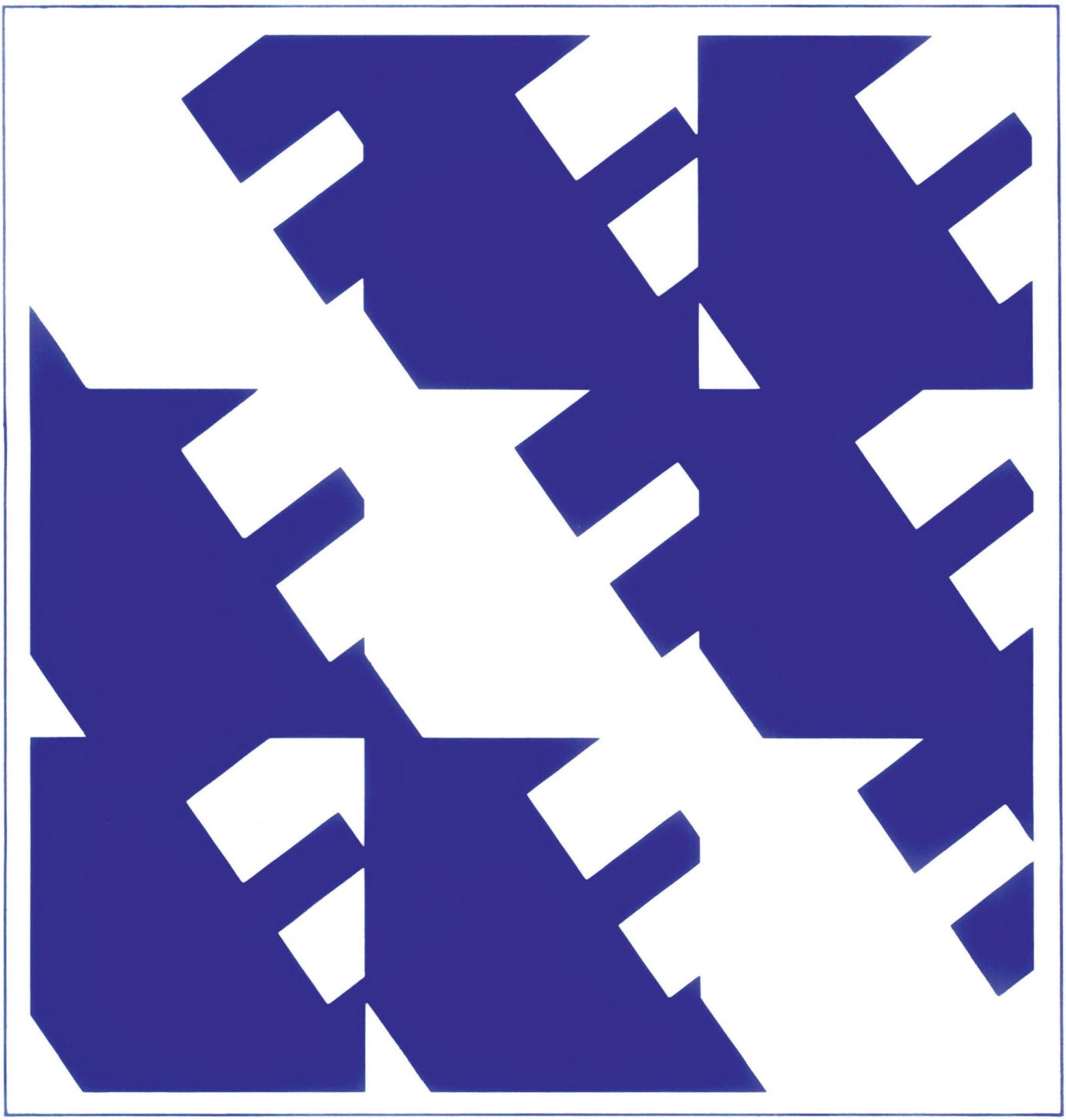
IEEE Guide for Safety in Substation Grounding

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GUIDE FOR 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. The references, however, contain much information on this. At this point it will merely be stated that the greater impedance 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 Hz.

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

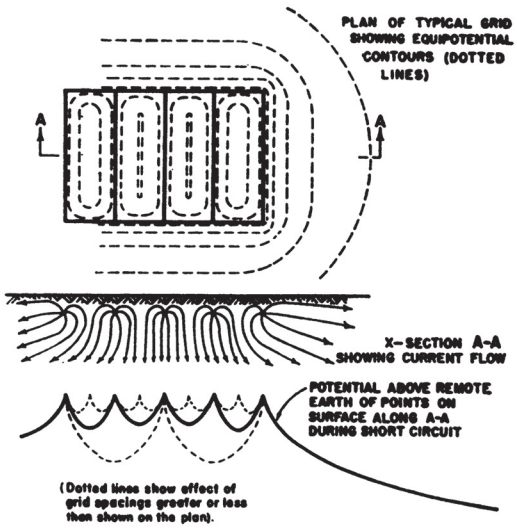


Figure 1. Currents and potentials in and around ground mat area

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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 achivement 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 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, some 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.[28]

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 Hz. Authorities generally agree that the body can tolerate slightly higher currents at 25 Hz, 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 1958 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.[32, 53, 66]

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 milliampere.

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.[56]

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.

*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.

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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.[2, 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 concludes that 99.5 percent of all persons could withstand, without ventricular fibrillation, currents determined by the equation:[32, 88]

$$I_K^2 t = 0.0135 \qquad (1)$$

from which* $$I_K = \frac{0.116}{\sqrt{t}} \text{ amperes} \qquad (2)$$

where: I_K is rms current through the body, in amperes
t is time duration of shock, in seconds
0.0135 is an empirically derived "energy constant"†

* The value 0.116 is a change from the previously accepted value of 0.165 reflecting a person's body weight of approximately 50kg.[88]

† 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 116 milliamperes for 1 second and 367 milliamperes for 0.1 second (6 cycles).

Equation (2) is based on tests limited to three seconds duration. 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.[56]

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-

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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.

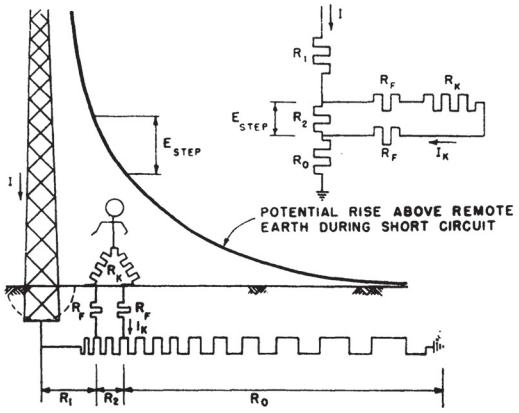


Figure 2. Step potentials near grounded structure

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.

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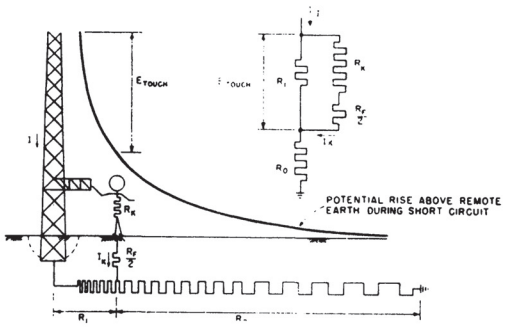


Figure 3. Touch potentials near grounded structure

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.

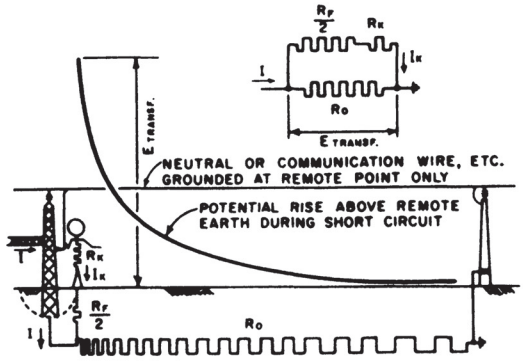


Figure 4. Example of hazard from transferred potential

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_F of the ground immediately under each foot; and the body resistance R_K.

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 ρ_s ohms, and the resistance of the two feet in parallel (touch contact) is approximately 1.5 ρ_s ohms. For practical purposes, therefore, the resistance R_F in ohms for each foot can be assumed to be 3 ρ_s.[2, 16, 28, 38, 59, 68]

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 Hz 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 Hz.

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 58 for the figure 116 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,

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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 Helmholz 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:

$$E_{step} = (R_K + 2R_F)\ (I_K)$$

$$= (1000 + 6\rho_s)\frac{(0.116)}{\sqrt{t}}$$

$$= \frac{116 + 0.7\rho_s}{\sqrt{t}} \quad \text{volts} \qquad (3)$$

$$E_{touch} = \left(R_K + \frac{R_F}{2}\right)\ (I_K)$$

$$= (1000 + 1.5\rho_s)\frac{(0.116)}{\sqrt{t}}$$

$$= \frac{116 + 0.17\rho_s}{\sqrt{t}} \quad \text{volts} \qquad (4)$$

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.

To minimize calculation time, some designers prefer to assume a maximum premissible mesh voltage and to calculate the minimum length of grounding conductor 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, 45]

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

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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.[55]

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, 31, 55, 71, 72]

Then:

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

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:

$$\rho = 2\pi A R \qquad (6)$$

(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 resistivi-

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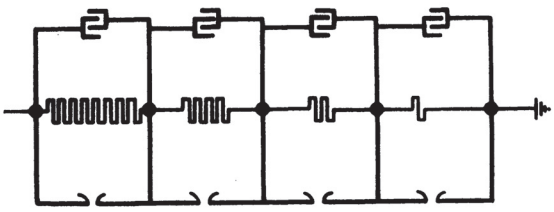


Figure 5. Schematic representation of ground electrode or system

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.[16, 28]

8.6—Effect of Moisture

The resistivity of soil rises abruptly when the moisture content falls below about 15 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, 68]

8.7—Effect of Temperature

The resistivity of soils rises abruptly when the temperature falls below 32F. Hence the electrode system should extend below the frost line wherever feasible.[5]

For increasing temperatures above 32F, 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, 48]

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:

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

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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:

$$I'' = \frac{3E}{X''_1 + X_2 + X_0} \text{ amperes} \qquad (8)$$

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.

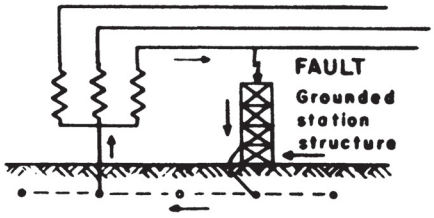
R = Estimated resistance to earth of local station ground system, in ohms.

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

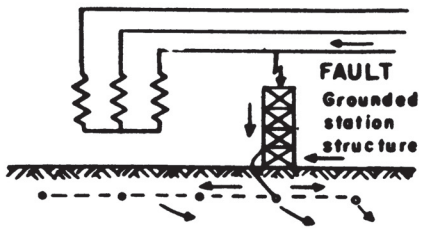
R_1 = Positive-sequence resistance, ohms per phase.

R_2 = Negative-sequence resistance, ohms per phase.

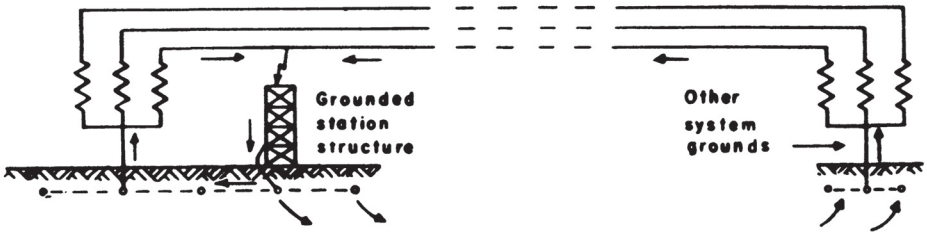
R_0 = Zero-sequence resistance, ohms per phase.



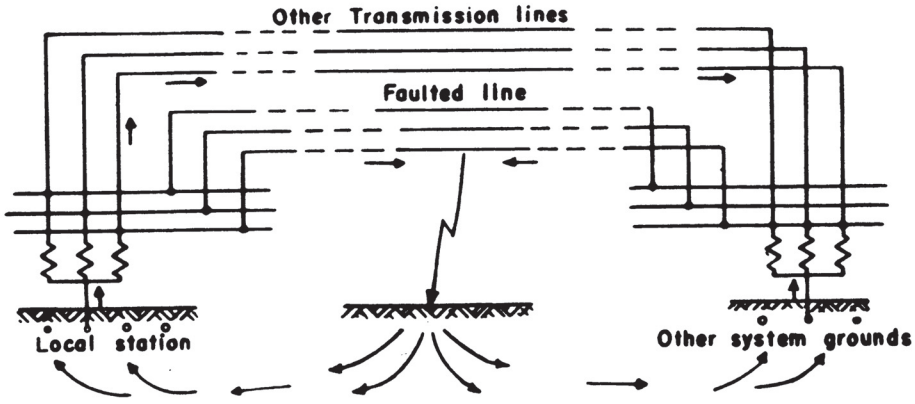
Case 1—Fault within local station. Local neutral ground only. Fault current follows metallic path provided by ground grid. No appreciable current flow in earth.



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 thrrough 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.

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X''_1 = Direct-axis positive-sequence reactance (subtransient) 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:

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

where:

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

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 IEEE Std 320-1972, Application Guide for AC High Voltage Circuit Breakers Rated on a Symmetrical Current Basis (ANSI C37.010-1972) 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 multiplying factor given by IEEE Std 320-1972 by 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 Hz Alternating Current)*	
0.008	½	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 must not be confused with the multiplying factors given by IEEE Std 320-1972. The decrement factors are used to determine the effective current *during* a given time interval after inception of a fault, whereas the multiplying factors given by IEEE Std 320-1972 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 factors given by IEEE Std 320-1972 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,

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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:

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

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.[16, 28, 45, 61, 62, 65, 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

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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. 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.

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 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 perimiter, 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 ⅝-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

* 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 0.10ρ; that of the buried connection cables alone as electrodes will be about 0.11ρ; and the over-all resistance will be about 0.08ρ; 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. [28, 42]

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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, "Silfos" 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] Exothermic connections should be classified as cable only:

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

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 C.

T_a is ambient temperature, in degrees C.

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

Ambient temperature of 40 degrees C.

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.

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 3 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.

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

TABLE III

Minimum Copper Conductor Sizes to Avoid Fusing

Time Duration of Fault	*Copper-weld 40% cable only*	*Circular Mils per Ampere*		
		Cable Only	*With Brazed Joints*	*With Bolted Joints*
30 seconds	47	40	50	65
4 seconds	17	14	20	24
1 second	8.5	7	10	12
0.5 second	6	5	6.5	8.5

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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 short-time fusing current of copperweld on a size-for-size basis is within 20% of that of 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. American National Standard C5.1-1969, Lightning Protection Code, 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.[41]

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.

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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. [38, 41, 51]

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[16] points out that for the usual range of conductor size, burial depth and spacing, local values will be of the following order:[28]

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

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

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

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.[64, 65]

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

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

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

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

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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:

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

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_i 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:

$$\frac{K_m K_i \rho I}{L} = \frac{116 + 0.17\rho_s}{\sqrt{t}} \quad (18)$$

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

$$L = \frac{K_m K_i \rho I \sqrt{t}}{116 + 0.17\rho_s} \quad (19)$$

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_i will vary from about 1.2 to 2 or even more, depending on the geometry of the grid. See Section 10.8 below.[36]

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_i

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 and Armstrong on tests of scale models in water tanks.[36, 54]

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. 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_i 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, I, and L. These resistances were therefore computed using Schwarz's method and were checked (agreement within about 6 percent) using that of Laurent.[42, 28]

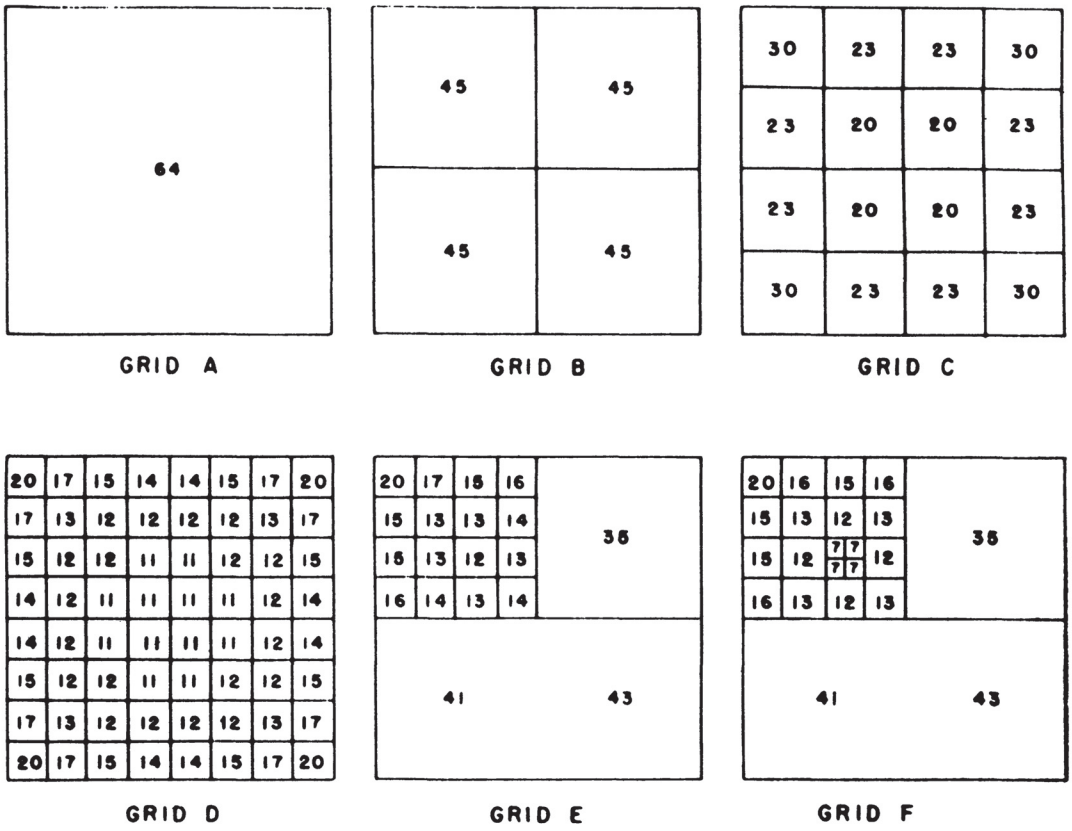
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By multiplying these computed values for the total voltage IR, by each of the respective percentages from Figure 7, coefficients have been derived and plotted in Figure 8. These coefficients are, in fact, the product of coefficients K_m and K_i for 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.[36]

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

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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 that 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 layers 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, 28, 49, 55, 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.[11, 16, 28]

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 homogenity is lacking).

Methods available include those proposed by Gross and his associates, by Schwarz, and Rudenberg.[34, 42, 46, 52, 50, 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:

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

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]

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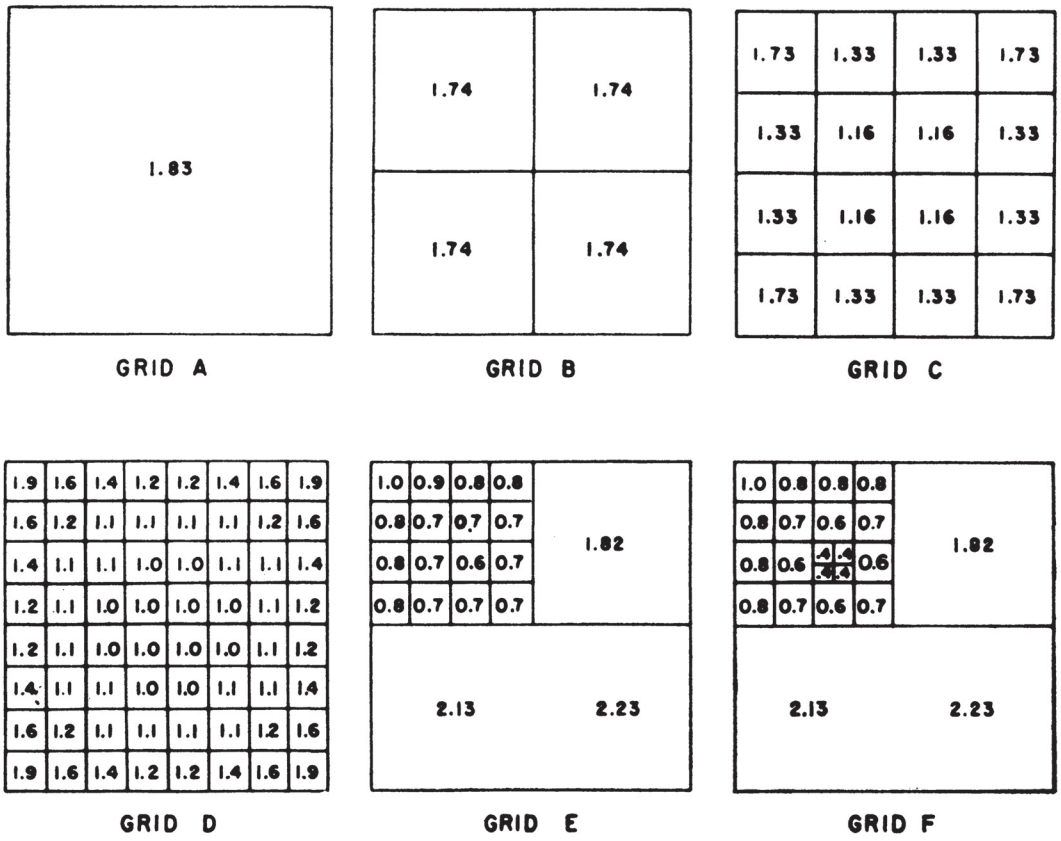
outside the grid periphery, where the problem could exist even for a theoretical solid plate. This problem may be serious in small stations where the grid can cover only a limited area. Fortunately, a station can usually be designed to eliminate the possibility of touch contacts beyond the ground system 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 ρi 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 ρi.[28, 30]

A coefficient of 0.2 was suggested in the 1958 AIEE report.[64]

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 x K_i determined from Koch experimental data.[54]

GRID	A	B	C	D	E	F
MAXIMUM VALUE K_M X 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. $K_I = \frac{K_M \times K_I}{KM}$	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: $E_{mesh} = K_m K_I \rho \frac{I}{L}$

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