Set variables:

$i := \sqrt{-1}$ $j := i$ $MVA := MW$

Design Data:

$t_f := 0.5\ s$ fault duration

$Z_1 := (4.0 + j \cdot 10.0)$ positive sequence equivalent system impedance at 115kV side

$Z_2 := Z_1$ negative sequence equivalent system impedance at 115kV side

$Z_0 := (10.0 + j \cdot 40)$ zero sequence equivalent system impedance at 115kV side

$S_f := 0.6$ current division factor

$V_{ll} := 115\ kV$ line to line voltage at worst fault location

$\rho := 400\ ohm \cdot m$ soil resistivity

$\rho_s := 2500\ ohm \cdot m$ crushed rock resistivity (wet)

$h_s := 0.102\ m$ thickness of crushed rock surfacing

$h := 0.5\ m$ depth of grid burial

$A_{available} := 63\ m \cdot 84\ m$ $A_{available} = 5292\ m^2$ available grounding area 63m x 84m

$Z_{T1} := (0.034 + j \cdot 1.014)$ positive transformer impedance at 13kV

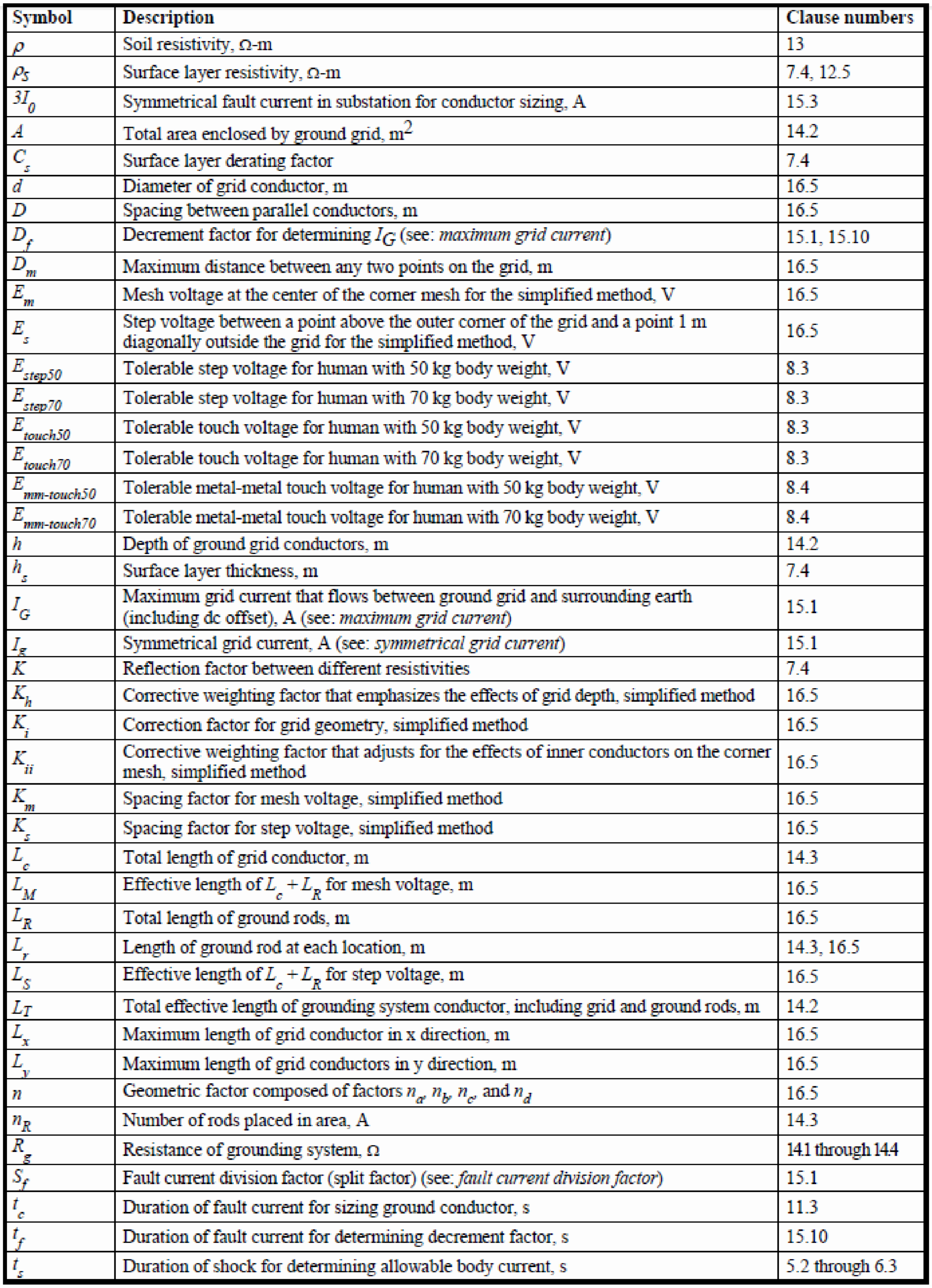
$Z_{T2} := Z_{T1}$ $Z_{T0} := Z_{T1}$ neg and zero seq same as positive sequence

$S_T := 15\ MVA$ $Z_T := 0.09$ transformer data impedance 9% and S = 15MVA

$V_{T\_pri\_ll} := 115\ kV$ $V_{T\_sec\_ll} := 13\ kV$ step down transformer voltage pri-sec

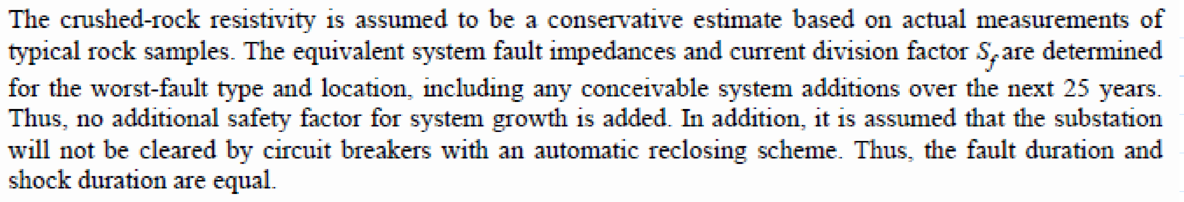
Karl S Bogha
IEEE Std 80 - 2013 (Guide for Safety of AC Substation Grounding)
Annex B
Sample Calculation: B1.

Index of design parameters.



Symbol	Description	Clause numbers
ρ	Soil resistivity, Ω-m	13
ρ_S	Surface layer resistivity, Ω-m	7.4, 12.5
$3I_0$	Symmetrical fault current in substation for conductor sizing, A	15.3
A	Total area enclosed by ground grid, m^2	14.2
C_s	Surface layer derating factor	7.4
d	Diameter of grid conductor, m	16.5
D	Spacing between parallel conductors, m	16.5
D_f	Decrement factor for determining I_G (see: *maximum grid current*)	15.1, 15.10
D_m	Maximum distance between any two points on the grid, m	16.5
E_m	Mesh voltage at the center of the corner mesh for the simplified method, V	16.5
E_s	Step voltage between a point above the outer corner of the grid and a point 1 m diagonally outside the grid for the simplified method, V	16.5
E_{step50}	Tolerable step voltage for human with 50 kg body weight, V	8.3
E_{step70}	Tolerable step voltage for human with 70 kg body weight, V	8.3
$E_{touch50}$	Tolerable touch voltage for human with 50 kg body weight, V	8.3
$E_{touch70}$	Tolerable touch voltage for human with 70 kg body weight, V	8.3
$E_{mm\text{-}touch50}$	Tolerable metal-metal touch voltage for human with 50 kg body weight, V	8.4
$E_{mm\text{-}touch70}$	Tolerable metal-metal touch voltage for human with 70 kg body weight, V	8.4
h	Depth of ground grid conductors, m	14.2
h_s	Surface layer thickness, m	7.4
I_G	Maximum grid current that flows between ground grid and surrounding earth (including dc offset), A (see: *maximum grid current*)	15.1
I_g	Symmetrical grid current, A (see: *symmetrical grid current*)	15.1
K	Reflection factor between different resistivities	7.4
K_h	Corrective weighting factor that emphasizes the effects of grid depth, simplified method	16.5
K_i	Correction factor for grid geometry, simplified method	16.5
K_{ii}	Corrective weighting factor that adjusts for the effects of inner conductors on the corner mesh, simplified method	16.5
K_m	Spacing factor for mesh voltage, simplified method	16.5
K_s	Spacing factor for step voltage, simplified method	16.5
L_c	Total length of grid conductor, m	14.3
L_M	Effective length of $L_c + L_R$ for mesh voltage, m	16.5
L_R	Total length of ground rods, m	16.5
L_r	Length of ground rod at each location, m	14.3, 16.5
L_S	Effective length of $L_c + L_R$ for step voltage, m	16.5
L_T	Total effective length of grounding system conductor, including grid and ground rods, m	14.2
L_x	Maximum length of grid conductor in x direction, m	16.5
L_y	Maximum length of grid conductors in y direction, m	16.5
n	Geometric factor composed of factors n_a, n_b, n_c, and n_d	16.5
n_R	Number of rods placed in area, A	14.3
R_g	Resistance of grounding system, Ω	14.1 through 14.4
S_f	Fault current division factor (split factor) (see: *fault current division factor*)	15.1
t_c	Duration of fault current for sizing ground conductor, s	11.3
t_f	Duration of fault current for determining decrement factor, s	15.10
t_s	Duration of shock for determining allowable body current, s	5.2 through 6.3

Assumptions:



The crushed-rock resistivity is assumed to be a conservative estimate based on actual measurements of typical rock samples. The equivalent system fault impedances and current division factor S_f are determined for the worst-fault type and location, including any conceivable system additions over the next 25 years. Thus, no additional safety factor for system growth is added. In addition, it is assumed that the substation will not be cleared by circuit breakers with an automatic reclosing scheme. Thus, the fault duration and shock duration are equal.

Solution:

Step 1: Field Data

Use a grid of 70m x 70m, equal distances, to the tenth value, and square shape.

$A_{available} := 63\ m \cdot 84\ m$ $\quad A_{available} = 5292\ m^2$

$A_{sgtd} := 70\ m \cdot 70\ m$ $\quad A_{sgtd} = 4900\ m^2$ Area suggested sgtd, also it prevents errror with unit for Amperes A when A is used for Area

Step 2: Conductor size

Ignoring station resistance, symmetrical ground fault current If = 3I0 is calculated

$V_{ln} := \frac{V_{ll}}{(\sqrt{3})} = (66.395 \cdot 10^3)\ V$ HV primary side of step down transformer

$R_f := 0$

$Z_1 = 4 + 10j$ $\quad R_1 := Re(Z_1) = 4$ $\quad X_1 := Im(Z_1) = 10$

$Z_2 = 4 + 10j$ $\quad R_2 := Re(Z_2) = 4$ $\quad X_2 := Im(Z_2) = 10$

$Z_0 = 10 + 40j$ $\quad R_0 := Re(Z_0) = 10$ $\quad X_0 := Im(Z_0) = 40$

$$ThreeI_0 := \left| \frac{3 \cdot V_{ln}}{((3 \cdot R_f) + (R_1 + R_2 + R_0) + j \cdot (X_1 + X_2 + X_0))\ ohm} \right|$$

$ThreeI_0 = 3180\ A$

$$XoverR := \frac{(X_1 + X_2 + X_0)}{(R_1 + R_2 + R_0)}$$

$XoverR = 3.333$

Transfer the fault from the 115kV side of transfomer to the 13kV side. Since the transformer is delta-wye connected, only the positive seq is transferred to 13kV side.

$V_{T\_pri\_ll} := 115\ \mathrm{kV}$ $\quad V_{T\_sec\_ll} := 13\ \mathrm{kV}$

$Z_1 = 4 + 10j$ $\quad Z_{T1} = 0.034 + 1.014j$

$Z_{T1} = 0.034 + 1.014j$

$$Z_{T1lv\_new} := \left(\frac{V_{T\_sec\_ll}}{V_{T\_pri\_ll}}\right)^2 \left(Z_1\right) + Z_{T1}$$

Sequence impedances on the secondary side of step down transformer:

$Z_{T1lv\_new} = 0.085 + 1.142j$ $\quad Z_{T2lv\_new} := Z_{T1lv\_new}$ $\quad Z_{T0} = 0.034 + 1.014j$

$R_{1lv} := \mathrm{Re}\left(Z_{T1lv\_new}\right) = 0.085$ $\quad R_{2lv} := R_{1lv}$ $\quad R_{0lv} := \mathrm{Re}\left(Z_{T0}\right) = 0.034$

$X_{1lv} := \mathrm{Im}\left(Z_{T1lv\_new}\right) = 1.142$ $\quad X_{2lv} := X_{1lv}$ $\quad X_{0lv} := \mathrm{Im}\left(Z_{T0}\right) = 1.014$

$V_{ln\_lv} := \dfrac{V_{T\_sec\_ll}}{\sqrt{3}}$ $\quad V_{ln\_lv} = \left(7.506 \cdot 10^3\right)\ \mathrm{V}$

$$ThreeI_{0lv} := \left|\frac{3 \cdot V_{ln\_lv}}{\left(\left(3 \cdot R_f\right) + \left(R_{1lv} + R_{2lv} + R_{0lv}\right) + j \cdot \left(X_{1lv} + X_{2lv} + X_{0lv}\right)\right)\ \mathrm{ohm}}\right|$$

$ThreeI_{0lv} = 6815\ \mathrm{A}$

$I_F := ThreeI_{0lv}$

$$XoverR_{lv} := \frac{\left(X_{1lv} + X_{2lv} + X_{0lv}\right)}{\left(R_{1lv} + R_{2lv} + R_{0lv}\right)}$$

$XoverR_{lv} = 16.146$

The 13kV bus on the low voltage side of the transformer should be used for sizing the grounding conductor as it is higher than the high volatage side o transformer.

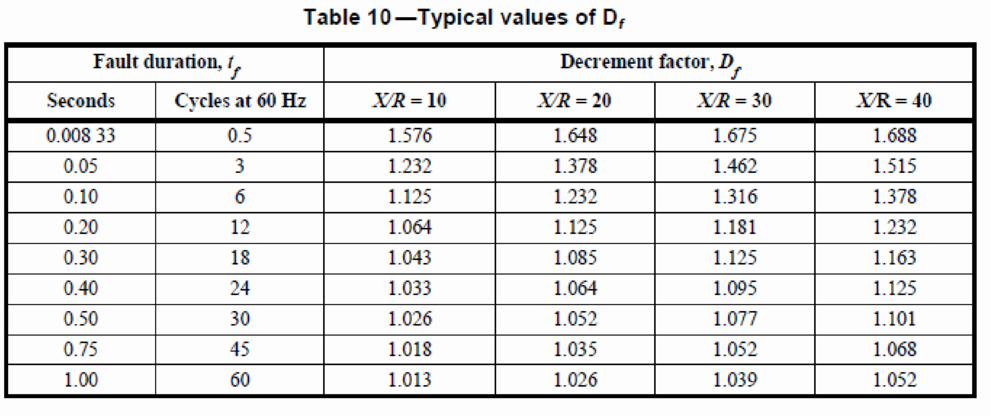


Table 10—Typical values of D_f

Fault duration, t_f		Decrement factor, D_f			
Seconds	Cycles at 60 Hz	X/R = 10	X/R = 20	X/R = 30	X/R = 40
0.008 33	0.5	1.576	1.648	1.675	1.688
0.05	3	1.232	1.378	1.462	1.515
0.10	6	1.125	1.232	1.316	1.378
0.20	12	1.064	1.125	1.181	1.232
0.30	18	1.043	1.085	1.125	1.163
0.40	24	1.033	1.064	1.095	1.125
0.50	30	1.026	1.052	1.077	1.101
0.75	45	1.018	1.035	1.052	1.068
1.00	60	1.013	1.026	1.039	1.052

Using Table 10 above for fault duration of 0.5s, the decrement factor Df is approximately 1.0. Thus the rms assymmterical fault current is also 6815A.
If asymmetrical rms = Df x rms symmetrical = 1.0 x 6815A = 6815A
Assymetrical fault = symmetrical + dc offset fault (transient fault)

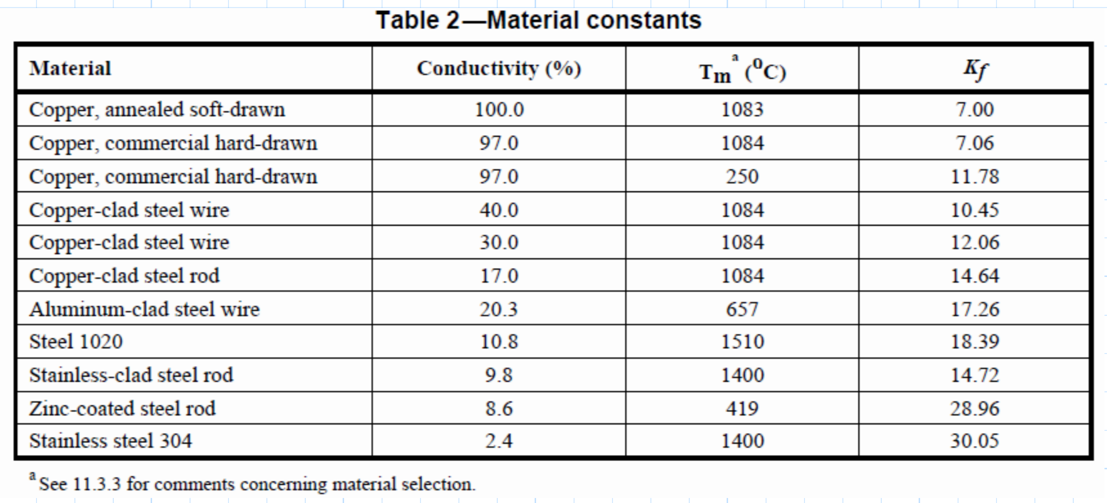


Table 2—Material constants

Material	Conductivity (%)	T_m[a] (°C)	K_f
Copper, annealed soft-drawn	100.0	1083	7.00
Copper, commercial hard-drawn	97.0	1084	7.06
Copper, commercial hard-drawn	97.0	250	11.78
Copper-clad steel wire	40.0	1084	10.45
Copper-clad steel wire	30.0	1084	12.06
Copper-clad steel rod	17.0	1084	14.64
Aluminum-clad steel wire	20.3	657	17.26
Steel 1020	10.8	1510	18.39
Stainless-clad steel rod	9.8	1400	14.72
Zinc-coated steel rod	8.6	419	28.96
Stainless steel 304	2.4	1400	30.05

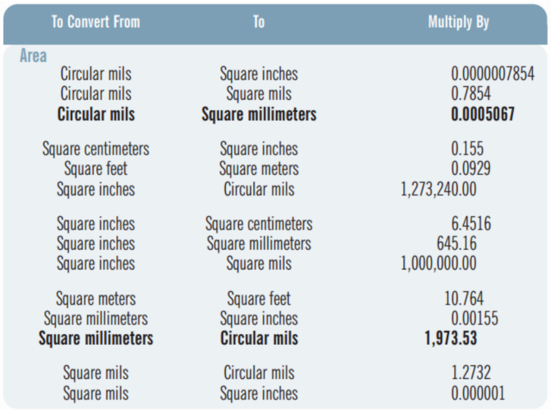
[a] See 11.3.3 for comments concerning material selection.

Start with first choice of conductor copper cable, at ambient temperature 40 deg C.
From table 10 above Copper, commercial hard drawn Tm= 1084 deg C, Kf = 7.06
We need to find the required cross sectional area of the conductor.
Akcmil = I(kA) x Kf x Sqrt(tc duration of fault current)

$K_f := 7.06$ $t_c := 0.5$ $I_F = (6.815 \cdot 10^3)\ A$ $I_{F\_unitless} := 6815$

$$A_{kcmil} := \frac{(I_{F\_unitless}) \cdot K_f \cdot (\sqrt{t_c})}{1000} = 34.022$$ kcmil (Typically American Unit)

Convert to metric (mm) units for cross section:



To Convert From	To	Multiply By
Area		
Circular mils	Square inches	0.0000007854
Circular mils	Square mils	0.7854
Circular mils	**Square millimeters**	**0.0005067**
Square centimeters	Square inches	0.155
Square feet	Square meters	0.0929
Square inches	Circular mils	1,273,240.00
Square inches	Square centimeters	6.4516
Square inches	Square millimeters	645.16
Square inches	Square mils	1,000,000.00
Square meters	Square feet	10.764
Square millimeters	Square inches	0.00155
Square millimeters	**Circular mils**	**1,973.53**
Square mils	Circular mils	1.2732
Square mils	Square inches	0.000001

$A_{mm} := 0.5097 \cdot A_{kcmil}$

$A_{mm} = 17.341$ square milimeters

Referring to electrical cable charts, the 17.3mm cross section will be accomodated by metric size 25mm cable or American Gauge number 4.

However this cable size will not have the adequate mechanical strength and ruggedness requirements for the installation.

A larger crosss section area cable size 70mm is used, and American Gauge 2/0. Stranded conductor, instead of solid.

$A_{70} := 70$ mm

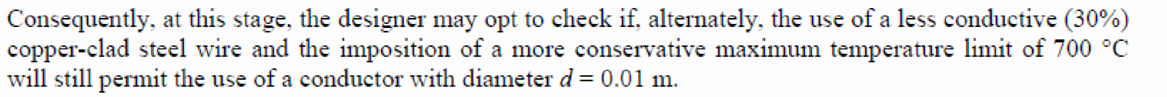
$d_{mm} := \sqrt{\left(\frac{A_{70} \cdot 4}{\pi}\right)}$ $d_{mm} = 9.441$ $d_m := \frac{d_{mm}}{1000}$

$d_m = 0.0094$ m approximately for stranded conductor

American Wire Gauge diameter for 2/0 in meter from wire charts:

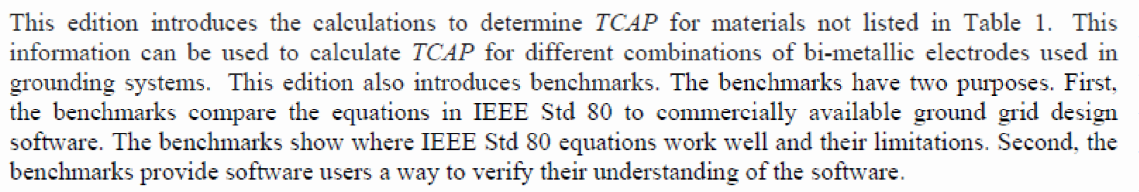
$d_{awg\_m} := 0.0105$

Since the diameter is in metric for AWG and Metric cables, we will approximate it to d = 0.01m



Consequently, at this stage, the designer may opt to check if, alternately, the use of a less conductive (30%) copper-clad steel wire and the imposition of a more conservative maximum temperature limit of 700 °C will still permit the use of a conductor with diameter $d = 0.01$ m.

$d_m := 0.01$



This edition introduces the calculations to determine *TCAP* for materials not listed in Table 1. This information can be used to calculate *TCAP* for different combinations of bi-metallic electrodes used in grounding systems. This edition also introduces benchmarks. The benchmarks have two purposes. First, the benchmarks compare the equations in IEEE Std 80 to commercially available ground grid design software. The benchmarks show where IEEE Std 80 equations work well and their limitations. Second, the benchmarks provide software users a way to verify their understanding of the software.

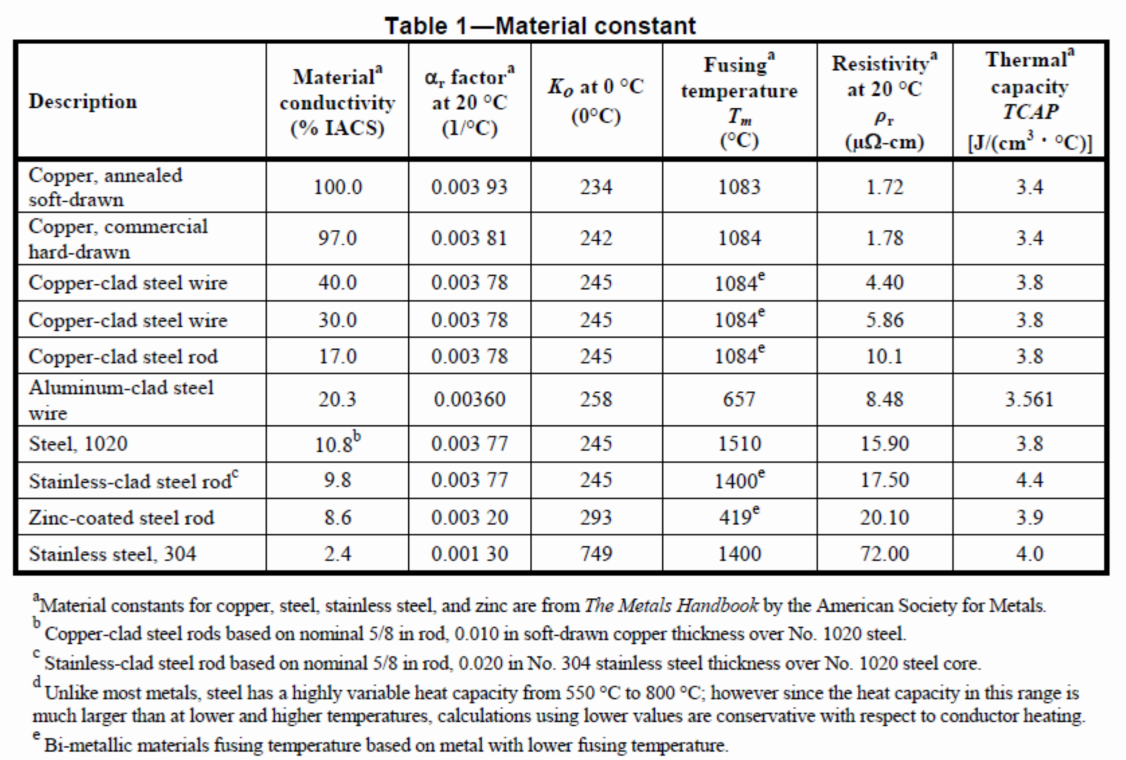


Table 1—Material constant

Description	Material[a] conductivity (% IACS)	α_r factor[a] at 20 °C (1/°C)	K_o at 0 °C (0°C)	Fusing[a] temperature T_m (°C)	Resistivity[a] at 20 °C ρ_r (μΩ-cm)	Thermal[a] capacity *TCAP* [J/(cm^3 · °C)]
Copper, annealed soft-drawn	100.0	0.003 93	234	1083	1.72	3.4
Copper, commercial hard-drawn	97.0	0.003 81	242	1084	1.78	3.4
Copper-clad steel wire	40.0	0.003 78	245	1084[e]	4.40	3.8
Copper-clad steel wire	30.0	0.003 78	245	1084[e]	5.86	3.8
Copper-clad steel rod	17.0	0.003 78	245	1084[e]	10.1	3.8
Aluminum-clad steel wire	20.3	0.00360	258	657	8.48	3.561
Steel, 1020	10.8[b]	0.003 77	245	1510	15.90	3.8
Stainless-clad steel rod[c]	9.8	0.003 77	245	1400[e]	17.50	4.4
Zinc-coated steel rod	8.6	0.003 20	293	419[e]	20.10	3.9
Stainless steel, 304	2.4	0.001 30	749	1400	72.00	4.0

[a] Material constants for copper, steel, stainless steel, and zinc are from *The Metals Handbook* by the American Society for Metals.

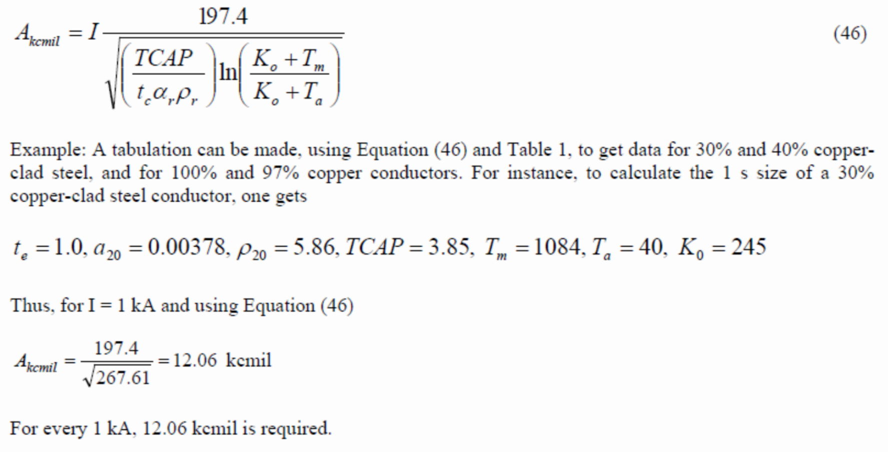
[b] Copper-clad steel rods based on nominal 5/8 in rod, 0.010 in soft-drawn copper thickness over No. 1020 steel.

[c] Stainless-clad steel rod based on nominal 5/8 in rod, 0.020 in No. 304 stainless steel thickness over No. 1020 steel core.

[d] Unlike most metals, steel has a highly variable heat capacity from 550 °C to 800 °C; however since the heat capacity in this range is much larger than at lower and higher temperatures, calculations using lower values are conservative with respect to conductor heating.

[e] Bi-metallic materials fusing temperature based on metal with lower fusing temperature.

Example to explain use of Table 1, values from Table 1.



$$A_{kcmil} = I \frac{197.4}{\sqrt{\left(\frac{TCAP}{t_c \alpha_r \rho_r}\right) \ln\left(\frac{K_o + T_m}{K_o + T_a}\right)}} \tag{46}$$

Example: A tabulation can be made, using Equation (46) and Table 1, to get data for 30% and 40% copper-clad steel, and for 100% and 97% copper conductors. For instance, to calculate the 1 s size of a 30% copper-clad steel conductor, one gets

$$t_e = 1.0,\ a_{20} = 0.00378,\ \rho_{20} = 5.86,\ TCAP = 3.85,\ T_m = 1084,\ T_a = 40,\ K_0 = 245$$

Thus, for I = 1 kA and using Equation (46)

$$A_{kcmil} = \frac{197.4}{\sqrt{267.61}} = 12.06\ \text{kcmil}$$

For every 1 kA, 12.06 kcmil is required.

Use values from Table 1, copper clad steel wire with 30% conductivity.

$\alpha_r := 0.00378$
$K_0 := 245$
$T_m := 1084$
$\rho_r := 5.86$
$T_m := 700$ design value - conservative maximum limit as stated above in description of action to take, user input.
$TCAP := 3.8$
$T_a := 40$ ambient temperature

Current IF in kA

$I_{F\_kA} := \frac{I_{F\_unitless}}{1000}$ $I_{F\_kA} = 6.815$

Initialise Variables used pior:

$A_{kcmil} := 0$ $A_{mm} := 0$

$$A_{kcmil} := I_{F\_kA} \cdot \frac{(197.4)}{\sqrt{\left(\frac{TCAP}{t_c \cdot \alpha_r \cdot \rho_r}\right) \cdot \ln\left(\frac{K_0 + T_m}{K_0 + T_a}\right)}}$$

$A_{kcmil} = 66.336$ kcmil

$A_{mm} := 0.5097 \cdot A_{kcmil}$

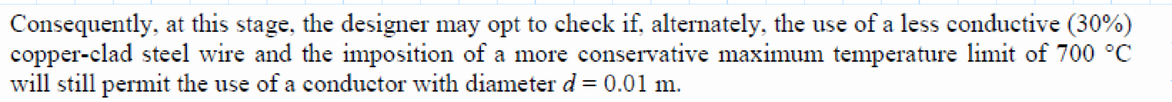
$A_{mm} = 33.811$ mm

Now calculate diameter d minimum for this case:

$d_{min\_mm} := \sqrt{\left(\frac{A_{mm} \cdot 4}{\pi}\right)}$ $d_{min\_mm} = 6.561$ $d_{min\_m} := \frac{d_{min\_mm}}{1000}$

$d_{min\_m} = 0.0066$ m approximately for stranded conductor

Our design goals as stated earlier shown below.

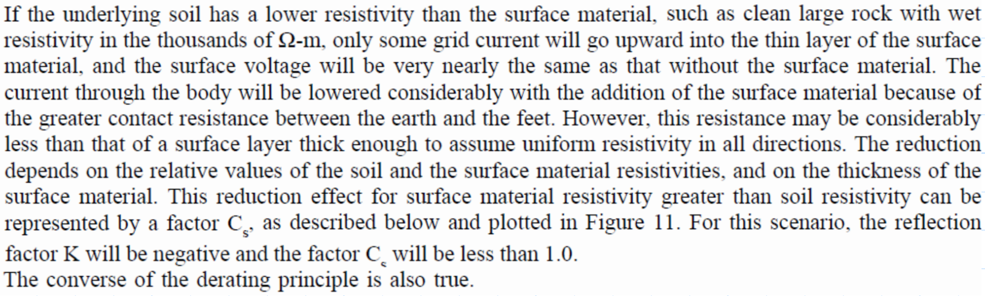


Consequently, at this stage, the designer may opt to check if, alternately, the use of a less conductive (30%) copper-clad steel wire and the imposition of a more conservative maximum temperature limit of 700 °C will still permit the use of a conductor with diameter $d = 0.01$ m.

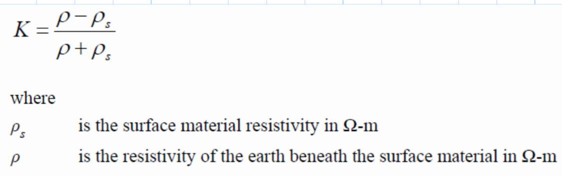
Our d_min as calculated is lower than d = 0.01 m. Hence the 30% copper-clad steel cable of approximately 70mm is a viable alternative for grid conductor, even if a conservative maximum temperature of 700C is imposed. See page 6 when 70m mcable was used.

Step 3: Touch and Step Criteria

For a 0.102m (4inch) layer of surface layer material, with a wet resistivity of 2500 ohm meter, and for an earth with resitivity of 400 ohm-m, the reflection factor K is computed using equation (21).
Note: Approximately 1 inch = 25mm.



If the underlying soil has a lower resistivity than the surface material, such as clean large rock with wet resistivity in the thousands of Ω-m, only some grid current will go upward into the thin layer of the surface material, and the surface voltage will be very nearly the same as that without the surface material. The current through the body will be lowered considerably with the addition of the surface material because of the greater contact resistance between the earth and the feet. However, this resistance may be considerably less than that of a surface layer thick enough to assume uniform resistivity in all directions. The reduction depends on the relative values of the soil and the surface material resistivities, and on the thickness of the surface material. This reduction effect for surface material resistivity greater than soil resistivity can be represented by a factor C_s, as described below and plotted in Figure 11. For this scenario, the reflection factor K will be negative and the factor C_s will be less than 1.0.
The converse of the derating principle is also true.



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

where
ρ_s is the surface material resistivity in Ω-m
ρ is the resistivity of the earth beneath the surface material in Ω-m

$\rho := 400\ \mathrm{ohm \cdot m}$

Initialise variable used prior:

$\rho_S := 0$

$\rho_S := 2500\ \mathrm{ohm \cdot m}$

$$K := \frac{\rho - \rho_S}{\rho + \rho_S}$$ K is the reflection factor

$K = -0.724$ negative value as expected due to surface material resistivity greater than soil resistivity, in this case only some grid current goes up the surface. the reverse would had more current going up the surface with K as a positive value.

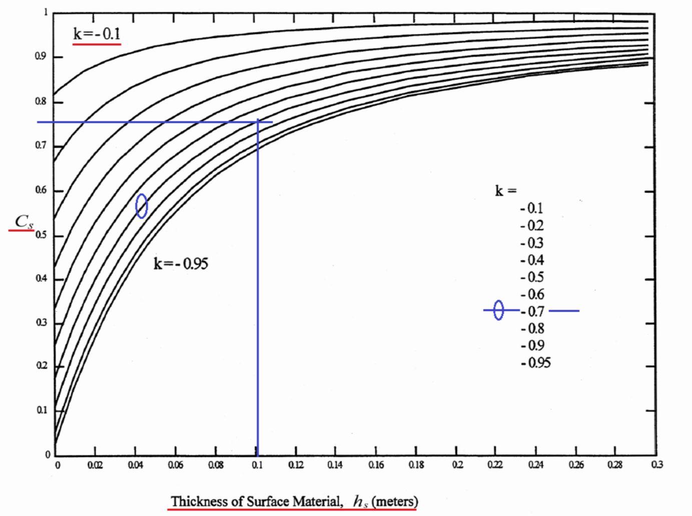


Figure 11—C_s versus h_s

hs thickness of surface material was given in the design data = 0.102m

From the figure above for K=-0.724 (-0.7) the resistivity of the surface material is to be reduced by a factor of approximately Cs = 0.74

$C_{s\_graph} := 0.74$

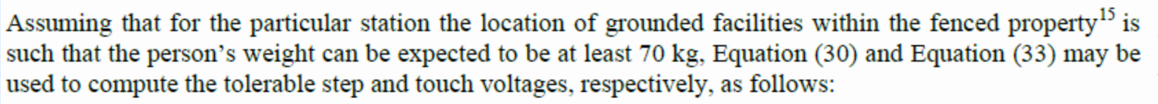
If the graph was not accurate enough the equation below does calulcate the reduction factor Cs.

$h_s = 0.102\ \text{m}$

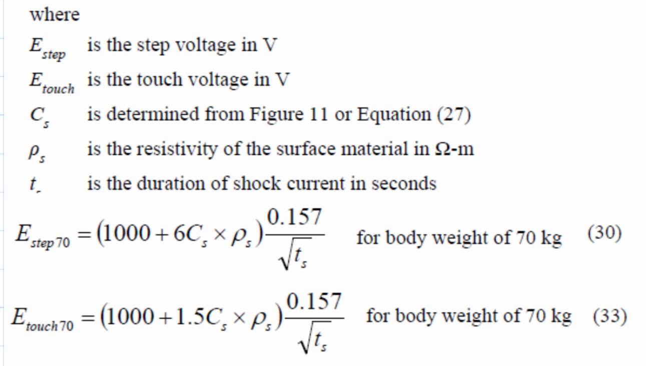
$h_s := 0.102$ value re-entered without unit meter to make result work

$$C_s := 1 - \frac{\left(0.09 \cdot \left(1 - \frac{\rho}{\rho_s}\right)\right)}{2 \cdot h_s + 0.09}$$

$C_s = 0.743$ This vaue is close to the grpah for the first 2 decimal places, its accurate.



Assuming that for the particular station the location of grounded facilities within the fenced property[15] is such that the person's weight can be expected to be at least 70 kg, Equation (30) and Equation (33) may be used to compute the tolerable step and touch voltages, respectively, as follows:



where

E_{step} is the step voltage in V

E_{touch} is the touch voltage in V

C_s is determined from Figure 11 or Equation (27)

ρ_s is the resistivity of the surface material in Ω-m

t_s is the duration of shock current in seconds

$$E_{step70} = \left(1000 + 6C_s \times \rho_s\right)\frac{0.157}{\sqrt{t_s}} \quad \text{for body weight of 70 kg} \qquad (30)$$

$$E_{touch70} = \left(1000 + 1.5C_s \times \rho_s\right)\frac{0.157}{\sqrt{t_s}} \quad \text{for body weight of 70 kg} \qquad (33)$$

Re-enter values without units to make the result work

$\rho := 400$ $\rho_s := 2500$

$t_s := 0.5$ duration of shock for allowing alloable body currents, in seconds

$$E_{step70} := \left(1000 + 6 \cdot C_s \cdot \rho_s\right) \cdot \frac{0.157}{\left(\sqrt{t_s}\right)} \qquad E_{step70} = 2696.097 \quad \text{Volts}$$

$$E_{touch70} := \left(1000 + 1.5 \cdot C_s \cdot \rho_s\right) \cdot \frac{0.157}{\left(\sqrt{t_s}\right)} \qquad E_{touch70} = 840.548 \quad \text{Volts}$$

Step 4: Initial design

We start with a preliminary layout of 70m x 70m square.
Equally spaced conductors.
Consuctors spaced 7m apart.
For a distance of 70 meters, spacing of 7m there are 11 rows of conductors.
The grid burial depth hs = 0.5m
No ground rods in this design just the grid.

Total length of buried conductor:

$L_T := (11 \cdot 70\ \text{m}) \cdot 2$ $\qquad$ $L_T = 1540\ \text{m}$

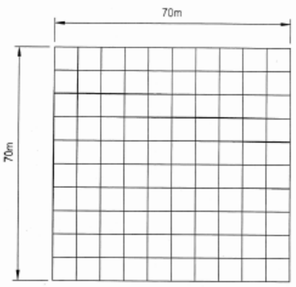
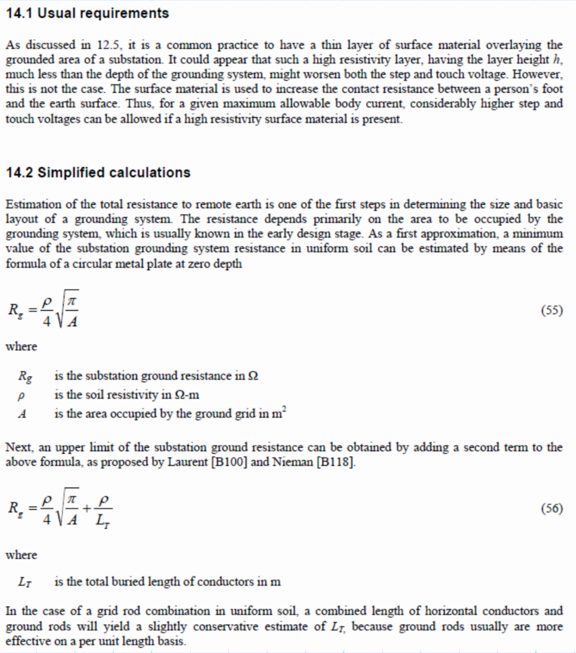


Figure B.1—Square grid without ground rods

Grounded facilities within the fenced area is NOT accessible to the general public.

Step 5: Determination of grid resistance:

$L_T = (1.54 \cdot 10^3)\ \text{m}$



14.1 Usual requirements

As discussed in 12.5, it is a common practice to have a thin layer of surface material overlaying the grounded area of a substation. It could appear that such a high resistivity layer, having the layer height *h*, much less than the depth of the grounding system, might worsen both the step and touch voltage. However, this is not the case. The surface material is used to increase the contact resistance between a person's foot and the earth surface. Thus, for a given maximum allowable body current, considerably higher step and touch voltages can be allowed if a high resistivity surface material is present.

14.2 Simplified calculations

Estimation of the total resistance to remote earth is one of the first steps in determining the size and basic layout of a grounding system. The resistance depends primarily on the area to be occupied by the grounding system, which is usually known in the early design stage. As a first approximation, a minimum value of the substation grounding system resistance in uniform soil can be estimated by means of the formula of a circular metal plate at zero depth

$$R_g = \frac{\rho}{4}\sqrt{\frac{\pi}{A}} \qquad (55)$$

where

R_g is the substation ground resistance in Ω
ρ is the soil resistivity in Ω-m
A is the area occupied by the ground grid in m^2

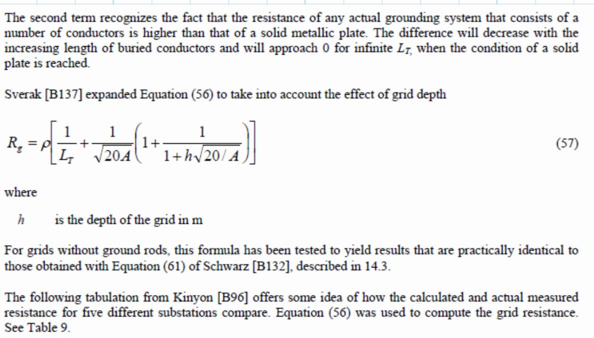
Next, an upper limit of the substation ground resistance can be obtained by adding a second term to the above formula, as proposed by Laurent [B100] and Nieman [B118].

$$R_g = \frac{\rho}{4}\sqrt{\frac{\pi}{A}} + \frac{\rho}{L_T} \qquad (56)$$

where

L_T is the total buried length of conductors in m

In the case of a grid rod combination in uniform soil, a combined length of horizontal conductors and ground rods will yield a slightly conservative estimate of L_T, because ground rods usually are more effective on a per unit length basis.



The second term recognizes the fact that the resistance of any actual grounding system that consists of a number of conductors is higher than that of a solid metallic plate. The difference will decrease with the increasing length of buried conductors and will approach 0 for infinite L_T, when the condition of a solid plate is reached.

Sverak [B137] expanded Equation (56) to take into account the effect of grid depth

$$R_g = \rho\left[\frac{1}{L_T} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1 + h\sqrt{20/A}}\right)\right] \qquad (57)$$

where

h is the depth of the grid in m

For grids without ground rods, this formula has been tested to yield results that are practically identical to those obtained with Equation (61) of Schwarz [B132], described in 14.3.

The following tabulation from Kinyon [B96] offers some idea of how the calculated and actual measured resistance for five different substations compare. Equation (56) was used to compute the grid resistance. See Table 9.

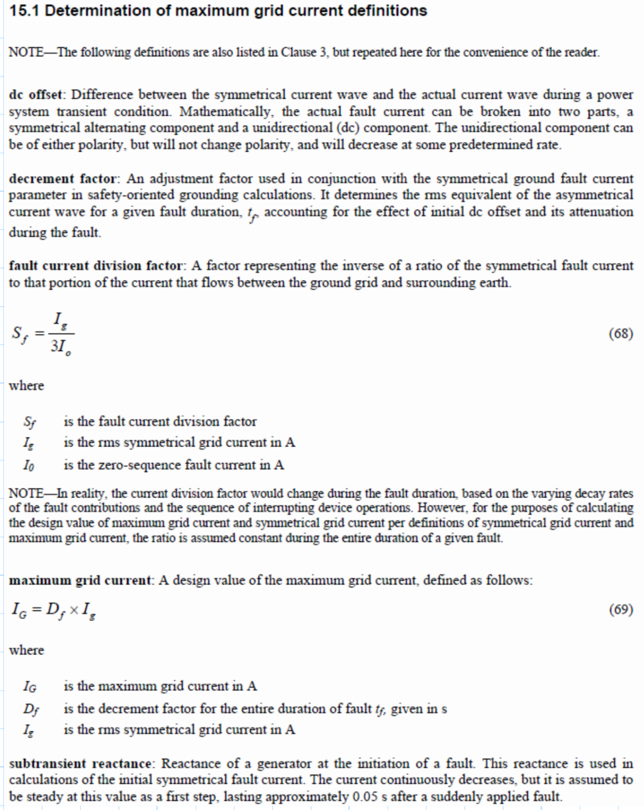
$\rho := 400$

$$R_g := \rho \left(\left(\frac{1}{L_T} \right) + \left(\frac{1}{\sqrt{20 \cdot A_{sgtd}}} \right) \cdot \left(1 + \frac{1}{\left(1 + h \cdot \left(\sqrt{\frac{20}{A_{sgtd}}} \right) \right)} \right) \right) \text{ohm} \cdot \text{m}$$

$R_g = 2.776\ \Omega$

Step 6: Maximum grid current Ig

Per 15.1 shown below. The maximum grid current Ig is determined by combining equation (68) and equation (69). Referring to step 2 for Df = 1.0 (which was part of the calculation process) and the given current division factor Sf = 0.6 was given in the earthing problem data.



15.1 Determination of maximum grid current definitions

NOTE—The following definitions are also listed in Clause 3, but repeated here for the convenience of the reader.

dc offset: Difference between the symmetrical current wave and the actual current wave during a power system transient condition. Mathematically, the actual fault current can be broken into two parts, a symmetrical alternating component and a unidirectional (dc) component. The unidirectional component can be of either polarity, but will not change polarity, and will decrease at some predetermined rate.

decrement factor: An adjustment factor used in conjunction with the symmetrical ground fault current parameter in safety-oriented grounding calculations. It determines the rms equivalent of the asymmetrical current wave for a given fault duration, t_f, accounting for the effect of initial dc offset and its attenuation during the fault.

fault current division factor: A factor representing the inverse of a ratio of the symmetrical fault current to that portion of the current that flows between the ground grid and surrounding earth.

$$S_f = \frac{I_g}{3I_o} \tag{68}$$

where

S_f is the fault current division factor
I_g is the rms symmetrical grid current in A
I_0 is the zero-sequence fault current in A

NOTE—In reality, the current division factor would change during the fault duration, based on the varying decay rates of the fault contributions and the sequence of interrupting device operations. However, for the purposes of calculating the design value of maximum grid current and symmetrical grid current per definitions of symmetrical grid current and maximum grid current, the ratio is assumed constant during the entire duration of a given fault.

maximum grid current: A design value of the maximum grid current, defined as follows:

$$I_G = D_f \times I_g \tag{69}$$

where

I_G is the maximum grid current in A
D_f is the decrement factor for the entire duration of fault t_f, given in s
I_g is the rms symmetrical grid current in A

subtransient reactance: Reactance of a generator at the initiation of a fault. This reactance is used in calculations of the initial symmetrical fault current. The current continuously decreases, but it is assumed to be steady at this value as a first step, lasting approximately 0.05 s after a suddenly applied fault.

Note:
Though the 13kV bus fault value of 6815A is greater than the 115kV bus fault value of 3180A, it is recalled from clause 15 of the standard that the wye-grounded 13kV transformer winding is a local source of fault current and does not contribute to the GPR. Thus the maximum grid current is based on the 3180A fault on the 115kV bus.

$\text{ThreeI}_0 = 3180\ \text{A}$ 115kV bus fault
$D_f := 1.0$ $S_f = 0.6$

Ig = Df x Sf x 3I0

$I_G := D_f \cdot S_f \cdot \text{ThreeI}_0$ $I_G = 1908\ \text{A}$ Maximum ground grid current

Step 7: GPR (Ground Potential Rise).

Now it isnecessary to compare the product of Ig and Rg, or GPR, to the tolerable touch voltage Etouch70

$$GPR := I_G \cdot R_g$$

$$GPR = 5296\ \mathrm{V}$$

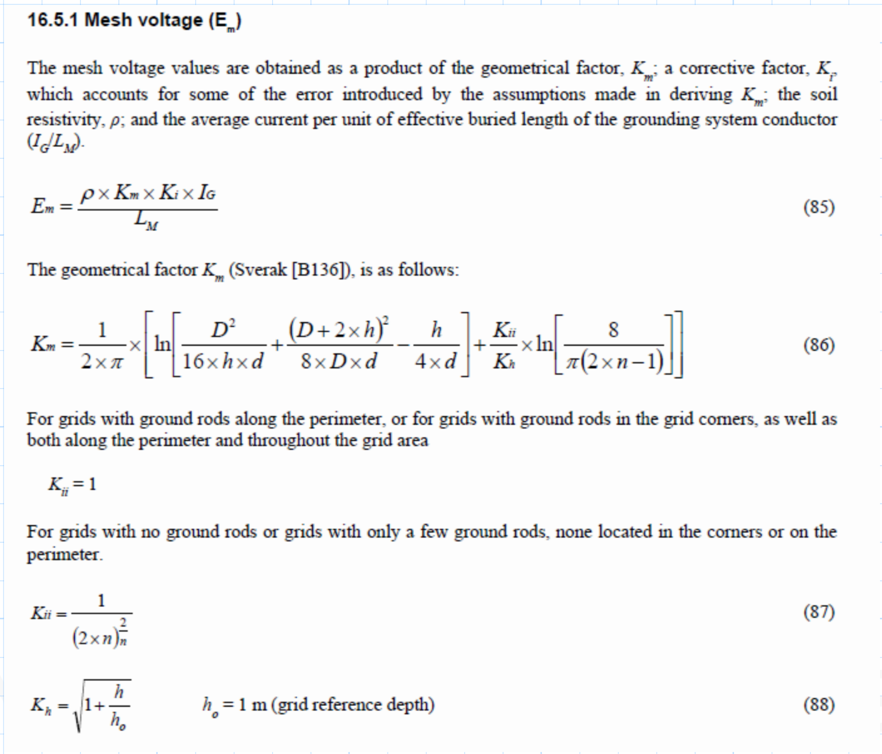
From step 3 the calculated value of Etouch70:

$$E_{touch70} = 840.548$$

The voltage of GPR is greater than Etouch70. The ground potential rise is greater than the touch voltage for the weight of a 70kg person. So this is UNACCEPTABLE. Therefore further design calculations/ evaluations are necessary.

Step 8: Mesh voltage:

Using equations 86, 87 and 88 Km is computed.
Read the explanation below given for Mesh Voltage Em



16.5.1 Mesh voltage (E_m)

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

$$E_m = \frac{\rho \times K_m \times K_i \times I_G}{L_M} \tag{85}$$

The geometrical factor K_m (Sverak [B136]), is as follows:

$$K_m = \frac{1}{2\times\pi}\times\left[\ln\left[\frac{D^2}{16\times h\times d}+\frac{(D+2\times h)^2}{8\times D\times d}-\frac{h}{4\times d}\right]+\frac{K_{ii}}{K_h}\times\ln\left[\frac{8}{\pi(2\times n-1)}\right]\right] \tag{86}$$

For grids with ground rods along the perimeter, or for grids with ground rods in the grid corners, as well as both along the perimeter and throughout the grid area

$$K_{ii} = 1$$

For grids with no ground rods or grids with only a few ground rods, none located in the corners or on the perimeter.

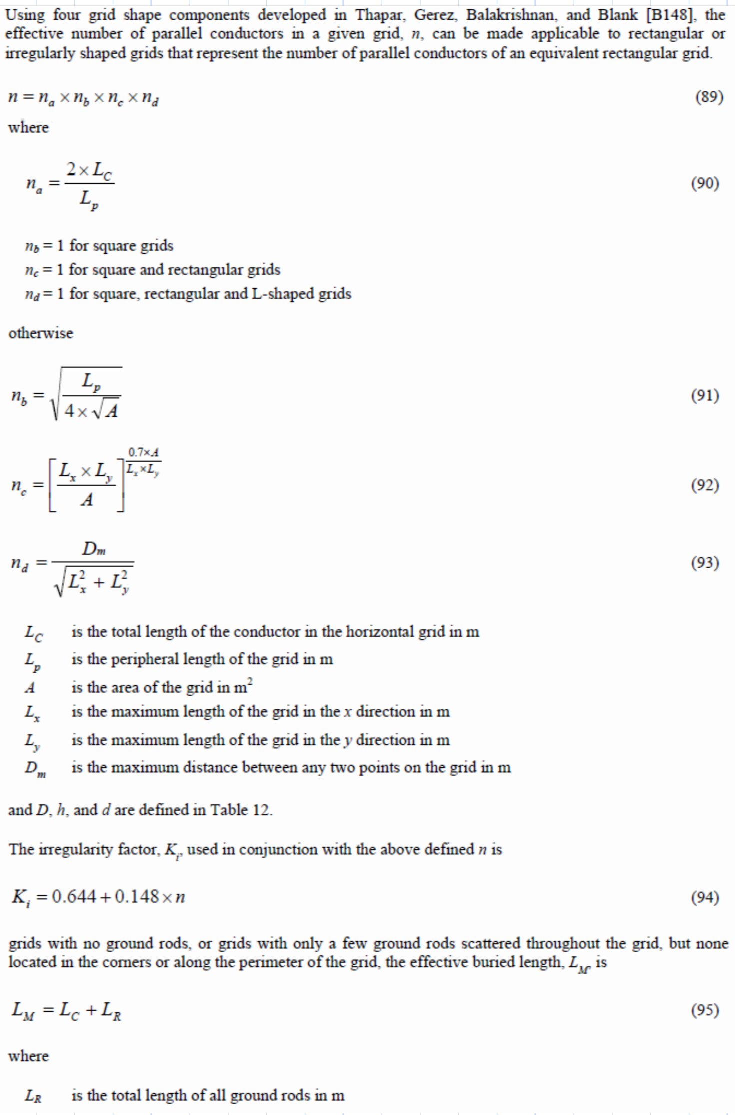
$$K_{ii} = \frac{1}{(2\times n)^{\frac{2}{n}}} \tag{87}$$

$$K_h = \sqrt{1+\frac{h}{h_o}} \qquad h_o = 1\ \mathrm{m}\ \text{(grid reference depth)} \tag{88}$$

Calculate geometrical factor Km:
Data re-entered to avoid unit errors

$D := 7$ spacing between parallel conductors in meters
$d := d_m = 0.01$ diameter of grid conductor as set in above step 2

Next calculate n the 'effective number of parallel conductors' in a given grid.



Using four grid shape components developed in Thapar, Gerez, Balakrishnan, and Blank [B148], the effective number of parallel conductors in a given grid, *n*, can be made applicable to rectangular or irregularly shaped grids that represent the number of parallel conductors of an equivalent rectangular grid.

$$n = n_a \times n_b \times n_c \times n_d \qquad (89)$$

where

$$n_a = \frac{2 \times L_C}{L_p} \qquad (90)$$

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

otherwise

$$n_b = \sqrt{\frac{L_p}{4 \times \sqrt{A}}} \qquad (91)$$

$$n_c = \left[\frac{L_x \times L_y}{A}\right]^{\frac{0.7 \times A}{L_x \times L_y}} \qquad (92)$$

$$n_d = \frac{D_m}{\sqrt{L_x^2 + L_y^2}} \qquad (93)$$

L_C	is the total length of the conductor in the horizontal grid in m
L_p	is the peripheral length of the grid in m
A	is the area of the grid in m^2
L_x	is the maximum length of the grid in the *x* direction in m
L_y	is the maximum length of the grid in the *y* direction in m
D_m	is the maximum distance between any two points on the grid in m

and *D*, *h*, and *d* are defined in Table 12.

The irregularity factor, K_i, used in conjunction with the above defined *n* is

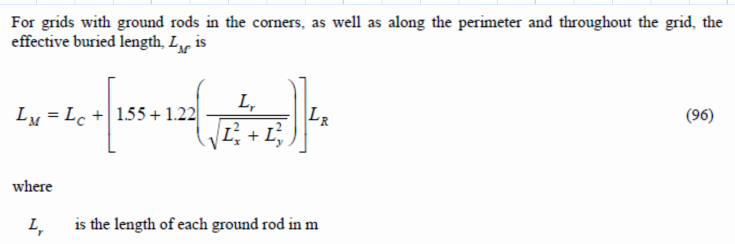
$$K_i = 0.644 + 0.148 \times n \qquad (94)$$

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

$$L_M = L_C + L_R \qquad (95)$$

where

L_R is the total length of all ground rods in m



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

$$L_M = L_C + \left[1.55 + 1.22\left(\frac{L_r}{\sqrt{L_x^2 + L_y^2}}\right)\right] L_R \qquad (96)$$

where

L_r is the length of each ground rod in m

$L_C := L_T = 1540\ \text{m}$

$L_P := (70 + 70 + 70 + 70)\ \text{m} = 280\ \text{m}$ Perimeter of the grid

$n_a := \dfrac{2 \cdot L_C}{L_P}$ $n_a = 11$

For a square grid nb, nc, and nd = 1
$n_b := 1$ $n_c := 1$ $n_d := 1$

$n := n_a \cdot n_b \cdot n_c \cdot n_d$

$n = 11$

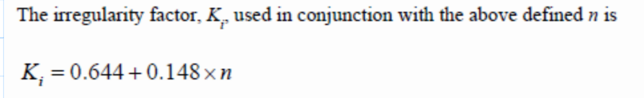
$K_{ii} := \dfrac{1}{(2 \cdot n)^{\frac{2}{n}}}$ $K_{ii} = 0.57$

$h_0 := 1$ h0 = 1m grid reference depth as in equation 88
$h := 0.5$ depth of buried conductor - reentered to avoid unit errors

$K_h := \sqrt{\left(1 + \left(\dfrac{h}{h_0}\right)\right)}$ $K_h = 1.225$

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

$K_m = 0.883$ geometrical factor



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

$K_i = 0.644 + 0.148 \times n$

$K_i := 0.644 + 0.148 \cdot n$

$K_i = 2.272$

Calculate mesh voltage Em:

Em = (p x Ig x Km x Ki)/ (Lc + Lr)
Here Lr is the ground rod length, which we do not have so the denominator is the total grid conductors length LT which is LC
Note: Units removed to prevent inappropriate results in units. IGunitless = IG

$L_C := \frac{L_T}{m} = 1540$ $\rho = 400$ $I_{Gunitless} := \frac{I_G}{A} = 1907.854$

$E_m := \frac{\left(\rho \cdot I_{Gunitless} \cdot K_m \cdot K_i\right)}{L_C}$ $E_m = 994.689$ Volts

Step 9: Em versus Etouch:

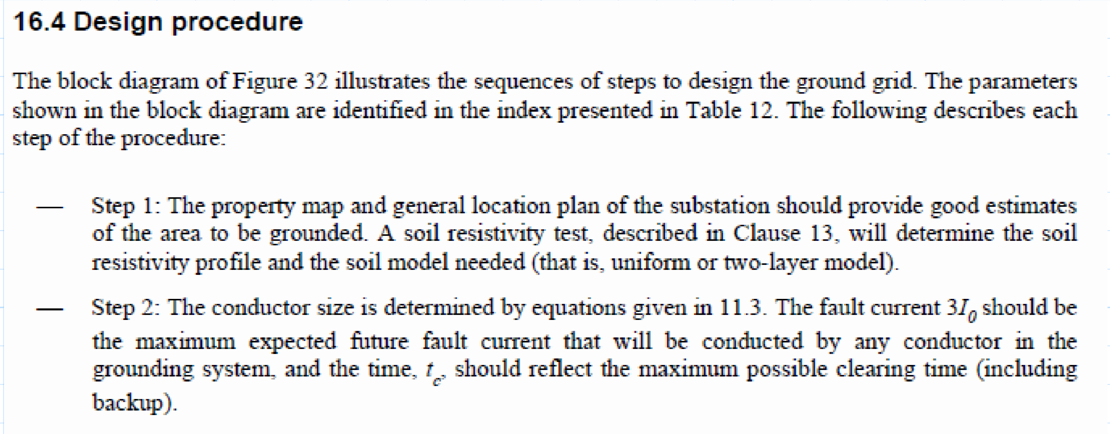
$E_{touch70} = 840.548$ Volts

$E_m = 994.689$ Volts

Mesh voltage Em calculated is HIGHER than the tolerable touch voltage Etouch70, this is UNACCEPTABLE.

The grid must be modified.

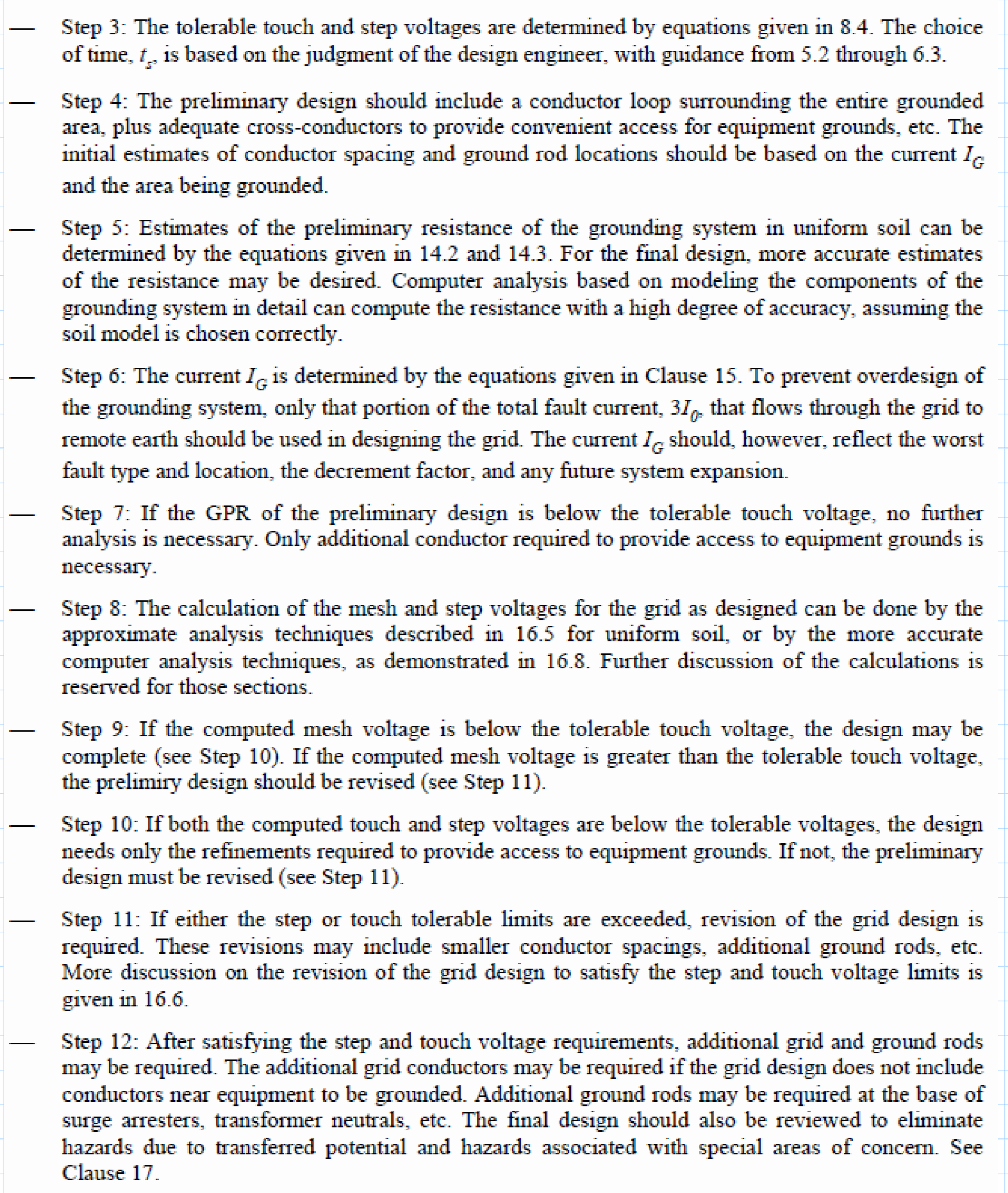
Design Procedure steps 1 through 12, and flow chart is provided.
Also figures for ground faults at substations are provided after the flow chart.



16.4 Design procedure

The block diagram of Figure 32 illustrates the sequences of steps to design the ground grid. The parameters shown in the block diagram are identified in the index presented in Table 12. The following describes each step of the procedure:

- Step 1: The property map and general location plan of the substation should provide good estimates of the area to be grounded. A soil resistivity test, described in Clause 13, will determine the soil resistivity profile and the soil model needed (that is, uniform or two-layer model).
- Step 2: The conductor size is determined by equations given in 11.3. The fault current $3I_0$ should be the maximum expected future fault current that will be conducted by any conductor in the grounding system, and the time, t_c, should reflect the maximum possible clearing time (including backup).



- Step 3: The tolerable touch and step voltages are determined by equations given in 8.4. The choice of time, t_s, is based on the judgment of the design engineer, with guidance from 5.2 through 6.3.
- Step 4: The preliminary design should include a conductor loop surrounding the entire grounded area, plus adequate cross-conductors to provide convenient access for equipment grounds, etc. The initial estimates of conductor spacing and ground rod locations should be based on the current I_G and the area being grounded.
- Step 5: Estimates of the preliminary resistance of the grounding system in uniform soil can be determined by the equations given in 14.2 and 14.3. For the final design, more accurate estimates of the resistance may be desired. Computer analysis based on modeling the components of the grounding system in detail can compute the resistance with a high degree of accuracy, assuming the soil model is chosen correctly.
- Step 6: The current I_G is determined by the equations given in Clause 15. To prevent overdesign of the grounding system, only that portion of the total fault current, $3I_0$, that flows through the grid to remote earth should be used in designing the grid. The current I_G should, however, reflect the worst fault type and location, the decrement factor, and any future system expansion.
- Step 7: If the GPR of the preliminary design is below the tolerable touch voltage, no further analysis is necessary. Only additional conductor required to provide access to equipment grounds is necessary.
- Step 8: The calculation of the mesh and step voltages for the grid as designed can be done by the approximate analysis techniques described in 16.5 for uniform soil, or by the more accurate computer analysis techniques, as demonstrated in 16.8. Further discussion of the calculations is reserved for those sections.
- Step 9: If the computed mesh voltage is below the tolerable touch voltage, the design may be complete (see Step 10). If the computed mesh voltage is greater than the tolerable touch voltage, the prelimiry design should be revised (see Step 11).
- Step 10: If both the computed touch and step voltages are below the tolerable voltages, the design needs only the refinements required to provide access to equipment grounds. If not, the preliminary design must be revised (see Step 11).
- Step 11: If either the step or touch tolerable limits are exceeded, revision of the grid design is required. These revisions may include smaller conductor spacings, additional ground rods, etc. More discussion on the revision of the grid design to satisfy the step and touch voltage limits is given in 16.6.
- Step 12: After satisfying the step and touch voltage requirements, additional grid and ground rods may be required. The additional grid conductors may be required if the grid design does not include conductors near equipment to be grounded. Additional ground rods may be required at the base of surge arresters, transformer neutrals, etc. The final design should also be reviewed to eliminate hazards due to transferred potential and hazards associated with special areas of concern. See Clause 17.

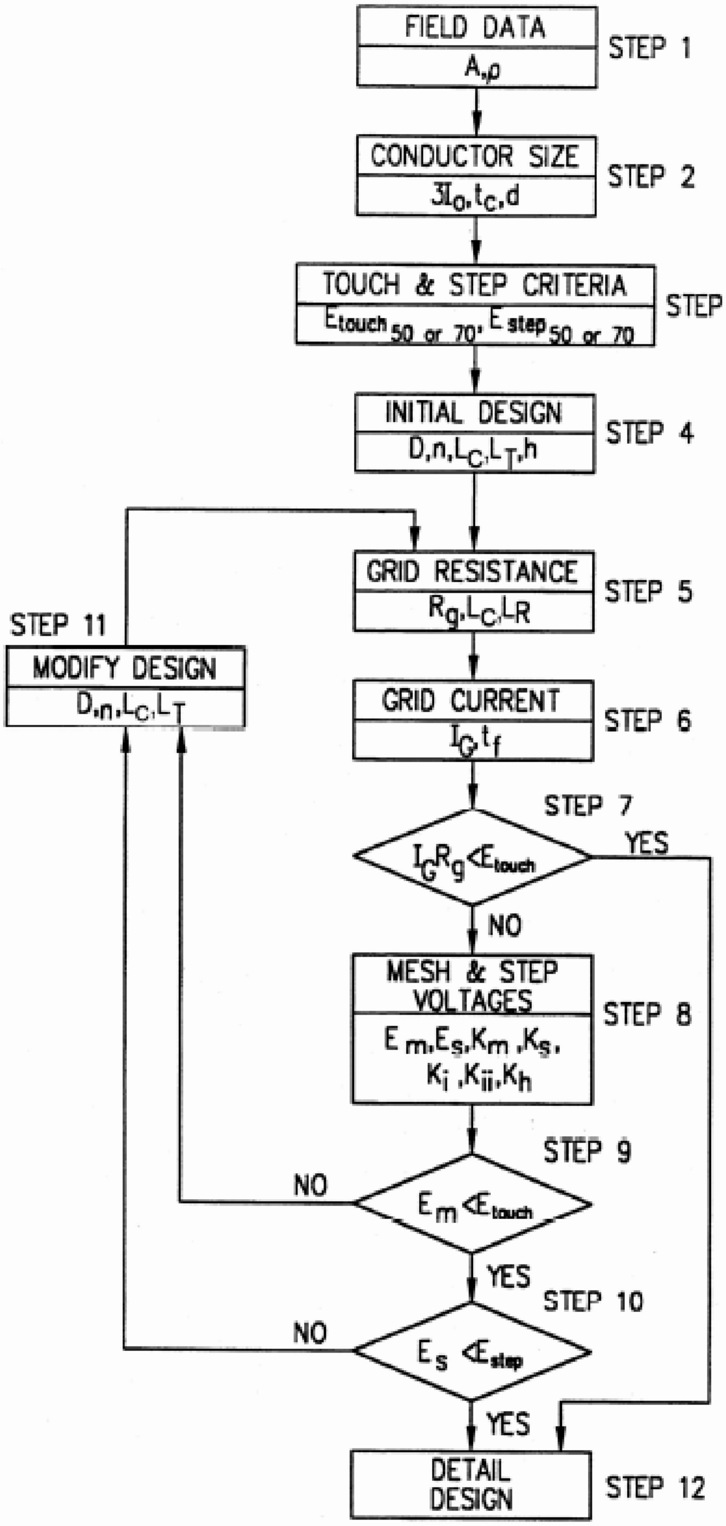


Figure 32—Design procedure block diagram

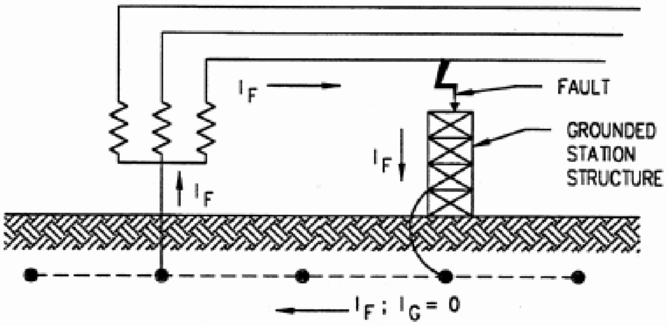


Figure 27—Fault within local substation; local neutral grounded

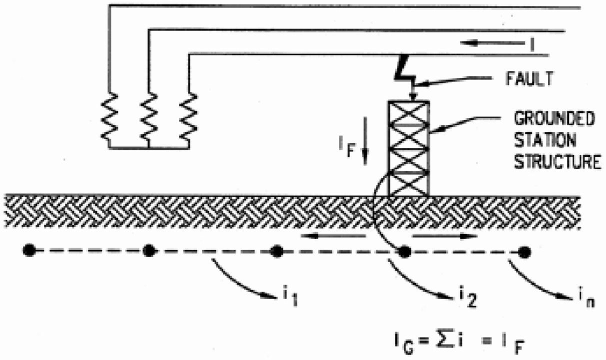


Figure 28—Fault within local substation; neutral grounded at remote location

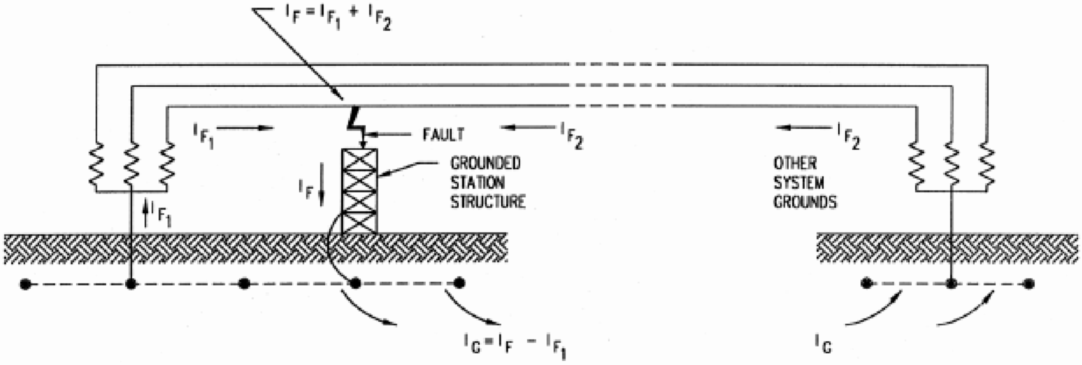


Figure 29—Fault in substation; system grounded at local substation and also at other points

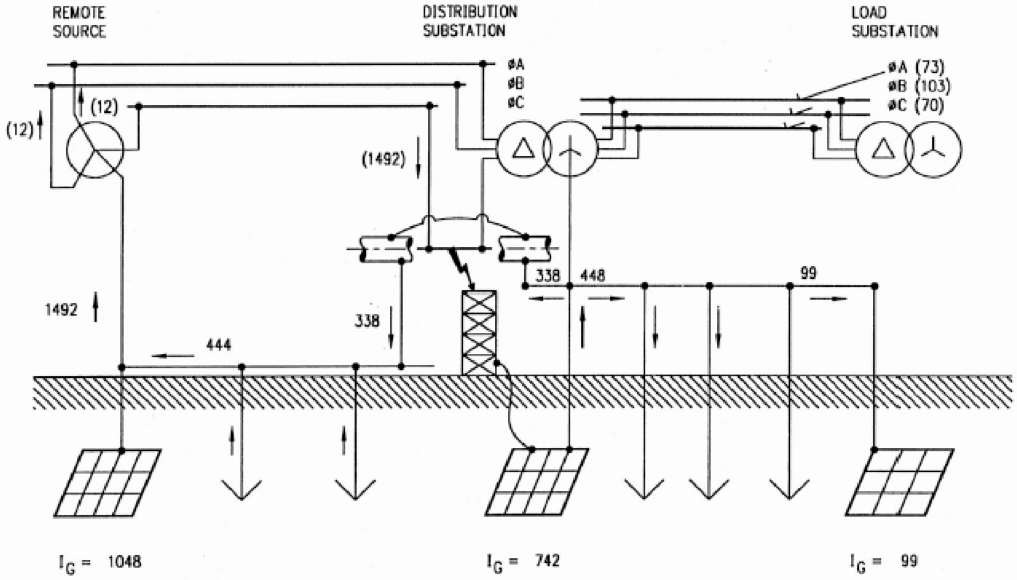


Figure 30—Typical current division for a fault on high side of distribution substation