPENDIX I

MATHEMATICAL ANALYSIS OF GRADIENT PROBLEM

The calculations below are intended, first, to provide a better understanding of the factors which determine the potential gradients and the step, touch and mesh voltages at a substation. Second, they are intended to supply a basis for determining the coefficients K_m and K_i of Equations (16) and (21), respectively, when these are used to design a station ground system.

These calculations show that the danger voltages at a given spot in a given station are *directly proportional* to ρ , the earth resistivity, and to i , the current per unit length of conductor.

The calculations show that the step voltages are also affected by the number, spacing and depth of burial of the grid conductors; and that the touch and mesh voltages are affected by these and by the conductor diameter as well. However, these four factors all appear within the logarithms of the respective equations; hence, any of them can vary over a reasonable range with a relatively small effect on the danger voltages.

It is this latter fact that has permitted the simplified approach used by Laurent (Appendix IV), upon which are based Equations (13), (14), and (15) in Section 10.7 of this Guide.

Unfortunately, tests and calculations seem to show some practical designs which fall outside the range where the simplified equations are valid.

Using the equations developed below, it is fairly easy to achieve somewhat better accuracy by taking into account the number, spacing, diameter, and depth of burial of the grid conductor as actually included in a specific design.

It should, however, be pointed out that the equations developed in this Appendix still retain some simplifying assumptions, which should be carefully noted. For example, in applying the equations below, even to a symmetrical grid, allowance must be made (a) for somewhat higher unit current in the outer parallel wires than in those nearer the center; (b) for higher unit current from near the ends of this wire than from parts near its center; and (c) for the effect of cross connections, special electrodes, etc. These factors are discussed more fully in the body of the report, and are the basis for the irregularity factor there defined.

Assumptions Used in Calculations

Gradients and potentials will be studied for a grid as shown in Figure 11.

" n " conductors, of diameter " d ", are buried in parallel lines at a uniform depth " h " below a flat ground surface. In the equations they are designated a_1, a_3, a_5 , etc., starting with the conductor a_1 at the right-hand edge of the grid. a_2, a_4, a_6 , etc. are the corresponding "image" conductors used to simplify computations and are at a uniform distance " h " above the ground surface.

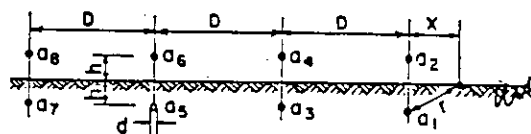


Figure 11. Cross section of typical ground grid

Gradients in the plane of the paper at right angles to the conductors will be studied.

The following simplifying assumptions are made:

Homogeneous soil of uniform resistivity ρ

Conductors extend so far from the plane in both directions that end effects can be neglected.

Cross connections are sufficiently distant from the plane studied to have negligible effect on current flow and potential gradients within the plane.

$D \gg h \gg d$

Potential drop within the grid is assumed to be negligible, as compared to that within the soil. That is, for practical purposes, the absolute potentials of all points on all grid conductors are assumed to be equal.

Since the soil is homogeneous and the voltage-current relation is linear, the method of super-position can be used, i.e., the magnitude and direction of the current component at any point due to any real or image conductor can be determined separately, and all such components can be added vectorially to give the magnitude and direction of the total actual current at that point.

All values will be expressed in the mks system of units.

For the conditions assumed, it is apparent that the current from each conductor will flow radially in all directions and at right angles to the conductor. Equipotential shells will be cylinders. Since the area of these is directly proportional to the distance " r " from the center of the conductor, the current density, and hence the gradient, will be inversely proportional to " r ." (This is in contrast to the spherical electrode where the gradient varies inversely as the square of " r ", the equipotential shells being spherical.)

Consider a point on the surface at a horizontal distance " x " to the right of conductor " a_1 " and determine in turn the current per unit area due to each grid conductor and each corresponding "image" conductor. Assume:

i is the current flowing into the ground per unit length of conductor (real or image).

δ is the current per unit area at any point due to the current i per unit length of conductor.

r is the distance from the same point to the conductor.

α is the angle between the direction of the current δ and the horizontal plane.

Then, as a scalar quantity:

$$\delta = \frac{i}{2\pi r} \quad (29)$$

And, as a vector in space:

$$\delta = \frac{i}{2\pi r} (\cos \alpha + j \sin \alpha) \quad (30)$$

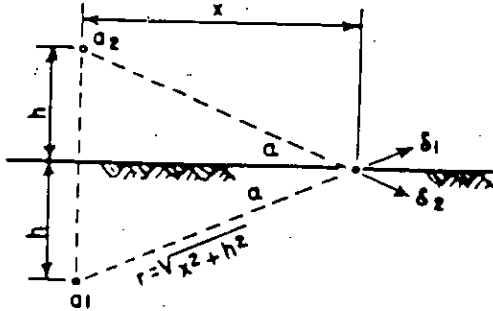


Figure 12. Computation of ground currents due to conductor a_1 and its image a_2 .

Consider first the current δ_1 , due to conductor a_1 , and the current δ_2 , due to its image a_2 : (See Figure 12). As vectors in space:

$$\delta_1 = \frac{i}{2\pi \sqrt{x^2 + h^2}} (\cos \alpha + j \sin \alpha) \quad (31)$$

$$= \frac{i}{2\pi \sqrt{x^2 + h^2}} \left(\frac{x}{\sqrt{x^2 + h^2}} + j \frac{h}{\sqrt{x^2 + h^2}} \right) \quad (32)$$

$$= \frac{i}{2\pi (x^2 + h^2)} (x + jh) \quad (33)$$

And, similarly:

$$\delta_2 = \frac{i}{2\pi (x^2 + h^2)} (x - jh) \quad (34)$$

Hence:

$$\delta_1 + \delta_2 = \frac{i (2x)}{2\pi (x^2 + h^2)} \quad (35)$$

$$= \frac{i x}{\pi (x^2 + h^2)} \quad (36)$$

Consider next the current at the same point due to conductor a_3 and its image a_4 (Figure 13).

$$\delta_3 = \frac{i}{2\pi r} \left(\frac{D+x}{r} + j \frac{h}{r} \right) \quad (37)$$

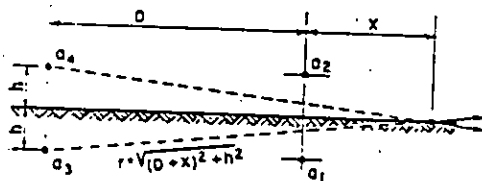


Figure 13. Computation of ground currents due to conductor a_3 and its image a_4 .

And

$$\delta_4 = \frac{i}{2\pi r} \left(\frac{D+x}{r} - j \frac{h}{r} \right) \quad (38)$$

From which:

$$\delta_3 + \delta_4 = \frac{i}{\pi r^2} (D+x) \quad (39)$$

$$= \frac{i (D+x)}{\pi [(D+x)^2 + h^2]} \quad (40)$$

Similarly it can be shown that:

$$\delta_5 + \delta_6 = \frac{i (2D+x)}{\pi [(2D+x)^2 + h^2]} \quad (41)$$

$$\delta_7 + \delta_8 = \frac{i (3D+x)}{\pi [(3D+x)^2 + h^2]} \quad (42)$$

$$\delta_9 + \delta_{10} = \frac{i (4D+x)}{\pi [(4D+x)^2 + h^2]} \quad (43)$$

etc.

However, if we limit ourselves to the more severe cases where x is positive, or has a negative value no greater than

$\frac{D}{2}$ then:

$$(2D+x)^2 \gg h^2$$

$$\text{and } (4D+x)^2 \gg h^2 \text{ etc.}$$

Thus, without appreciable error the equations can be written:

$$\delta_3 + \delta_4 = \frac{i}{\pi (2D+x)} \quad (44)$$

$$\delta_7 + \delta_8 = \frac{i}{\pi (3D+x)} \quad (45)$$

$$\delta_9 + \delta_{10} = \frac{i}{\pi (4D+x)} \quad (46)$$

etc.

From which, by super-position, the total surface current density at x becomes:

$$\delta = \frac{i}{\pi} \left[\frac{x}{x^2 + h^2} + \frac{D+x}{(D+x)^2 + h^2} + \frac{1}{2D+x} + \frac{1}{3D+x} \text{ etc.} \right] \quad (47)$$

The gradient at x is:

$$G_x = \rho \delta = \frac{\rho i}{\pi} \left[\frac{x}{x^2 + h^2} + \frac{D+x}{(D+x)^2 + h^2} + \frac{1}{2D+x} + \frac{1}{3D+x} \text{ etc.} \right] \quad (48)$$

In the usual case, where $(D+x)^2 \gg h^2$, the second term may be written:

$$\frac{1}{D+x}$$

The point of maximum gradient can then be determined by taking the derivative of Equation (48), so simplified, and making it equal to zero, from which it can be shown that the point of maximum gradient occurs where:

$$x^2 = h^2 - \left[\frac{1}{(D+x)^2} + \frac{1}{(2D+x)^2} \text{ etc.} \right] (x^2 + h^2)^2 \quad (49)$$

The second term on the right hand side represents the effect of wires of the grid other than a_1 . Its result is to bring the point of maximum gradient slightly closer to the point on the surface above conductor a_1 . However, in the usual case where $D \gg h$, the effect of this second term is negligible, and the maximum gradient can be assumed to occur where $x = h$.

Step Voltage

For maximum step voltage, it is usually most convenient, and sufficiently accurate, to use the numerical value of maximum volts per meter derived by solving Equation (48) for $x = h$. That is:

$$\text{Max. } E_{step} = \frac{1}{\pi} \left[\frac{1}{2h} + \frac{1}{D+h} + \frac{1}{2D+h} + \dots \text{etc.} \right] \rho i \quad (50)$$

In the usual case where $D \gg h$, this may be written:

$$\text{Max. } E_{step} = \frac{1}{\pi} \left[\frac{1}{2h} + \frac{1}{D+h} + \frac{1}{2D} + \frac{1}{3D} + \dots \text{etc.} \right] \rho i = K_s \rho i \quad (51)$$

where:

$$K_s = \frac{1}{\pi} \left[\frac{1}{2h} + \frac{1}{D+h} + \frac{1}{2D} + \frac{1}{3D} + \dots \text{etc.} \right] \quad (52)$$

Strictly speaking, of course, the maximum step voltage is the maximum value integrated over a distance of one meter, which may be determined from Equation (54) below, selecting the proper limits. It will, of course, be a little less than the maximum gradient figure. However, since this difference is usually small (roughly of the order of 10 percent for some typical cases studied), this refinement is seldom warranted.

Voltage Difference Between Two Points on Ground Surface

The voltage E_x between any two points on the surface x_1 and x_2 can be found by integration:

$$\begin{aligned} E_x &= \frac{\rho i}{\pi} \int_{x_1}^{x_2} \left[\frac{x}{x^2 + h^2} + \frac{D+x}{(D+x)^2 + h^2} + \frac{1}{2D+x} + \frac{1}{3D+x} + \dots \text{etc.} \right] dx \\ &= \frac{\rho i}{\pi} \left[\frac{1}{2} \ln(h^2 + x^2) + \frac{1}{2} \ln[h^2 + (D+x)^2] + \ln(2D+x) + \ln(3D+x) + \dots \text{etc.} \right]_{x_1}^{x_2} \quad (53) \end{aligned}$$

Touch Voltage

Determination of touch voltage is somewhat more complex. It can be found by computing E_s from $x = 0$ to the point of foot contact on the ground surface, and adding E_v , the voltage between the buried conductor a_1 and the point on the ground surface immediately above it.

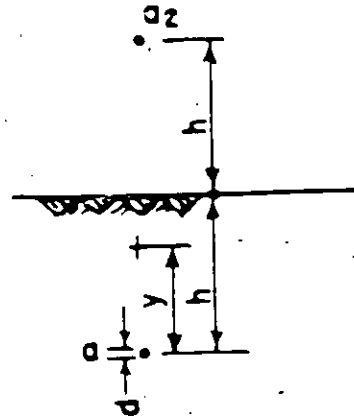


Figure 14. Computation of potential difference between conductor and point on surface directly above.

E_v may be derived as follows (See Figure 14):

Since it has been assumed that $D \gg h$, then any point along the vertical line connecting a_1 and a_2 is nearly equidistant from any real conductor and its corresponding image, other than a_1 and a_2 . Therefore, these other conductors will not make any significant contributions to the vertical components of currents along the line $a_1 - a_2$. Hence:

$$\delta_1 = \frac{i}{2\pi y} \quad (55)$$

$$\delta_2 = -\frac{i}{2\pi(2h-y)} \quad (56)$$

$$\delta = \delta_1 + \delta_2 = \frac{i}{2\pi} \left[\frac{1}{y} - \frac{1}{2h-y} \right] \quad (57)$$

The vertical potential gradient is:

$$\rho \delta = \frac{\rho i}{2\pi} \left[\frac{1}{y} - \frac{1}{2h-y} \right] \quad (58)$$

Hence the voltage E_v between conductor a_1 and a point on the surface above it is:

$$\begin{aligned} E_v &= \frac{\rho i}{2\pi} \int_{\frac{d}{2}}^h \left(\frac{1}{y} - \frac{1}{2h-y} \right) dy \\ &= \frac{\rho i}{2\pi} \left[\ln y + \ln(2h-y) \right]_{\frac{d}{2}}^h \\ &= \frac{\rho i}{2\pi} \left[\ln y(2h-y) \right]_{\frac{d}{2}}^h \quad (59) \end{aligned}$$

Substituting limits:

$$E_v = \frac{\rho i}{2\pi} \ln \frac{4h^2}{4dh - d^2} \quad (60)$$

Or, to a close approximation, since usually $4dh \gg d^2$:

$$E_v \approx \frac{\rho i}{2\pi} \ln \frac{h}{d} \quad (61)$$

Next, it is necessary to determine the potential difference

E_z between any point on the surface at a horizontal distance x from the outer grid conductor, and a point on the surface directly above that wire. This can be done by substituting, as limits, $x_2 = x$ and $x_1 = 0$ in Equation (54) as follows:

$$E_z = \frac{\rho i}{2\pi} \ln \frac{(h^2 + x^2) [h^2 + (D+x)^2]}{(h^2) (h^2 + D^2)} + \frac{\rho i}{\pi} \ln \left[\left(\frac{2D+x}{2D} \right) \left(\frac{3D+x}{3D} \right) \dots \text{etc.} \right] \quad (64)$$

The touch voltage at a point on the surface at a horizontal distance x from the outer conductor is simply the sum of the above plus the vertical component of voltage derived from Equation 63. That is,

$$E_{\text{touch}} = E_z + E_y = \frac{\rho i}{2\pi} \ln \frac{(h^2 + x^2) [h^2 + (D+x)^2]}{h d (h^2 + D^2)} + \frac{\rho i}{\pi} \ln \left[\left(\frac{2D+x}{2D} \right) \left(\frac{3D+x}{3D} \right) \dots \text{etc.} \right] \quad (65)$$

This can be simplified in the usual case, where $D \gg h$, as follows:

$$E_{\text{touch}} = \left[\frac{1}{2\pi} \ln \frac{(h^2 + x^2) (D+x)^2}{h d D^2} + \frac{1}{\pi} \ln \left[\left(\frac{2D+x}{2D} \right) \left(\frac{3D+x}{3D} \right) \dots \text{etc.} \right] \right] \rho i \quad (67)$$

In the above, E_{touch} is as defined in Section 6 of the Guide. To obtain the touch voltage at a horizontal distance of one meter from a buried conductor, x can be made equal to 1. However, this value is of less practical significance than the mesh voltage.

Mesh Voltage

The mesh voltage (defined in Section 10.7) tends to be highest in the mesh rectangle nearest the perimeter. To compute the mesh voltage to the geometrical center of this mesh, it is only necessary to substitute

$$x = \frac{-D}{2}$$

in Equation (67). This gives:

$$E_{\text{mesh}} \approx \left[\frac{1}{2\pi} \ln \frac{D^2}{16 h d} + \frac{1}{\pi} \ln \left(\frac{3}{4} \right) \left(\frac{5}{6} \right) \left(\frac{7}{8} \right) \dots \text{etc.} \right] \rho i = K_m \rho i \quad (68)$$

where

$$K_m = \frac{1}{2\pi} \ln \frac{D^2}{16 h d} + \frac{1}{\pi} \ln \left[\left(\frac{3}{4} \right) \left(\frac{5}{6} \right) \left(\frac{7}{8} \right) \dots \text{etc.} \right] \quad (69)$$

Use of the geometrical center is not rigorously correct for grids with more than two parallel conductors, since one effect of the additional conductors (such as a_3, a_7, a_{11} , etc. in Figure 11) is to displace the point of maximum potential somewhat away from the center and toward the grid perimeter conductor a_1 . For this reason, Equation (68) will give results slightly on the low side, the error

being roughly of the order of 5 or 10 percent for typical designs using up to about eight parallel conductors. Error may be greater where more parallel conductors than this are used.

If greater accuracy is desired, a curve can be plotted from Equation (67) to determine the actual location within the mesh and the magnitude of the actual maximum mesh potential.

Example 1

Assume:

n = number of parallel grid conductors = 8

d = diameter of conductor (4/0 - 12 strand) = 0.01403 m

h = depth of burial = 0.5 m

D = conductor spacing = 8 m

From Equation (68)

$$E_{\text{mesh}} \approx \frac{\rho i}{2\pi} \ln \frac{64}{(16)(0.5)(0.01403)} + \frac{\rho i}{\pi} \ln \left[\left(\frac{3}{4} \right) \left(\frac{5}{6} \right) \left(\frac{7}{8} \right) \left(\frac{9}{10} \right) \left(\frac{11}{12} \right) \left(\frac{13}{14} \right) \right] = 0.733 \rho i \quad (70)$$

For a more accurate solution, a curve can be plotted by substituting the appropriate values in Equation (67). This shows that the point of maximum mesh potential is actually not at the geometrical center ($x = -1$), but is only approximately 2.4 meters from the outer conductor. At this point $E_{\text{mesh}} = 0.803 \rho i$ (71)

That is to say, the result by the approximate method is about 8 percent low.

From Equation (48):

$$E_{\text{step}} \approx G_z = \frac{\rho i}{\pi} \left[\frac{x}{x^2 + h^2} + \frac{D+x}{(D+x)^2 + h^2} + \frac{1}{2D+x} + \frac{1}{3D+x} \dots \text{etc.} \right] \quad (72)$$

For most severe conditions, where $x = h = 0.5$ meter,

$$E_{\text{step}} \approx 1.31 \frac{\rho i}{\pi} = 0.418 \rho i \text{ volt} \quad (73)$$

Example 2

For similar conditions except with one-meter-depth-of-burial:

By the approximate method, letting $x = \frac{-D}{2}$ in Equation (68):

$$E_{\text{mesh}} = 0.622 \rho i \text{ volt} \quad (74)$$

By plotting curve from Equation (67), actual point of maximum mesh voltage is found to be where $x = -2.1$ and:

$$E_{\text{mesh}} = 0.714 \rho i \text{ volt}$$

Hence, the result by the approximate method is about 11.5 percent low.

From Equation (48):

$$E_{\text{step}} = 0.256 \rho i \text{ volt} \quad (75)$$

APPENDIX II

SAMPLE CALCULATION

A station of moderate physical dimensions on high-resistivity soil and of irregular shape has been chosen to better illustrate the handling of the more difficult problems.

The first plan in Figure 15 shows a preliminary design to provide only a perimeter ground conductor and minimum connections to structures and equipment. Where soil resistivity and maximum fault currents are low, such a minimum grid may be sufficient. However, for the conditions of this problem, calculations will show a much closer mesh is needed for gradient control. The revised design to accomplish this is shown in the right hand plan in Figure 15.

The proposed design takes advantage of crushed rock surfacing to lessen the amount of grid conductor needed and to lower perimeter potentials.

Note that, while the station ground resistance remains relatively high and probably could not be decreased materially without considerably increasing ground grid area (which is assumed to be impractical), it is nevertheless possible to make the station safe.

Basic Design and Test Data:

Clearing time 0.5 second

Resistivity ρ

Natural ground (average test value) 1316 ohm-meters

Wet crushed rock (estimate) 3000 ohm-meters

Depth of burial "h" 12 inches = 0.305 meter

Circuit voltage 115,000 volts

Equivalent "lumped" impedance looking into system from fault:

$$R_1 + R_2 + R_0 = 31.74 \text{ ohms}$$

$$X_1 + X_2 + X_0 = 181.5 \text{ ohms}$$

Area "A" included within grid:

51,700 square feet (See Figure 15) 4,800 square meters

Transmission line overhead ground wires connected to station grid None

Computations

Radius "r" of circular plate of same area as grid: 39.1 meters

Approximate station ground resistance "R" calculated by Equation 20, assuming a trial value of 1000 meters for total buried conductor:

$$R \approx \frac{1316}{(4)(39.1)} + \frac{1316}{1000} = 8.41 + 1.31 = 9.72 \text{ ohms}$$

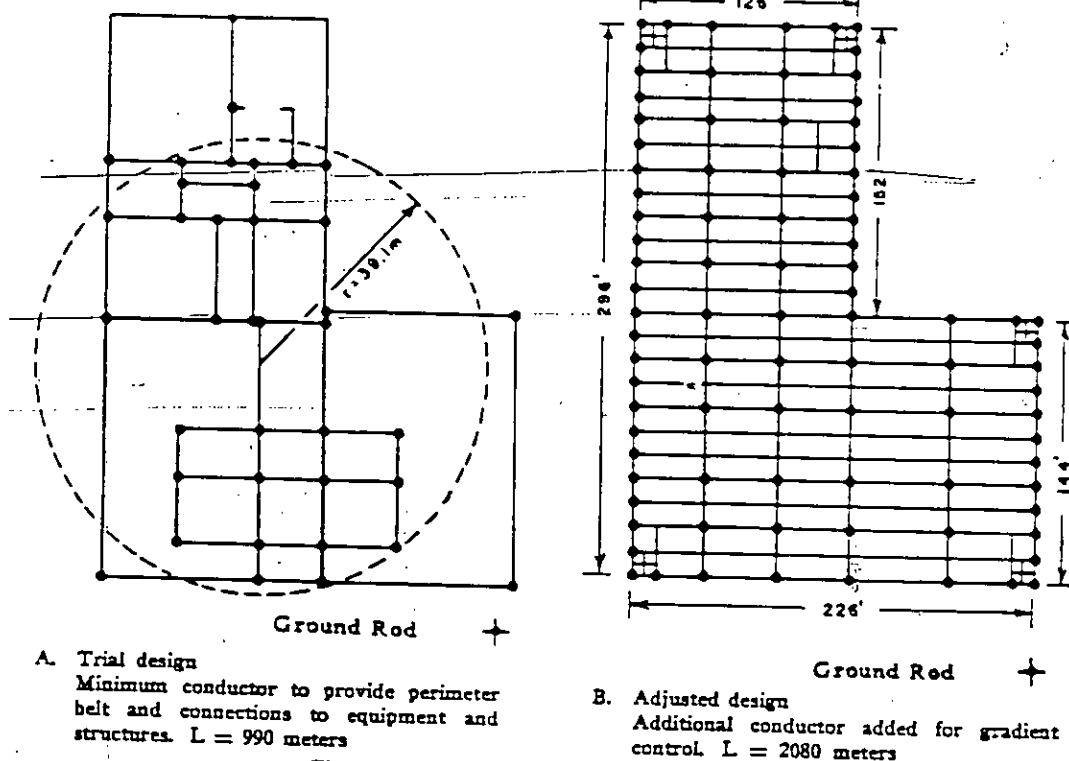


Figure 15. Sample station ground grid design

Symmetrical rms Ground Fault Current, per Equation 8:

$$I'' = \frac{(3)(115,000)}{(1.732)(181.5)} = 1097 \text{ amperes}$$

Decrement factor "D", per Table II

$$= 1.0$$

Factor to allow for system growth = 1.5

Adjusted Ground Fault Current for use in Calculations:

$$I'' = (1097)(1.0)(1.5) = 1645 \text{ amperes}$$

It will be obvious that the system resistance will have had a negligible effect on the calculated current. Moreover, conditions at this station are as in Figure 6, Case 2, and the maximum fault-current flow between ground grid and earth will occur for a short circuit to ground within the station area. No significant resistance value can be assumed for the fault itself. However, it is apparent that the station ground resistance will be relatively large. If it is taken into account, together with the system resistance, then according to Equation 7.

$$I'' = \frac{(3)(115,000)}{(1.732)[(3)(9.72) + 31.7 + j181.5]} \\ = \frac{(3)(115,000)}{(1.732)(191.4)} \\ = 1040 \text{ amperes}$$

For the conditions assumed, with fault duration "T" equal to 0.5 second, D is equal to 1.00 (See Table II). The factor to allow for future growth is arbitrarily taken as 1.5. Thus the adjusted value of fault current for use in design calculations becomes:

$$I'' = (1040)(1.0)(1.5) \\ = 1560 \text{ amperes}$$

It will be seen that the station ground resistance, though high, has only a small effect here in limiting the maximum fault current. Its effect might have been more important had the station been closer to a "stiff" bus, with a very low system impedance to the fault.

The size of grid conductor required to avoid fusing under this current, per Table III, assuming brazed joints, 4-second time duration, and one conductor to be capable of carrying entire current, is as follows:

$$(20)(1560) = 31,200 \text{ CM.}$$

In this case, a conductor considerably larger than the minimum required above is selected, in part for mechanical ruggedness. Assume use of 2/0 AWG with cross-section area of 133,100 CM.

Grid conductor diameter "d" 0.414 inch = 0.0105 meter
Grid conductor spacing "D" = 4 meters
(assumed trial value)

Number of conductors based on trial spacing, wide part of yard (width = 296 feet) = 24

Number of conductors narrow part of yard (width = 144 feet) = 12

Determination of coefficient K_m (solu-

tion for narrow section with $n = 12$ will give the more conservative value):

From Equation (17):

$$K_m = \left[\frac{1}{2\pi} \ln \frac{(16)}{(16)(0.305)(0.0105)} \right. \\ \left. + \frac{1}{\pi} \ln \frac{(3)(5)(7)(9)(11)(13)(15)(17)(19)(21)}{(4)(6)(8)(10)(12)(14)(16)(18)(20)(22)} \right] \\ = 0.568$$

Determination of coefficient K_1 :

Based on inspection of Figure 8 and use of half of normal mesh interval at corners, assume

$$K_1 = 2.0$$

Then, by Equation (19):

$$L = \frac{(0.568)(2.0)(1316)(1560) \sqrt{0.5}}{165 + (0.25)(3000)} = 1800 \text{ meters}$$

The adjusted design shown in Figure 15 provides this required length of buried conductor as follows:

Basic grid:

12 wires at 226' 2712

12 wires at 126' 1512

Cross connections:

4 wires at 296' 1184

2 wires at 144' 288

Miscellaneous 250

5946

Ground rods (39) (10)

390

$$6836 \text{ ft} = 2080 \text{ meters}$$

It is apparent that the grid spacing assumed, plus a reasonable number of cross connections and rods, has resulted in a length of buried conductor about 15 percent in excess of the computed amount needed. In this case, the assumed spacing will nevertheless be used, and the extra conductor length will provide a slight additional factor of safety.

Had the trial design resulted in too small a conductor length, it would have been necessary to revise the design to use a closer grid spacing. Likewise, if the trial design had resulted in a larger excess, it might have been decided to widen the spacing in the interest of economy. In such cases, it would, of course, be necessary to recompute K_m and review the assumptions for K_1 on the basis of the new design, and, finally, to recompute the required conductor length by substituting the appropriate new values in Equation (19).

It remains to check, as discussed in Section 14.2 whether a sustained ground current is below "let-go" value of the body current, i.e., whether

$$K_m K_1 \frac{I}{L} < (1000 + 1.5 \rho_s) \frac{9}{1000}$$

With the above values, the sustained ground current must be

$$I < \frac{[1 + (1.5)(3)]9}{(.568)(2.0)(1316)} (2080) = 69.5 \text{ amperes}$$

Ground relays clearing a ground fault must, therefore, be set for a minimum pickup current of less than 69.5 amperes, or if that proves inconvenient, additional conductor length is to be buried to satisfy the above equation for any lower relay setting.

Calculation of step voltages:

(Solution for wide part of yard will give the more conservative values.)

At point of maximum surface gradient at perimeter, where $x=h$ it follows from Equation (22), since $D \gg h$, that:

$$K_s = \frac{1}{\pi} \left[\frac{1}{2h} + \frac{1}{D+h} + \frac{1}{2D} + \frac{1}{3D} \text{ etc. } \dots \right]$$

$$= \frac{1}{\pi} \left[\frac{1}{(2)(0.305)} + \frac{1}{4.3} + \frac{1}{8} + \frac{1}{12} + \frac{1}{16} + \dots \right]$$

$$= \frac{1.64 + 0.917}{\pi}$$

$$= 0.814$$

Assume $K_1 = 2.5^*$

Then by Equation (21):

$$\text{Max } E_{step} = \frac{(0.814)(2.5)(1316)(1560)}{2080}$$

$$= 2010 \text{ volts}$$

Tolerable E_{step} by Equation 3, is

$$\frac{165 + \rho_s}{\sqrt{t}}$$

For natural earth where $\rho = 1316$ ohm-meters, this becomes

$$\frac{1481}{0.707} = 2100 \text{ volts}$$

The computed step voltage thus falls just within the tolerable value as determined above for natural ground. For wet crushed-rock surfacing, with resistivity of the order of 3000 ohm-meters, the tolerable E_{step} would have been:

$$\frac{3165}{0.707} = 4480 \text{ volts}$$

Thus, had it proved necessary, the design could have called for carrying the crushed-rock surfacing four feet outside the perimeter conductor, beyond which the step voltage should be well below its maximum value.

It is proposed in this case, that the fence be located so far inside the perimeter ground conductor that a man touching it from the outside will be protected by the limits established on mesh voltage. Had it been placed above or outside the perimeter conductor, it would have been necessary to check the touch voltage one meter outside

* A higher value has been assigned than before due to the local irregularity being greater than average.

the fence, due consideration being given to resistivity of the surface covering.

Resistance for adjusted design

By method of Laurent (Equation 20):

$$R = \frac{1316}{(4)(39.1)} + \frac{1316}{2080}$$

$$= 9.04 \text{ ohms}$$

By method of Schwarz (Ref. 42):

$$R = \frac{1316}{1810\pi} \left[\ln \frac{3620}{\sqrt{(0.0105)(2)(0.305)}} + \frac{(1.33)(1810)}{\sqrt{4800}} \right]$$

$$- 5.7 = 9.27 \text{ ohms}$$

The latter method neglects the effect of the ground rods. However, a calculation (Ref. 42) would show the effect of these on the resistance to be negligible.

Used in calculations $R = 9.3$ ohms.

Maximum grid potential rise

$$IR = (1560)(9.3) = 14,500 \text{ volts}$$

Note: Maximum grid potential rise is large and indicates need of guarding personnel and communication equipment against transferred potential.

Solution for Faster Clearing Time:

To illustrate the effect of faster clearing time, assume that the fault duration is cut to 6 cycles (0.1 second) by use of higher speed relays and switchgear. Then:

$$\text{Decrement factor "D" per Table II} = 1.25$$

$$\text{Factor assumed to allow for system growth (same as before)} = 1.5$$

Adjusted fault current then becomes

$$I'' = (1040)(1.25)(1.5) = 1950 \text{ amperes}$$

However, the conductor size to avoid fusing will be based as before on t seconds. Hence, it is not necessary to apply the higher decrement factor to this particular calculation and the minimum conductor size is unchanged at 31,200 CM. Further, it will be assumed, as before, that 2/0 AWG is selected for mechanical ruggedness.

With the change in fault duration, it is apparent that there will be a change in some of the factors in Equation (19) which is used to determine the required length of grid conductor.

The current is increased 25 percent or from 1560 to 1950 because of the higher decrement factor.

$\sqrt{t}$ is decreased 55.3 percent or from 0.707 to 0.316 because of the shorter fault duration.

Taken together, this would apparently permit a 44 percent reduction in length of grid conductor. However, not all of this saving can be realized because an increase in spacing will tend to increase the product of K_m times K_1 (See Figure 8).