Appendix H

Worked Example for the Calculation of Earthing Current and Electric Shock Hazard Potential Difference in a Rod and Grid Earthing System

H.1 WORKED EXAMPLE

A 33 kV overhead line terminates at a pole in a small switching station. The distance to the pole from the source is 15 km, but of course there are many other poles along the route. The subject pole is earthed at its footings.

The overhead line ohmic data are:-

$$\text{Positive sequence impedance } Z_{1\text{pkm}} = 0.35 + j0.4 \text{ ohms/km.}$$

$$\text{Negative sequence impedance } Z_{2\text{pkm}} = 0.35 + j0.4 \text{ ohms/km.}$$

$$\text{Zero sequence impedance } Z_{0\text{pkm}} = 0.7 + j1.5 \text{ ohms/km.}$$

The sending end of the line has a 100 MVA transformer that has the following ohmic data:-

$$\text{Positive sequence impedance } Z_{1t} = 0.1084 + j1.084 \text{ ohms/phase.}$$

$$\text{Negative sequence impedance } Z_{2t} = Z_{1t} \text{ ohms/phase.}$$

$$\text{Zero sequence impedance } Z_{0t} = Z_{1t} \text{ ohms/phase.}$$

It will be assumed that the source impedance Z_s feeding the transformers is small enough to be neglected. To illustrate the difficulty in finding a suitably low resistance to earth it will be assumed that the secondary winding of the transformer is solidly earthed and hence the NER resistance R_n is zero, a non-zero value will be recommended at the conclusion of the calculations. However, it will be assumed that the resistance to earth R_{en} at the source transformer is 1.5 ohms. The resistance to earth at the far end pole is R_{ep}, which needs to be determined. This requires a suitable grid and rod system to be chosen. The calculation process will be carried out in a series of steps.

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Step 1. Find the total positive, negative and zero sequence impedances in the circuit.

The total positive sequence impedance Z_1 is:-

$$\begin{aligned} Z_1 &= 15.0(0.35 + j0.4) + 0.1084 + j1.084 \\ &= 5.3584 + j7.084 \text{ ohms} \end{aligned}$$

The total negative sequence impedance Z_2 is:-

$$Z_2 = Z_1 = 5.3584 + j7.084 \text{ ohms}$$

The total zero sequence impedance Z_0 is:-

$$\begin{aligned} Z_0 &= \frac{15.0Z_{0\text{pkm}}(R_{\text{en}} + R_{\text{ep}})}{(15.0 \times Z_{0\text{pkm}}) + R_{\text{en}} + R_{\text{ep}}} + Z_{0p} + Z_{0t} \\ &= \frac{(10.5 + j22.5)(1.5 + R_{\text{ep}})}{12.0 + R_{\text{ep}} + j22.5} + 10.6084 + j23.584 \end{aligned} \quad \text{(H.1.1)}$$

Hence Z_0 is a function of R_{ep}.

In this worked example the zero sequence impedance includes the impedance of the over-head earthing conductor as a simple conductor spanning the 15 km route length. In practice the intermediate poles will be earthed at their own footings and also bonded to the over-head earthing conductor. These bonding connections will form a type of 'ladder' network that involves the resistance to earth at each pole. The effect of this may be to reduce the amount of current entering the ground at the far end pole, i.e. the subject of these calculations. Table H.1a would then contain different values of currents.

Step 2. Find the total root-mean-square fault current.

The total root-mean-square fault current I_f is:-

$$I_f = 3I_0 = \frac{3V_p}{3R_f + Z_1 + Z_2 + Z_0} \quad \text{(H.1.2)}$$

Where I_0 = the symmetrical rms zero sequence current.
V_p = the phase-to-neutral driving voltage at the source.
R_f = the resistance of the fault itself, assumed to be zero.
Z_1 = the total positive sequence impedance.
Z_2 = the total negative sequence impedance.
Z_0 = the total zero sequence impedance.

Therefore inserting the numerical data gives,

$R_1 = 5.3584$ ohms, $X_1 = 7.084$ ohms,

$R_2 = 5.3584$ ohms, $X_2 = 7.084$ ohms,

R_0 = real part of Z_0, X_0 = imaginary part of Z_0.

$V_p = 33{,}000/\sqrt{3} = 19{,}053$ volts/phase.

Table H.1a. Earth fault current as a function of earth resistance

Earth resistance (ohms)	Earth fault current (amps)	Proportion of current diverted to the		X-to-R ratio (pu)
		O/H line (pu)	Pole (pu)	
0.25	1314.73	0.0683	0.9692	1.6023
0.50	1310.23	0.0777	0.9647	1.5876
0.75	1305.70	0.0870	0.9601	1.5736
1.00	1301.13	0.0962	0.9555	1.5602
1.25	1296.54	0.1053	0.9509	1.5474
1.50	1201.92	0.1143	0.9463	1.5351
1.75	1287.30	0.1233	0.9416	1.5233
2.00	1282.66	0.1321	0.9370	1.5121
4.00	1245.83	0.1992	0.8993	1.4383
6.00	1210.65	0.2603	0.8617	1.3874
8.00	1178.15	0.3156	0.8248	1.3532
10.0	1148.73	0.3654	0.7890	1.3311
15.0	1088.41	0.4695	0.7065	1.3094
20.0	1043.88	0.5496	0.6347	1.3141
25.0	1010.86	0.6120	0.5734	1.3307
30.0	985.98	0.6611	0.5211	1.3523
35.0	966.84	0.7005	0.4754	1.3754
40.0	951.83	0.7325	0.4382	1.3985
50.0	930.11	0.7808	0.3765	1.4417
60.0	915.38	0.8153	0.3292	1.4794
70.0	904.88	0.8409	0.2920	1.5120
80.0	897.07	0.8605	0.2622	1.5399
90.0	891.08	0.8760	0.2377	1.5640
100.0	886.36	0.8885	0.2173	1.5850

Note 1. These are in relation to the magnitude of the total current, since both currents are complex quantities having different phase angles.

Table H.1a shows the value of I_f for different values of R_{ep}. It also shows the division of current between the overhead line earthing conductor and the footings of the pole.

Table H.1b shows the 'doubling factor', the peak factor and the power factor of currents that flow in an inductive circuit that has different X-to-R or R-to-X factors.

A small site may be constrained by a number of factors. Assume the site is located in a region of high resistivity with a low water table. The constraints on the design are:-

- The surface resistivity is higher than that of the lower soil.
- A grid with earthing rods attached will be needed.
- Use a rod diameter no less than 0.01 m.
- Allow the rods to be driven deep into the ground.
- Use the least site area as possible, i.e. 30 to 256 m^2.
- Let the overhead earthing conductor divert some of the fault current.

Table H.1b. Properties of the fault current for different X-to-R ratios

X-to-R ratio (pu)	R-to-X ratio (pu)	Doubling factor (pu)	Peak factor (pu)	Power factor (pu)
0.1	10.0000	1.0000	1.4142	0.9950
0.2	5.0000	1.0000	1.4142	0.9806
0.3	3.3333	1.0000	1.4143	0.9578
0.4	2.5000	1.0004	1.4148	0.9285
0.5	2.0000	1.0019	1.4169	0.8944
0.6	1.6667	1.0053	1.4217	0.8575
0.7	1.4286	1.0112	1.4301	0.8192
0.8	1.2500	1.0197	1.4421	0.7809
0.9	1.1111	1.0305	1.4573	0.7433
1.0	1.0000	1.0432	1.4753	0.7071
1.1	0.9091	1.0575	1.4955	0.6727
1.2	0.8333	1.0729	1.5174	0.6402
1.3	0.7692	1.0892	1.5404	0.6097
1.4	0.7143	1.1060	1.5642	0.5812
1.5	0.6667	1.1231	1.5884	0.5547
1.6	0.6250	1.1404	1.6127	0.5300
1.7	0.5882	1.1576	1.6370	0.5070
1.8	0.5556	1.1746	1.6611	0.4856
1.9	0.5263	1.1914	1.6859	0.4657
2.0	0.5000	1.2079	1.7082	0.4472
3.0	0.3333	1.3509	1.9105	0.3162
4.0	0.2500	1.4559	2.0590	0.2425
5.0	0.2000	1.5335	2.1687	0.1961
6.0	0.1667	1.5924	2.2520	0.1644
7.0	0.1429	1.6384	2.3170	0.1414
8.0	0.1250	1.6752	2.3691	0.1240
9.0	0.1111	1.7053	2.4117	0.1104
10.0	0.1000	1.7304	2.4472	0.0995
15.0	0.0667	1.8110	2.5612	0.0665
20.0	0.0500	1.8546	2.6229	0.0499
25.0	0.0400	1.8819	2.6614	0.0400
30.0	0.0333	1.9006	2.6878	0.0333
35.0	0.0286	1.9142	2.7070	0.0286
40.0	0.0250	1.9245	2.7216	0.0250
45.0	0.0222	1.9326	2.7331	0.0222
50.0	0.0200	1.9391	2.7423	0.0200
100.0	0.0100	1.9691	2.7847	0.0100
200.0	0.0050	1.9844	2.8064	0.0050
300.0	0.0033	1.9896	2.8137	0.0033
400.0	0.0025	1.9922	2.8174	0.0025
500.0	0.0020	1.9937	2.8196	0.0020

- Use the method described in IEEE80 sub-section 14.4 even though it is more applicable to much larger sites, but include the earthing rods.
- If possible limit the maximum resistance to earth at the site to 5 ohms.

Step 3. Find the resistance R_{ep} at the pole.

The following calculations are based on the methods given in IEEE80 Appendix C. The same symbols and notation are generally used to avoid confusion with the reference. The design data and constraints are:-

• Fault duration	t_s	=	0.5 sec
• Resistivity of lower layer	ρ	=	100 to 1000 ohm-m
• Resistivity of upper layer	ρ_s	=	1000 to 5000 ohm-m
• Thickness of upper layer	h_s	=	0.2 and 1.0 m
• Depth of burial of grid	h	=	0.5 and 1.0 m
• Site area	A	=	36 to 256 m^2
• Diameter of rods	d_r	=	0.02 and 0.2 m
• Depth of each rod	l_r	=	10 and 50 m
• Number of meshes in each side of the grid	N_{mesh}	=	3 to 8
• Spacing between the mesh nodes	d_{sp}	=	2.0 m

The results of the calculations are shown in Table H.1c; Case C.3 is used for the worked example. In this case the following additional information was used:-

• Number of outer peripheral rods	N_{rod1}	=	4
• Number of inner rods	N_{rod2}	=	0
• Number of rods on each side of grid	N	=	2
• Diameter of grid conductors	d_m	=	0.01 m

Calculate the resistivity derating factor $C_s\{h_s, K\}$ from (13.3), in which $u_s = \sqrt{(1 + (2\,\text{m}h_s/0.08)^2)}$. The number of terms m is taken to be 25 in order to obtain good convergence of the factor. The reflection factor K is found from ρ and ρ_s to be -0.6667 per-unit. $C_s\{h_s, K\}$ is found to be 0.8338 for this example.

The approximate grid resistance R_{epo} without the earthing rods can be found from Figure H.1a, which was derived from Figure B.1 of IEEE80 but applicable to small sizes of the mesh R_{epo}, is approximately:-

$$R_{\text{epo}} = \frac{\rho 51.94}{1000} = 51.94 \text{ ohms},$$

which is too high and indicates the need for rods.

At this stage the 50 kg step and touch voltages can be calculated from $C_s\{h_s, K\}$, since ρ_s and t_s are constants. The step voltage E_{step50} is: -

$$E_{\text{step50}} = \frac{(1000 + 6C_s\rho_s)\ 0.116}{\sqrt{t_s}} = 4267 \text{ volts}.$$

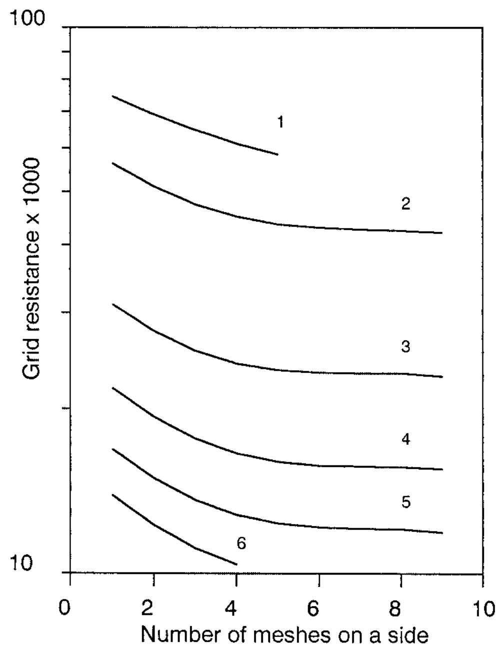

Figure H.1a Grid resistance versus the number of meshes on a side of a grid.

Similarly the touch voltage E_{touch50} is:-

$$E_{\text{touch50}} = \frac{(1000 + 1.5C_s\rho_s)\ 0.116}{\sqrt{t_s}} = 1190 \text{ volts.}$$

These two equations apply as criteria whether or not earthing rods are used. At this stage the magnitude of the portion of the fault current I_f entering the ground has not been used in the equations for voltages. It is necessary to calculate the corner mesh voltage E_m, which is given by equation 71 in IEEE80,

$$E_m = \frac{\rho_s I_g K_s K_i}{L} = 1854 \text{ volts.}$$

after solving equations 68 and 69 for K_m and K_i. However, K_m is also dependent on the current flowing into the ground, I_{fe}, and so the resistance to earth for the grid and rods must first be calculated. The corner mesh potential can also be found Figure H.1b, which was again derived from Figure B.2 of IEEE80.

Calculate the constants K_1 and K_2 that relate to the geometries of the grid and rods. They can be found from Figures 18(a) and 18(b) in IEEE 80. However, for the cases considered their approximate values are $K_1 = 1.15$ and $K_2 = 4.75$. The apparent resistivity ρ_a found from equation 46 in IEEE80 for the cases considered:-

$$\rho_a = \frac{l_r \rho \rho_s}{\rho(h_s - h) + \rho_s(l_r + h - h_r)} = 995.22 \text{ ohm-m.}$$

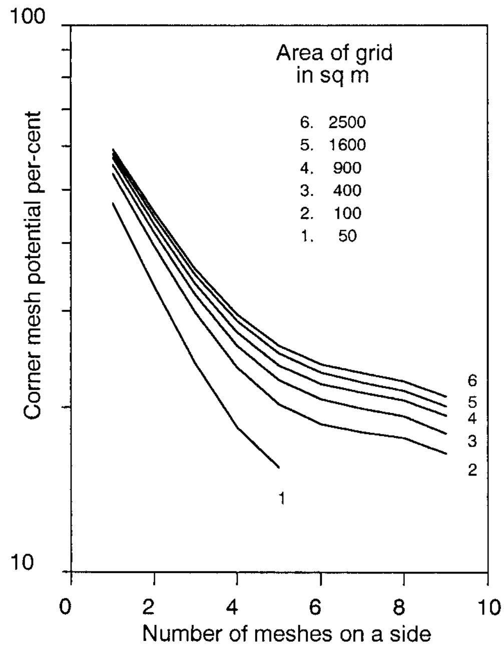

Figure H.1b Corner mesh potential versus the number of meshes.

If ρ_a is calculated to be close to ρ then take ρ_a to equal ρ as a conservative estimate, therefore $\rho_a = 1000$ for this example.

Now find the total amount of material to be used in the grid and rods.

The total length L_r of the ground rods is:-

$$L_r = (N_{\text{rod1}} + N_{\text{rod2}})l_r = 200 \text{ m}$$

Note, let the total number of rods be N_{rod} which equals $N_{\text{rod1}} + N_{\text{rod2}}$.

The total length L_g of the grid conductors is:-

$$L_g = 2nl_{\text{grid}} = 120 \text{ m}$$

Where $l_{\text{grid}} = (n - 1)d_{\text{sp}}$ is the buried length of one side of the grid, which is 10 m. The integer 'n' is the number of nodes on one side of the grid, or the number of meshes in one side plus 1.

The total length of buried rods and grid conductors including bonding connections is the weighted total L_c:-

$$L_c = L_g + 1.15L_r = 350 \text{ m}$$

Having now obtained the lengths of rods and grid conductors it is now possible to calculate the ground resistance R_{ep} using equations 41, 42, 43, 44 and 46 from sub-section 12.3 of IEEE80.

The following auxiliary equations are introduced to simplify the work involved:-

$$U_{11} = \frac{\rho_s}{\pi L_g} = 13.263$$

$$h_d = \sqrt{(d_m h)} = 0.0707$$

$$U_{12} = \log_e(2L_g/h_d) = 8.13$$

$$U_{13} = \frac{K_1 L_g}{A^{0.5}} = 13.8$$

$$U_{21} = \frac{\rho_a}{2\pi n l_r} = 0.531$$

$$U_{22} = \log_e(8l_r/d_r) = 9.903$$

$$U_{23} = \frac{2K_1 l_r}{A^{0.5}} = 11.5$$

$$U_{24} = (n^{0.5} - 1)^2 = 2.101$$

$$U_{31} = \frac{\rho_a}{\pi L_g} = 2.653$$

$$U_{32} = \log_e(2L_g/l_r) = 1.569$$

Where L_g = total length of the grid conductors
l_r = average length of a buried rod, but in this example all the rods are the same length
h_d = weighted depth of the grid

Let

R_{11} = resistance of the grid conductors

R_{22} = resistance of all the ground rods

R_{12} = mutual resistance between the whole grid and all the rods

From equations 42, 43 and 44 from IEEE80, these resistances are: -

$$R_{11} = U_{11}(U_{12} + U_{13} - K_2) = 227.86 \text{ ohms}$$

$$R_{22} = U_{21}(U_{22} - 1 + (U_{23}U_{24})) = 17.541 \text{ ohms}$$

$$R_{12} = U_{31}(U_{32} + U_{13} - K_2 + 1) = 30.82 \text{ ohms}$$

From equation 41, for both the grid and the rods R_{ep} becomes:-

$$R_{\text{ep}} = \frac{R_1 R_2 - {R_{12}}^2}{R_1 + R_2 - 2R_{12}} = 16.582 \text{ ohms}$$

Find the corner mesh voltage data.

Calculate the constants K_h, K_{ii} and K_m for use in equation 68 from IEEE80.

$$K_h = (1 + h)^{0.5} = 1.2247$$

Use the following auxiliary equations to simplify the work:-

$$U_1 = \frac{d_{\mathrm{sp}}{}^2}{16hd_m} = 50.0$$

$$U_2 = \frac{(d_{\mathrm{sp}} + 2h)^2}{8d_{\mathrm{sp}}d_m} = 56.25$$

$$U_3 = \frac{h}{4d_m} = 12.5$$

$$U_4 = \frac{8}{\pi(2n - 1)} = 0.2315$$

$$U_5 = \frac{K_{ii}}{K_h} = 0.8165$$

Where K_{ii} in this example is 1.

$$K_m = \frac{\log_e(U_1 + U_2 - U_3) + U_5 \log_e(U_4)}{2\pi} = 0.5325$$

Also from the explanation in sub-section 14.5.1 in IEEE80 the correction factor K_i is required, which is:-

$$K_i = 0.656 + 0.172N_n = 1.688$$

Where, $N_n = 6$ – number of parallel conductors in each direction of the grid, which equals the number of nodes on each side of the grid.

$K_h = 1.2247$ – correction factor for the depth of the grid.

$K_{ii} = 1.0$ – correction factor if the rods are placed inside the grid area.

$K_m = 0.5325$ – spacing factor for the mesh voltage.

$K_i = 1.688$ – correction factor for the grid geometry as a function of the number of nodes on each side of the grid.

Having found R_{ep}, K_m and K_i it is now possible to find the mesh voltage E_m as follows. The resistance R_{ep} is substituted into the fault current equations (H.1.1) and (H.1.2), to give the total fault current I_f. The earth return circuit between the pole at point A in Figure 13.12 and the earthing connection at point B at the source is a parallel circuit of the resistances to earth R_{en} and R_{ep} and the overhead earth return line impedance Z_{eoh}. The parallel combination is:-

$$Z_e = \frac{Z_{\mathrm{eoh}}(R_{\mathrm{en}} + R_{\mathrm{ep}})}{Z_{\mathrm{eoh}} + R_{\mathrm{en}} + R_{\mathrm{ep}}} = 11.019 + j5.5597 \text{ ohms}$$

Where

$$Z_{\mathrm{eoh}} = \text{route length } \times Z_{0\mathrm{pkm}} = 10.5 + j22.5 \text{ ohms.}$$

The proportion of current entering the ground I_{fe} is therefore:-

$$|I_{fe}| = |Z_e I_f/(R_{en} + R_{ep})|$$
$$= 0.6826 \times 1057.4 = 721.74 \text{ amps.}$$

See Case C.3 in Tables H.1c and H.1d.

The corner mesh voltage E_m in the centre of the mesh at any corner of the grid is: -

$$E_m = \frac{\rho I_{fe} K_m K_i}{L_g + 1.15 L_r} = 1853.6 \text{ volts}$$

Table H.1c. Data for earth resistance, touch voltage, ground potential rise and corner mesh voltage for different grid and rod designs

Case	Resistivities		Area A	dr	hs	h	Nrod	l_r	N_{mesh}
	ρ	ρ_s							
A.1	100	1000	36	0.02	0.2	0.5	2	10	3
A.2	100	1000	64	0.02	0.2	0.5	2	10	4
A.3	100	1000	100	0.02	0.2	0.5	4	10	5
A.4	100	1000	144	0.02	0.2	0.5	4	10	6
A.5	100	1000	196	0.02	0.2	0.5	5	10	7
A.6	100	1000	256	0.02	0.2	0.5	5	10	8
B.1	1000	5000	36	0.02	0.2	0.5	2	10	3
B.2	1000	5000	64	0.02	0.2	0.5	2	10	4
B.3	1000	5000	100	0.02	0.2	0.5	4	10	5
B.4	1000	5000	144	0.02	0.2	0.5	4	10	6
B.5	1000	5000	196	0.02	0.2	0.5	5	10	7
B.6	1000	5000	256	0.02	0.2	0.5	5	10	8
C.1	1000	5000	36	0.02	0.2	0.5	2	50	3
C.2	1000	5000	64	0.02	0.2	0.5	2	50	4
C.3	1000	5000	100	0.02	0.2	0.5	4	50	5
C.4	1000	5000	144	0.02	0.2	0.5	4	50	6
C.5	1000	5000	196	0.02	0.2	0.5	5	50	7
C.6	1000	5000	256	0.02	0.2	0.5	5	50	8
D.1	1000	5000	36	0.2	0.2	0.5	2	50	3
D.2	1000	5000	64	0.2	0.2	0.5	2	50	4
D.3	1000	5000	100	0.2	0.2	0.5	4	50	5
D.4	1000	5000	144	0.2	0.2	0.5	4	50	6
D.5	1000	5000	196	0.2	0.2	0.5	5	50	7
D.6	1000	5000	256	0.2	0.2	0.5	5	50	8
E.1	1000	5000	36	0.2	0.2	2.0	2	50	3
E.2	1000	5000	64	0.2	0.2	2.0	2	50	4
E.3	1000	5000	100	0.2	0.2	2.0	4	50	5
E.4	1000	5000	144	0.2	0.2	2.0	4	50	6
E.5	1000	5000	196	0.2	0.2	2.0	5	50	7
E.6	1000	5000	256	0.2	0.2	2.0	5	50	8

Table H.1d. Results for earth resistance, touch voltage, ground potential rise and corner mesh voltage for different grid and rod designs

Case	R_{ep}	$E_{touch50}$	GPR	E_m	I_{fe}	I_f
A.1	4.421	361	4796	1214	1085	1217
A.2	3.716	361	4133	914	1112	1229
A.3	3.215	361	3638	613	1132	1238
A.4	2.838	361	5254	509	1147	1245
A.5	2.544	361	2947	412	1158	1250
A.6	2.307	361	2694	343	1168	1254
B.1	44.13	1190	16,842	4271	382	929
B.2	37.11	1190	16,161	3580	435	947
B.3	32.12	1190	15,523	2618	483	964
B.4	28.37	1190	14,936	2338	526	980
B.5	25.43	1190	14,382	2009	565	995
B.6	23.07	1190	13,862	1766	601	1008
C.1	21.33	1190	13,431	3069	630	1020
C.2	18.59	1190	12,644	2953	680	1040
C.3	16.58	1190	11,968	1854	722	1057
C.4	15.02	1190	11,373	1808	757	1072
C.5	13.76	1190	10,841	1541	788	1085
C.6	12.71	1190	10,360	1351	815	1097
D.1	19.28	1190	12,856	3250	667	1035
D.2	16.92	1190	12,087	3103	715	1054
D.3	15.17	1190	11,433	1936	754	1071
D.4	13.80	1190	10,861	1879	787	1085
D.5	12.69	1190	10,351	1595	816	1097
D.6	11.76	1190	10,043	1394	841	1108
E.1	19.24	1190	12,947	3408	678	1035
E.2	16.88	1190	12,073	3286	715	1054
E.3	15.14	1190	11,421	2068	754	1071
E.4	13.78	1190	10,851	2022	787	1085
E.5	12.67	1190	10,343	1729	816	1098
E.6	11.75	1190	9884	1521	841	1109

It is also necessary to relate the corner mesh voltage E_m to the ground potential rise GPR of the grid and rod system.

$$\text{GPR} = I_{\text{fe}} R_{\text{ep}} = 11967.9 \text{ volts}$$

Hence expressing E_m as a percentage (E_{mpc}) of the GPR gives:-

$$E_{\text{mpc}} = \frac{E_m \times 100}{\text{GPR}} = 15.49\%$$

Comments on the results

Case A. The resistivity of the lower soil was chosen to be a moderate value of 100 ohm-m. Low values of resistance to earth at the pole, R_{ep}, were easily obtained. The main criterion is that the corner mesh voltage E_m must be less than the 50 kg touch voltage $E_{touch50}$. Only one case A.6 satisfies this criteria, 343 volts is less than 361 volts. This case requires a relatively large site area of 256 m^2 for a pole and its associated equipment.

Case B. The resistivities were raised to values typical of dry and arid locations. In all cases the resistance to earth could not be reduced to 5 ohms. Again the 'mesh-touch' criteria could not be achieved. A satisfactory design could not be found.

Case C. The rods were driven deeper into the ground, to a depth of 50 m. The increase in depth by a factor of 5 only reduced the resistances to about 50% of their values in Case B. Some reduction in the corner mesh voltage was obtained.

Case D and E. Increasing the rod diameter by a factor of 10 and burying the grid deeper by a factor of 4 made very little difference to the results in Case C.

Necessary improvements.

In view of the difficulties found in providing a satisfactory solution, it would be advisable to include the 'ladder' network referred to in H.1 and re-calculate the results. If this does not improve the situation significantly then two main improvements should be considered. Firstly use a neutral earth resistor at the source to restrict the earth return current to between 50 and 100 amps. This will directly reduce E_m to values below $E_{touch50}$. Secondly reduce the fault clearing time t_s from 0.5 to 0.2 seconds. This may not be easily achieved. A sensitive earth current protective relay may need to be installed, e.g. core balance 51 N or 50 N relay. Reducing t_s to 0.2 seconds will raise the $E_{touch50}$ by a factor of 1.581, which in Cases B to E causes $E_{touch50}$ to become 1881 volts. This allows several of the cases to become feasible, e.g. B6, C3, C4, C5 and C6. The whole exercise should be repeated for other poles along the route so as to check whether or not a poorer situation could exist.

It may be noted that the simple treatment of the zero sequence impedances in the example would tend to be more appropriate to a remote switching station fed by an underground cable.