5. Accidental Ground Circuit

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

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

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

Thus, for the purposes of this guide:

(1) Hand and shoe contact resistances will be assumed as equal to zero

(2) A value of 1000 Ω is selected for the calculations that follow as representing the resistance of a human body from hand-to-both-feet and also from hand-to-hand, or from one foot to the other foot:

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

5.2 Current Paths Through the Body. It should be remembered that the choice of a 1000 Ω resistance value relates to paths such as those between the hand and one or both feet, where a major part of the current passes through parts of the body containing vital organs, including the heart. It is generally agreed that current flowing from one foot to the other is far less dangerous. Referring to tests done in Germany, Loucks mentioned that much higher foot-to-foot than hand-to-foot currents had to be used to produce the same current in the heart region, stating that the ratio is as high as 25:1 [B69].

Based on these conclusions, resistance values greater than 1000 Ω could possibly be allowed, where a path from one foot to the other foot is concerned. However, the following factors should be considered.

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

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

It is apparent that the dangers from foot-to-foot contact are far less than from the other type. However, since deaths have occurred from the former, it is a hazard that should not be ignored [B10], [B66].

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

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

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

Obviously,

$I_A < I_B$ is always required for safety

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

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

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

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

where

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

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

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

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

where, in addition to the symbols described above,

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

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

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

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

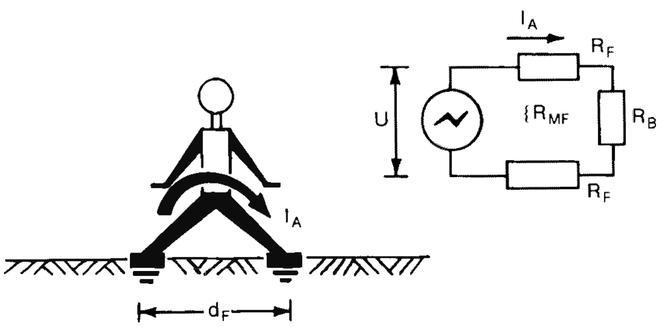
Next, the equivalent circuit for a hand-to-two-feet contact is illustrated in Fig 6.

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

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

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

Fig 5
Step Voltage Circuit



d_F = 1 m
$R_A = R_B + 2R_F - 2R_{MF}$
$I_A = U/R_A$
$R_B = 1000\Omega$

where

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

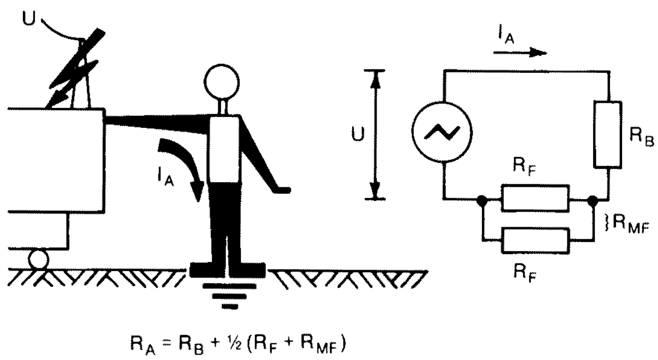


Fig 6
Touch Voltage Circuit

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

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

$$R_{2Fp} = 1½(\rho) \quad \text{(Eq 15)}$$

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

For example, if ρ = 2000 Ω-m, Eqs 14 and 15 yield 12 000 and 3000 Ω for the series and parallel resistances, respectively.

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

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

5.4 Effect of a Thin Surface Layer of Crushed Rock. Equations 8 and 9 are derived based on the assumption of uniform soil resistivity. However, a 0.08–0.15 m (3–6 in) layer of crushed rock is often spread on the earth's surface above the ground grid to increase the contact resistance between the soil and the feet of people in the substation. The crushed rock also improves the surface for the movement of equipment and vehicles in the substation. The area covered by this crushed rock layer is generally of sufficient size to validate the assumption of the feet being in contact with a material of uniform resistivity in the lateral direction. However, the relatively shallow depth of the crushed rock as compared to the equivalent radius of the foot precludes the assumption of uniform resistivity in the vertical direction when computing the self and mutual resistances of the feet.

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

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

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

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

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

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

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

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

where

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

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

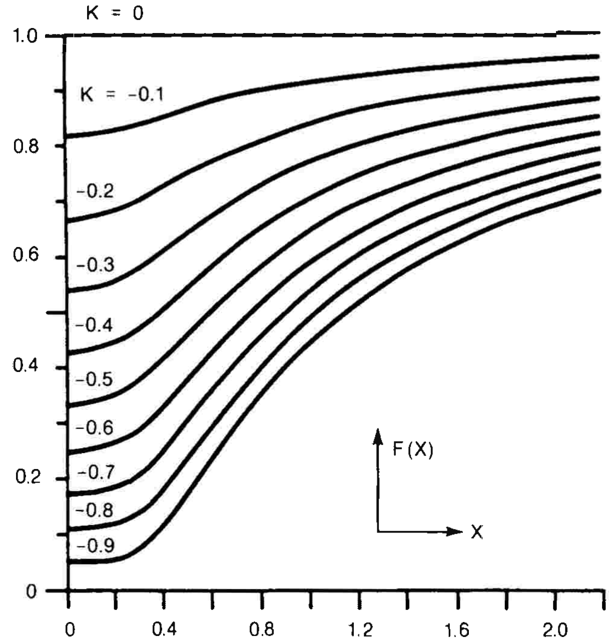


Fig 7
Function $F(X)$ Versus X and Reflection Factor K

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

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

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

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

and

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

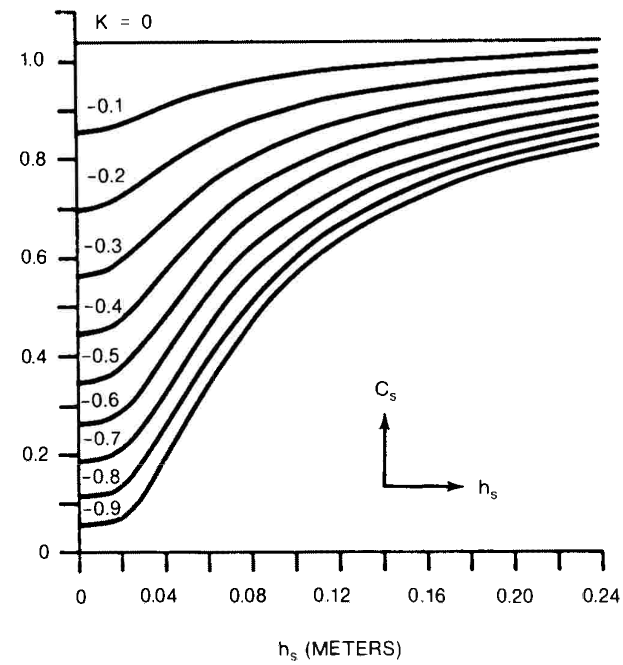


Fig 8
Reduction Factor C_s As a Function of Reflection Factor K and Crushed Rock Layer Thickness h_s

where

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

C_s = 1 for crushed stone resistivity equal to soil resistivity

Otherwise,[11]

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

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

[11] Simple alternative approaches, based on the equivalent hemisphere concept, such as $C_s \approx 1 - a\left[\frac{1-\frac{\rho}{\rho_s}}{2h_s + a}\right]$; $a = 0.106$ m, which avoids the infinite summation series, are also possible; refer to pp 14-15 of [B100] and to Jackson's discussion of Sverak's equations on p 19 of the same reference.

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

The converse of the derating principle is also true. If the underlying soil has a higher resistivity than the crushed rock, a substantial portion of the grid current will go upward into the thin layer of crushed rock. However, unlike the case described above, the surface potentials will be altered substantially, due to this concentration of current near the surface. Although Eqs 16 and 17 are valid for computing the self and mutual resistances of the feet even if the soil has a higher resistivity than the crushed rock, these equations do not account for the alteration of the surface potentials. Thus, the effective resistivity of the crushed rock should not be upgraded without taking into account this change in surface potential. This problem can best be solved by using multilayer soil analysis (see Section 11).