Ground Grid Studies

Theoretical Concepts

It is often assumed that any grounded object can be safely touched. A low substation 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 to which a person might be exposed. Therefore, a substation of relatively low ground resistance may be dangerous, while another substation with very high resistance may be safe or can be made safe by careful design.

The circumstances that make electric shock accidents possible are

- Relatively high fault current to ground in relation to the area of ground system~~,~~ and its high resistance to remote earth.
- Soil resistivity and distribution of ground current such that high potential gradients may occur at certain points at the earth surface.
- Presence of an individual at such a point in time, and in such a position, that the human body is bridging two points of high potential differences.
- Absence of sufficient contact resistance, or other series resistance, which would limit current through the human body to a safe value under the above circumstances.
- Duration of fault and body contact, and hence, of the flow of current through a human body for enough time to cause harm at the given current intensity.

The objectives of safe grounding is to

- Provide means to carry electric currents into the earth under normal and fault conditions without exceeding any operating and equipment limits or adversely affecting continuity of service.
- Assure that a person in the vicinity of grounded facilities is not exposed to the danger of critical electric shock.

A practical approach to safe grounding thus concerns and strives for controlling the interaction of two grounding systems, as follows

- The intentional ground, consisting of ground electrodes buried at some depth below the earth's surface.
- The accidental ground, temporarily established by a person exposed to a potential gradient in the vicinity of a grounded facility.

Ground Grid Studies

As per IEEE 80 standards, the following terms are defined

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.

Decrement factor (D_f) - 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, accounting for the effect of initial dc offset and its attenuation during the fault.

Effective asymmetrical fault current- The rms value of asymmetrical current wave, integrated over the interval of fault duration where,

IF = Df ×If

Where,

I_F is the effective asymmetrical fault current in A.

I_f is the initial symmetrical ground fault current in A.

D_f is the decrement factor accounting for the effect of DC offset during subtransient period of the fault current wave on an equivalent time basis on the entire fault duration t_f, for t_f in seconds.

Fault current division factor (S_f) - A factor representing the inverse of a ratio of the symmetrical fault current to that portion of the current that flows between the grounding grid and surrounding earth

$$Sf = \frac{Ig}{3Io}$$

Where,

S_f is the fault current division factor.

I_g is the rms symmetrical grid current in A.

I_o is the zero-sequence fault current in A.

Maximum grid current (I_G) - It is defined as the product of decrement factor & the rms grid current in ampere.

$$I_G = D_f \text{ x } Ig$$

Where D_f is the decrement factor for the entire duration of fault t_f.

Ig is the symmetrical grid current in A.

Ground potential rise (GPR) - The maximum electrical potential that a substation grounding grid may attain relative to a distant grounding point assumed to be at the potential of remote earth. This voltage, GPR, is equal to the maximum grid current times the grid resistance.

Ground return circuit - A circuit in which the earth or an equivalent conducting body is utilized to complete the circuit and allow current circulation from or to its current source.

Grounding grid - A system of horizontal ground electrodes that consists of a number of interconnected, bare conductors buried in the earth, providing a common ground for electrical devices or metallic structures, usually in one specific location

Step potential - The difference in surface potential experienced by a person bridging a distance of 1 m with the feet without contacting any grounded object.

Touch potential - The potential difference between the ground potential rise (GPR) and the surface potential at the point where a person is standing while at the same time having a hand in contact with a grounded structure.

Ground Grid Studies

Formulae used in deriving step and touch potentials

8.3 Step and touch voltage criteria

The safety of a person depends on preventing the critical amount of shock energy from being absorbed before the fault is cleared and the system de-energized. The maximum driving voltage of any accidental circuit should not exceed the limits defined as follows. For step voltage the limit is

$$E_{step} = (R_B + 2R_f) \cdot I_B \tag{28}$$

for body weight of 50 kg

$$E_{step50} = (1000 + 6C_s \cdot \rho_s)\frac{0.116}{\sqrt{t_s}} \tag{29}$$

for body weight of 70 kg

$$E_{step70} = (1000 + 6C_s \cdot \rho_s)\frac{0.157}{\sqrt{t_s}} \tag{30}$$

Similarly, the touch voltage limit is

$$E_{touch} = \left(R_B + \frac{R_f}{2}\right) \cdot I_B \tag{31}$$

for body weight of 50 kg

$$E_{touch50} = (1000 + 1.5C_s \cdot \rho_s)\frac{0.116}{\sqrt{t_s}} \tag{32}$$

for body weight of 70 kg

$$E_{touch70} = (1000 + 1.5C_s \cdot \rho_s)\frac{0.157}{\sqrt{t_s}} \tag{33}$$

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)
r_s	is the resistivity of the surface material in Ω·m
t_s	is the duration of shock current in seconds

If no protective surface layer is used, then $C_s = 1$ and $\rho_s = \rho$.

The metal-to-metal touch voltage limits are derived from the touch voltage equations, Equation (32) and Equation (33). Metal-to-metal contact, both hand-to-hand and hand-to-feet, will result in $\rho_s = 0$. Therefore, the total resistance of the accidental circuit is equal to the body resistance, R_B.

With the substitution of $\rho_s = 0$ in the foot resistance terms of Equation (32) and Equation (33), the metal-to-metal touch voltage limit is

for body weight of 50 kg

$$E_{mm-touch50} = \frac{116}{\sqrt{t_s}} \tag{34}$$

for body weight of 70 kg

$$E_{mm-touch70} = \frac{157}{\sqrt{t_s}} \tag{35}$$

where

E_{mm} is the metal-to-metal touch voltage in V

The actual step voltage, touch voltage, or metal-to-metal touch voltage should be less than the respective maximum allowable voltage limits to ensure safety. Hazards from external transferred voltages are best avoided by isolation or neutralizing devices and labeling these danger points as being equivalent to live lines.

Ground Grid Studies

In a system many types of faults occur, however for practical reasons, investigation is confined to single line to ground and line-line to ground faults as these faults occur frequently.
In most cases, the largest value of grid current will result in the most hazardous condition.
The below figures depicts grid current distribution for a single line to ground fault.
When the system neutral is locally grounded, during the fault, grid current flowing is zero since return path is provided as shown in *Figure 1*.

IN AC SUBSTATION GROUNDING

IEEE
Std 80-2000

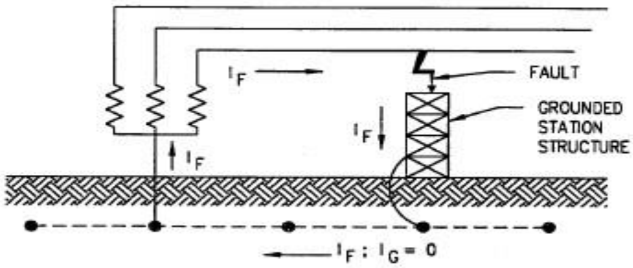


Figure 1

Actual step and touch voltages increases as more percentage of earth fault kA enters the soil for earth fault kA return to remote source neutral. During fault, grid current flowing when the system is grounded at remote location is shown in *Figure 2*.

Similarly, current flowing when the system is grounded locally & also at other points is shown in *Figure 3*.

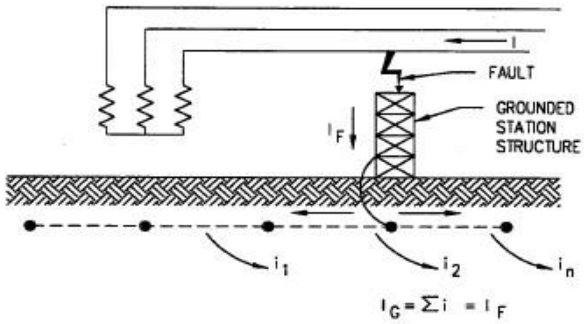


Figure 2

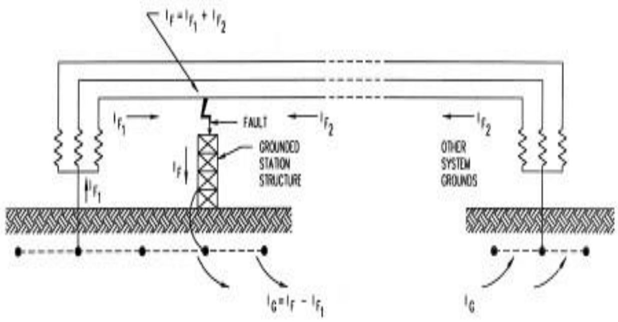


Figure 3

Ground Grid Studies

Typical current distribution for a fault on high voltage side of distribution substation is shown in *Figure 4*.

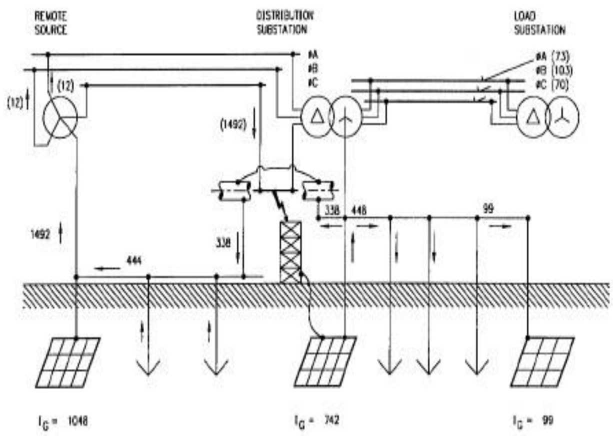


Figure 4

Design parameters for ground grid

The following site dependent parameters have found to have substantial impact on ground grid design i.e. maximum grid current I_G, fault duration t_f, shock duration t_s, soil resistivity ρ, surface material resistivity (ρ_s), and grid geometry. Several parameters define the geometry of the grid, but the area of the grounding system, the conductor spacing, and the depth of the ground grid have the most impact on the mesh voltage, while parameters such as the conductor diameter and the thickness of the surfacing material have less impact.

- In determining maximum grid fault current, consideration should be given to the resistance of the ground grid, division of the ground fault current between the alternate return paths and the grid, and the decrement factor.
- The fault duration and shock duration are normally assumed equal, unless the fault duration is the sum of successive shocks, such as from reclosures. The choices t_f and t_s should result in the most pessimistic combination of fault current decrement factor and allowable body current. Typical values for t_f and t_s range from 0.25 to 1.0 s.
- The grid resistance and the voltage gradients within a substation are directly dependent on the soil resistivity because in reality soil resistivity will vary horizontally as well as vertically. A layer of surface material helps in limiting the body current by adding resistance to the equivalent body resistance.
- The area of the grounding system is the single most important geometrical factor in determining the resistance of the grid. The larger the area grounded, the lower the grid resistance and, thus, the lower the GPR.

To increase resistivity between soil and feet of the persons in substation, high resistivity material such as gravel is spread on the earth's surface above the ground grid.

Tolerable voltages can be increased by increasing ρ_s, reducing t_s and also by reducing length of buried ground grid conductors

Ground Grid Studies

Purpose and description

The purpose of this module is to establish, as a basis for design, the safe limits of potential differences that can exist in a substation under fault and normal conditions between points that can be contacted by the human body.

Input Data Example 1

Annex B

(informative)

Sample calculations

This annex illustrates the application of equations, tables, and graphs for designing a substation grounding system. The specific objectives are as follows:

a) To show the application of principal equations of this guide for several refinements of the design concept toward a satisfactory final design solution.

b) To illustrate the typical differences to be expected between results obtained using the simplified calculations of this guide and the more rigorous computer solutions.

c) To illustrate such design conditions for which the use of simplified calculations of this guide would not be appropriate for a safe design, as some of the equations may only be used with caution.

In view of these objectives, the following series of examples (B.1–B.4) neither represents, nor is intended to be, the best or most efficient way to design a grounding system.

A computer-based grounding program described in EPRI TR-100622 [B63] was used to model the grids in these examples.

For the series of examples (B.1–B.4), the design data are as follows:

Fault duration t_f	= 0.5 s
Positive sequence equivalent system impedance Z_1	= 4.0 + j10.0 Ω (115 kV side)
Zero sequence equivalent system impedance Z_0	= 10.0 + j40.0 Ω (115 kV side)
Current division factor S_f	= 0.6
Line-to-line voltage at worst-fault location	= 115,000 V
Soil resistivity ρ	= 400 Ω·m
Crushed rock resistivity (wet) ρ_s	= 2500 Ω·m
Thickness of crushed rock surfacing h_s	= 0.102 m (4 in)
Depth of grid burial h	= 0.5 m
Available grounding area A	= 63 m × 84 m
Transformer impedance, (Z_1 and Z_0) (Z = 9% at 15 MVA, 115/13 kV)	= 0.034 + j1.014 Ω (13 kV)

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.

B.1 Square grid without ground rods—Example 1

Using the step-by-step procedure as described in 16.4 and illustrated in Figure 33, the following design evaluations can be made.

Ground Grid Studies

Step 1: Field data. Although the substation grounding grid is to be located within a rectangle of 63 m × 84 m (5292 m^2), for the initial design assessment it may be expedient to assume a square 70 m × 70 m grid with no ground rods. Consequently, the area occupied by such a grid is $A = 4900\ m^2$. An average soil resistivity of 400 Ω·m is assumed, based on soil resistivity measurements.

Step 2: Conductor size. Ignoring the station resistance, the symmetrical ground fault current $I_f = 3I_0$, is computed using Equation (67)

$$I_0 = \frac{E}{3 \cdot R_f + (R_1 + R_2 + R_0) + j(X_1 + X_2 + X_0)} \tag{B.1}$$

For the 115 kV bus fault

$$3I_0 = \frac{(3)(115,000/\sqrt{3})}{3(0) + (4.0 + 4.0 + 10.0) + j(10.0 + 10.0 + 40.0)}$$

and, hence

$|3I_0| = 3180$ A, and the X/R ratio = 3.33

For the 13 kV bus fault, the 115 kV equivalent fault impedances must be transferred to the 13 kV side of the transformer. It should be noted that, due to the delta-wye connection of the transformer, only the positive sequence 115 kV fault impedance is transferred. Thus

$$Z_1 = \left(\frac{13}{115}\right)^2 (4.0 + j10.0) + 0.034 + j1.014 = 0.085 + j1.142$$

$$Z_0 = 0.034 + j1.014$$

$$3I_0 = \frac{(3)(13,000/\sqrt{3})}{3(0) + (0.085 + 0.085 + 0.034) + j(1.142 + 1.142 + 1.014)}$$

and, hence

$$|3I_0| = 6814 \text{ A, and the } X/R \text{ ratio is } 16.2$$

The 13 kV bus fault value of 6814 A should be used to size the grounding conductor.

Using Table 10 for a fault duration of 0.5 s, the decrement factor D_f is approximately 1.0; thus, the rms asymmetrical fault current is also 6814 A. This current magnitude will be used to determine the minimum diameter of ground conductors.

Assuming the use of copper wire and an ambient temperature of 40 °C, Equation (42) and Table 2 are used to obtain the required conductor cross-sectional area. For 0.5 s and a melting temperature of 1084 °C for hard-drawn copper, the required cross-sectional area in circular mils is

$$A_{kcmil} = I \cdot K_f \sqrt{t_c} \tag{B.2}$$

$$A_{kcmil} = 6.814 \cdot 7.06\sqrt{0.5} = 34.02\,kcmil$$

Ground Grid Studies

34.02 kcmil = 17.2 mm^2

Because $A_{mm^2} = \pi d^2/4$, the conductor diameter is approximately 4.7 mm, or 0.0047 m if it is solid conductor.

Based on this computation, a copper wire as small as size #4 AWG could be used, but due to the mechanical strength and ruggedness requirements, a larger 2/0 AWG stranded conductor with diameter d = 0.0105 m (0.414 in) is usually preferred as a minimum.

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.

Using Equation (41) and Table 1 gives

$$A_{kcmil} = I\frac{197.4}{\sqrt{\left(\frac{TCAP}{t_c\alpha_r\rho_r}\right)\ln\left(\frac{K_o+T_m}{K_o+T_a}\right)}} \tag{B.3}$$

$$A_{kcmil} = 6.184\frac{197.4}{\sqrt{\frac{3.85}{(0.5)(0.00378)(5.862)}\left[\ln\left(\frac{245+700}{245+40}\right)\right]}} = 65.9\,kcmils \text{ or } 33.4\text{ mm}^2$$

Select next available size in ETAP i.e.35 mm^2

In this case, d_{min} = 6.5 mm, or 0.0065 m solid conductor, which is less than d = 0.01 m desired. Hence, a 30% copper-clad steel wire of approximately 2/0 AWG size is a viable alternative for grid wires, even if a conservative maximum temperature limit of 700 °C is imposed.

Step 3: Touch and step criteria. For a 0.102 m (4 in) layer of crushed rock surfacing, with resistivity of 2500 Ω·m, and for an earth with resistivity of 400 Ω·m, the reflection factor K is computed using Equation (21)

$$K = \frac{\rho-\rho_s}{\rho+\rho_s} \tag{B.4}$$

$$K = \frac{400-2500}{400+2500} = -0.72$$

Figure 11 indicates for K = –0.72 the resistivity of crushed rock is to be derated by a reduction factor C_s = 0.74. The reduction factor C_s can also be approximated using Equation (27)

$$C_s = 1-\frac{0.09\left(1-\frac{\rho}{\rho_s}\right)}{2h_s+0.09} \tag{B.5}$$

$$C_s = 1-\frac{0.09\left(1-\frac{400}{2500}\right)}{2(0.102)+0.09}$$

Ground Grid Studies

Assuming that for the particular station the location of grounded facilities within the fenced property[17] 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:

$$E_{step70} = (1000 + 6C_s\rho_s)0.157/\sqrt{t_s} \tag{B.6}$$

$$E_{step70} = [(1000 + 6(0.74)2500)]0.157/\sqrt{0.5} = 2686.6\text{ V}$$

$$E_{touch50}\cancel{E_{step70}} = (1000 + 1.5C_s\rho_s)0.157/\sqrt{t_s} \tag{B.7}$$

$$E_{touch70}\cancel{E_{step70}} = [(1000 + 1.5(0.74)2500)]0.157/\sqrt{0.5} = 838.2\text{ V}$$

Step 4: Initial design. Assume a preliminary layout of 70 m × 70 m grid with equally spaced conductors, as shown in Figure B.1, with spacing $D = 7$ m, grid burial depth $h = 0.5$ m, and no ground rods. The total length of buried conductor, L_T, is 2 × 11 × 70 m = 1540 m.

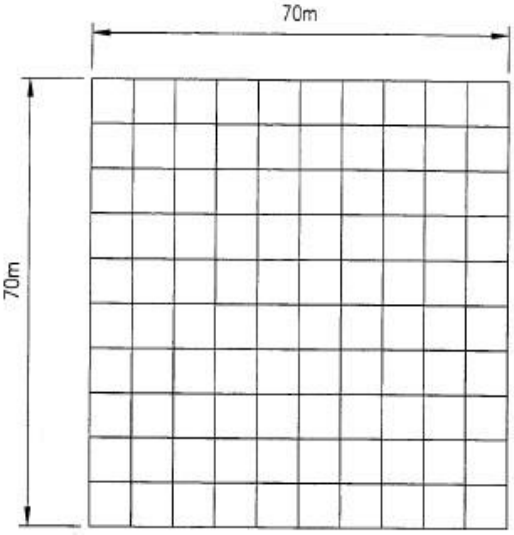


Figure B.1—Square grid without ground rods

Step 5: Determination of grid resistance. Using Equation (52) for $L = 1540$ m, and grid area $A = 4900\text{ m}^2$, the resistance is

$$R_g = \rho\left[\frac{1}{L_T} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1 + h\sqrt{20/A}}\right)\right] \tag{B.8}$$

[17] That is, not accessible to the general public.

Ground Grid Studies

$$R_g = 400\left[\frac{1}{1540} + \frac{1}{\sqrt{20\cdot 4900}}\left(1 + \frac{1}{1+0.5\sqrt{20/4900}}\right)\right] = \boxed{2.78\ \Omega}$$

Step 6: Maximum grid current I_G. Per the procedure and definitions of 15.1, the maximum grid current I_G is determined by combining Equation (63) and Equation (64). Referring to Step 2, for $D_f = 1.0$, and the given current division factor $S_f = 0.6$,

$$S_f = \frac{I_g}{3\cdot I_0} \tag{B.9}$$

and

$$I_G = D_f \cdot I_g \tag{B.10}$$

Though the 13 kV bus fault value of 6814 A is greater than the 115 kV bus fault value of 3180 A, it is recalled from Clause 15 that the wye-grounded 13 kV transformer winding is a "local" source of fault current and does not contribute to the GPR. Thus, the maximum grid current is based on 3180 A.

$$I_G = D_f \cdot S_f \cdot 3 \cdot I_0 \tag{B.11}$$

$$I_G = (1)(0.6)(3180) = 1908\ \text{A}$$

Step 7: GPR. Now it is necessary to compare the product of I_G and R_g, or GPR, to the tolerable touch voltage, $E_{touch70}$

$$GPR = I_G \cdot R_g \tag{B.12}$$

$$\boxed{GPR = 1908 \cdot 2.78 = 5304\ \text{V}}$$

which far exceeds 838 V, determined in Step 3 as the safe value of $E_{touch70}$. Therefore, further design evaluations are necessary.

Step 8: Mesh voltage. Using Equation (81) through Equation (83), K_m is computed

$$K_m = \frac{1}{2\cdot\pi}\cdot\left[\ln\left[\frac{D^2}{16\cdot h\cdot d} + \frac{(D+2+h)^2}{8\cdot D\cdot h} - \frac{h}{4\cdot d}\right] + \frac{K_{ii}}{K_h}\cdot\ln\left[\frac{8}{\pi(2\cdot n-1)}\right]\right] \tag{B.13}$$

where

$$K_{ii} = \frac{1}{(2\cdot n)^{\frac{2}{n}}} \tag{B.14}$$

$$K_{ii} = \frac{1}{(2\cdot 11)^{2/11}} = 0.57$$

and

$$K_h = \sqrt{1 + \frac{h}{h_0}} \tag{B.15}$$

Ground Grid Studies

$$K_h = \sqrt{1+\frac{0.5}{1.0}} = 1.225$$

$$K_m = \frac{1}{2\pi}\cdot\left[\ln\left[\frac{7^2}{16\cdot 0.5\cdot 0.01}+\frac{(7+2\cdot 0.5)^2}{8\cdot 7\cdot 0.01}-\frac{0.5}{4\cdot 0.01}\right]+\frac{0.57}{1.225}\ln\left[\frac{8}{\pi(2\cdot 11-1)}\right]\right]$$

The factor K_i is computed using Equation (84) through Equation (89)

$$K_i = 0.644 + 0.148\cdot n \tag{B.16}$$

where

$$n = n_a\cdot n_b\cdot n_c\cdot n_d \tag{B.17}$$

$$n_a = \frac{2\cdot L_C}{L_P} \tag{B.18}$$

$$n_a = \frac{2\cdot 1540}{280}$$

$n_b = 1$ for square grid
$n_c = 1$ for square grid
$n_d = 1$ for square grid

and

$$n = 11\cdot 1\cdot 1\cdot 1 = 11$$

$$K_i = 0.644 + 0.148\cdot 11 = 2.272$$

Finally, E_m is computed using Equation (80) and Equation (90)

$$E_m = \frac{\rho\cdot I_G\cdot K_m\cdot K_i}{L_C + L_R} \tag{B.19}$$

$$E_m = \frac{400\cdot 1908\cdot 0.89\cdot 2.272}{1540} = \boxed{1002.1\text{ V}}$$

Step 9: E_m vs. E_{touch}. The mesh voltage is higher than the tolerable touch voltage (that is, 1002.1 V versus 838.2 V). The grid design must be modified.

For comparison, the EPRI TR-100622 [B63] computer program resulted in 2.67 Ω and 984.3 V for the grid resistance and touch voltage, respectively, for this example.

Ground Grid Studies

Example 2

B.2 Square grid with ground rods—Example 2

In the previous example, B.1, Step 10 of the design procedure has not been reached due to the failure to meet the criterion of Step 9. Generally, there are two approaches to modifying the grid design to meet the tolerable touch voltage requirements

a) Reduce the GPR to a value below the tolerable touch voltage or to a value low enough to result in a value of E_m below the tolerable touch voltage.

b) Reduce the available ground fault current.

Usually reduction of the available ground fault current is difficult or impractical to achieve, so the grid is modified by changing any or all of the following: grid conductor spacing, total conductor length, grid depth, addition of ground rods, etc. In this example, the preliminary design will be modified to include 20 ground rods, each 7.5 m (24.6 ft) long, around the perimeter of the grid, as shown in Figure B.2.

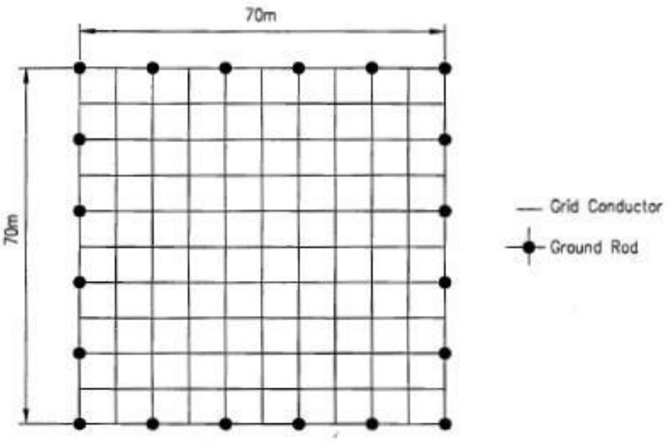


Figure B.2—Square grid with 20 7.5 m rods

Step 5. Using Equation (52) for $L_T = 1540 + 20 \cdot 7.5 = 1690$ m, and $A = 4900$ m^2 yields the following value of grid resistance R_g:

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

$$R_g = 400\left[\frac{1}{1690}+\frac{1}{\sqrt{20\cdot 4900}}\left(1+\frac{1}{1+0.5\sqrt{\frac{20}{4900}}}\right)\right] = 2.75\ \Omega$$

Steps 6 and 7. The revised GPR is (1908)(2.75) = 5247 V, which is still much greater than 838.2 V.

Take diameter of ground rod as typical=2 cm

Ground Grid Studies

Step 8. Using Equation (81) and Equation (83), K_m is computed

$$K_m = \frac{1}{2 \cdot \pi} \cdot \left[\ln\left[\frac{D^2}{16 \cdot h \cdot d} + \frac{(D+2 \cdot h)}{8 \cdot D \cdot d} - \frac{h}{4 \cdot d}\right] + \frac{K_{ii}}{K_h} \cdot \ln\left[\frac{8}{\pi(2 \cdot n - 1)}\right]\right] \quad \text{(B.21)}$$

where

$K_{ii} = 1.0$ with rods

and

$$K_h = \sqrt{1 + \frac{h}{h_0}} \quad \text{(B.22)}$$

$$K_h = \sqrt{1 + \frac{0.5}{1.0}} = 1.225$$

$$K_m = \frac{1}{2\pi}\left[\ln\left[\frac{7^2}{16 \cdot 0.5 \cdot 0.01} + \frac{(7+2 \cdot 0.5)^2}{8 \cdot 7 \cdot 0.01} - \frac{0.5}{4 \cdot 0.01}\right] + \frac{1.0}{1.225}\ln\left[\frac{8}{\pi(2 \cdot 11 - 1)}\right]\right] = 0.77$$

This time, E_m is computed using Equation (80) and Equation (91)

$$E_m = \frac{\rho \cdot I_G \cdot K_m \cdot K_i}{L_C + \left[1.55 + 1.22 \cdot \left(\frac{L_r}{\sqrt{L_x^2 + L_y^2}}\right)\right] \cdot L_R} \quad \text{(B.23)}$$

$$E_m = \frac{400 \cdot 1908 \cdot 0.77 \cdot 2.272}{1540 + \left[1.55 + 1.22\left(\frac{7.5}{\sqrt{70^2 + 70^2}}\right)\right]150} = 747.4 \text{ V}$$

Because the step voltage has not been calculated yet, Equation (89) and Equation (92) through Equation (94) are used to compute K_i, E_S, L_S, and K_s, respectively. Note that the value for K_i is still 2.272 (same as for mesh voltage).

$$K_s = \frac{1}{\pi}\left[\frac{1}{2 \cdot h} + \frac{1}{D+h} + \frac{1}{D}(1 - 0.5^{n-2})\right] \quad \text{(B.24)}$$

$$K_s = \frac{1}{\pi}\left[\frac{1}{2 \cdot 0.5} + \frac{1}{7+0.5} + \frac{1}{7}(1 - 0.5^{11-2})\right] = 0.406$$

Then

$$E_s = \frac{\rho \cdot I_G \cdot K_s \cdot K_i}{0.75 \cdot L_C + 0.85 \cdot L_R} \quad \text{(B.25)}$$

$$E_s = \frac{400 \cdot 1908 \cdot 0.406 \cdot 2.272}{0.75 \cdot 1540 + 0.85 \cdot 150} = 548.9 \text{ V}$$

Step 9: E_m vs. E_{touch}. Now the calculated corner mesh voltage is lower than the tolerable touch voltage (747.4 V versus 838.2 V), and we are ready to proceed to Step 10.

Step 10: E_S vs. E_{step}. The computed E_s is well below the tolerable step voltage determined in Step 3 of Example 1. That is, 548.9 V is much less than 2686.6 V.

Step 11: Modify design. Not necessary for this example.

Step 12: Detailed design. A safe design has been obtained. At this point, all equipment pigtails, additional ground rods for surge arresters, etc., should be added to complete the grid design details.

For comparison, the computer program of EPRI TR-100622 [B63] resulted in 2.52 Ω, 756.2 V and 459.1 V for the grid resistance, touch voltage and step voltage, respectively, for this example.

Ground Grid Studies

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

Ground Grid Studies

Procedure

Inputs required in Ground Grid Study (taken from appendix B of IEEE80 & shown from pages 6 to 14 of this exercise)

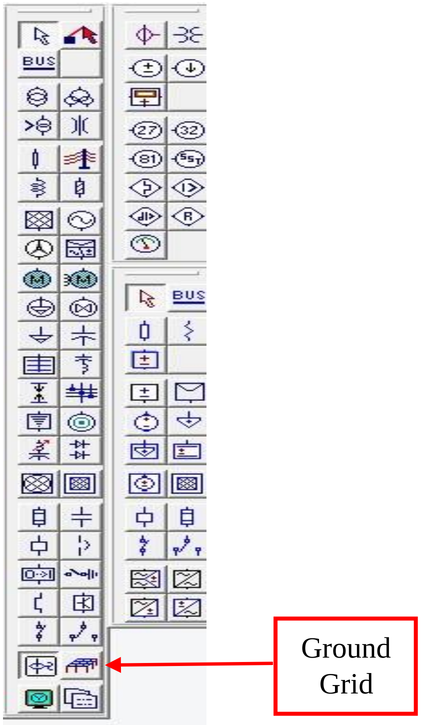
Parameters	Value			Page No	
Inputs without ground rod					
Basic soil resistivity Data					
	Resistivity	**Depth**			
Surface material: Crushed Rock	2500 ohm-meter	0.102	meter	**6**	
Top layer: Moist soil	400 ohm-meter	5	meter	**6**	Assumed
Lower layer: Moist soil	400 ohm-meter				Assumed
Grid & conductor data					
Grid size x * y (m)	70m x 70m			**7**	
Spacing between conductors	7	meter			
No of conductors in x direction	: (70/7) +1=11	Number			
No of conductors in y direction	: (70/7) +1=11	Number			
Conductor size	35	mm^2	Eq. B.3	**9**	
Conductor ambient temperature for selecting conductor size	40	Deg C		**7**	
Depth of grid burial	0.5	meter		**6**	
Study case data					
Wight of a person	70	kg		**9**	
Conductor ambient temperature	40	Deg C		**7**	Also see above conductor data
Fault duration to determine decrement factor	tf = 0.5	sec		**6**	
duration of fault for sizing ground conductors	tc = 0.5	sec			Assumed
duration of shock current to determine permissible levels for the human body	ts = 0.5	sec			Assumed
Fault current	3180	Amp		**7**	
X/R	3.33			**7**	
Current Division factor Sf	0.6	pu		**6**	
Ground rod input:					
No rods along periphery	20	number		**12**	
Depth of ground rod	7.50	meter		**12**	

Ground Grid Studies

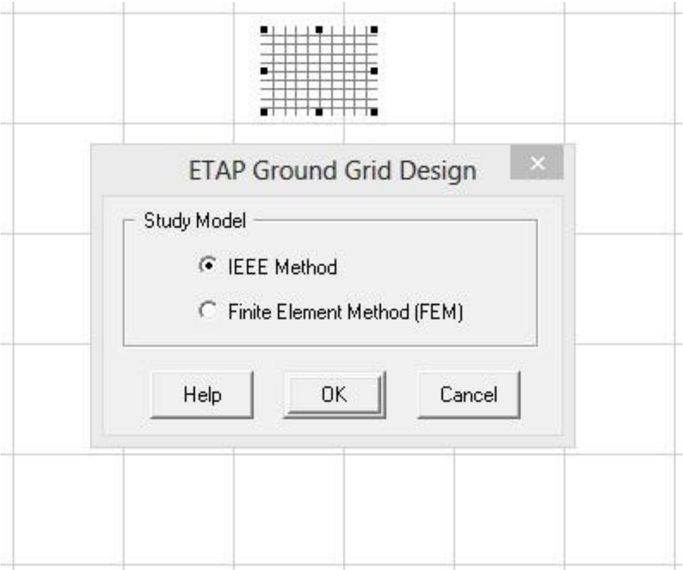
Study Model- IEEE method.

Case 1- Square grid with ground rods (input data as per Example-1).

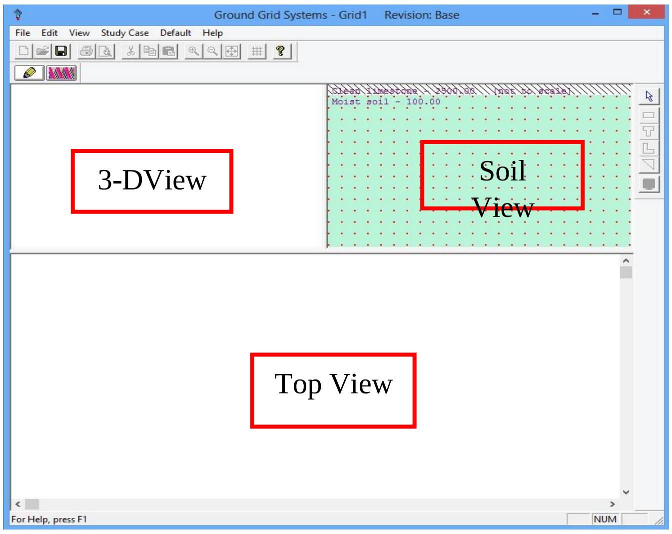
1. Drag and place Ground Grid on OLV.



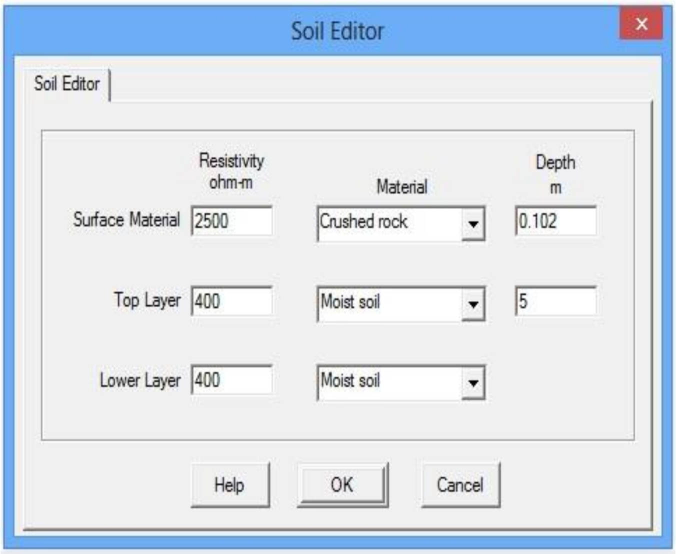
2. Double click on the Grid1, select Study Model as IEEE method to get Ground Grid System Revision: Base page as shown below.



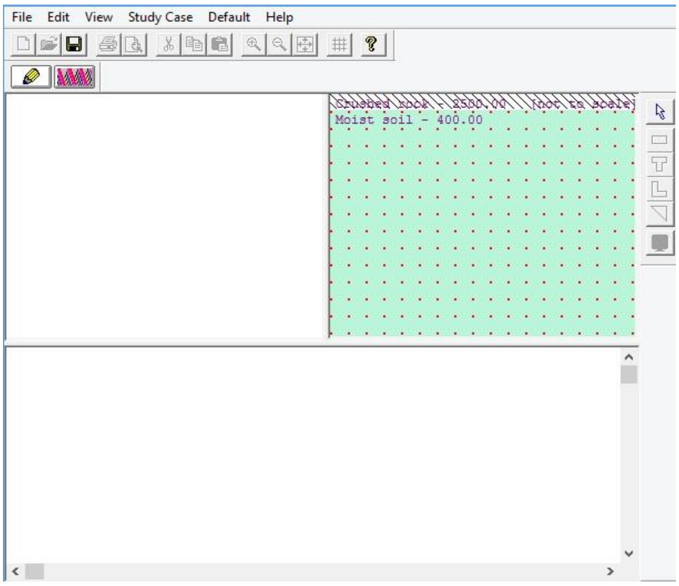
Ground Grid Studies



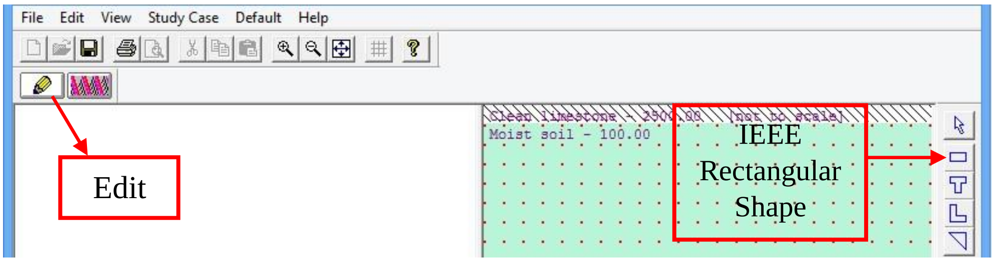
3. Double click on Soil View and enter data in Soil Editor shown below.



Ground Grid Studies

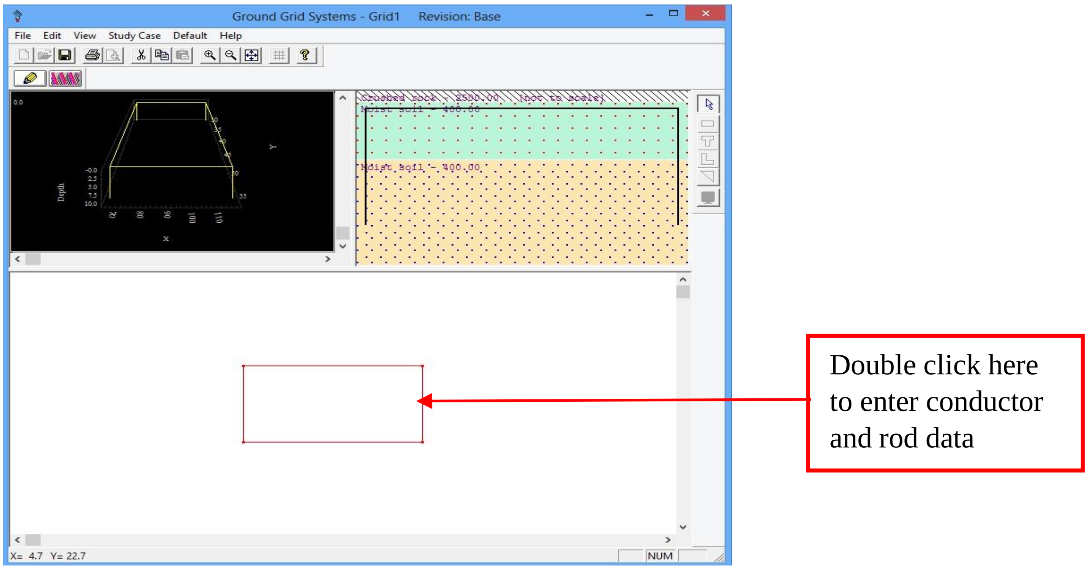


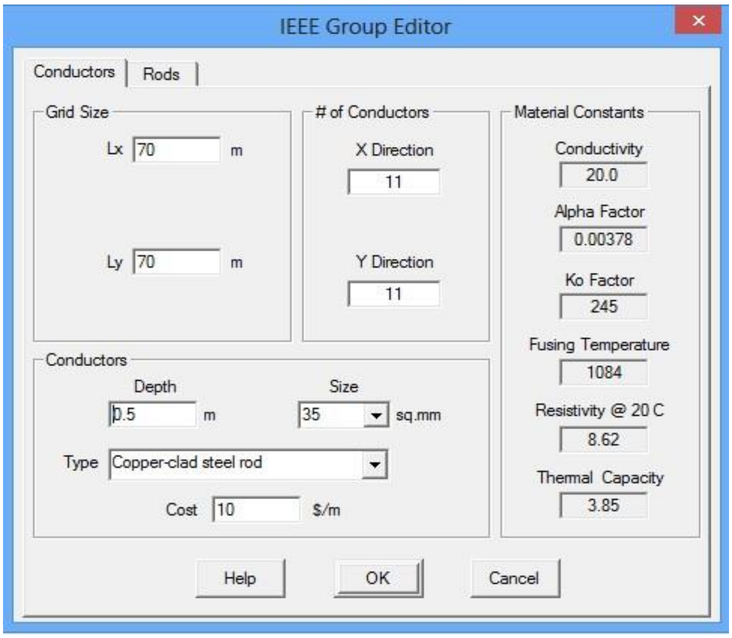
4. Go to Edit mode, select IEEE Rectangle Grid and place it on the top view as shown below.



5. Double click on top view and enter the conductor data in the Conductors page as shown below.

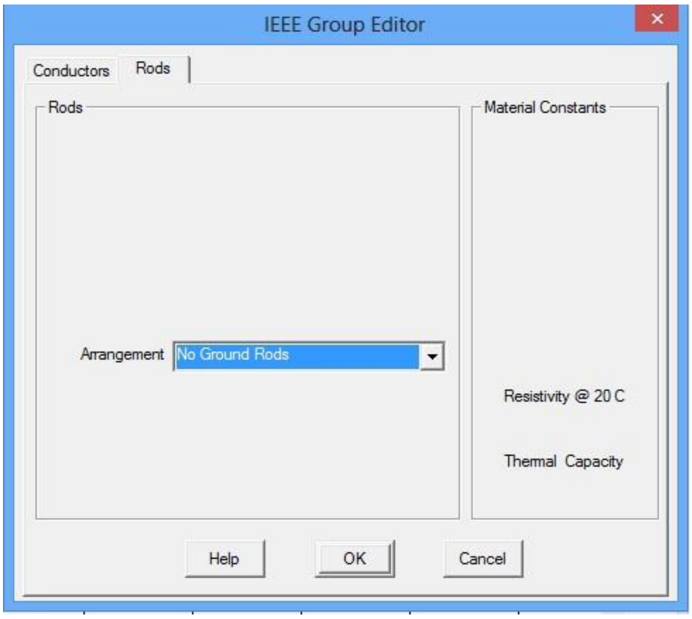
Ground Grid Studies

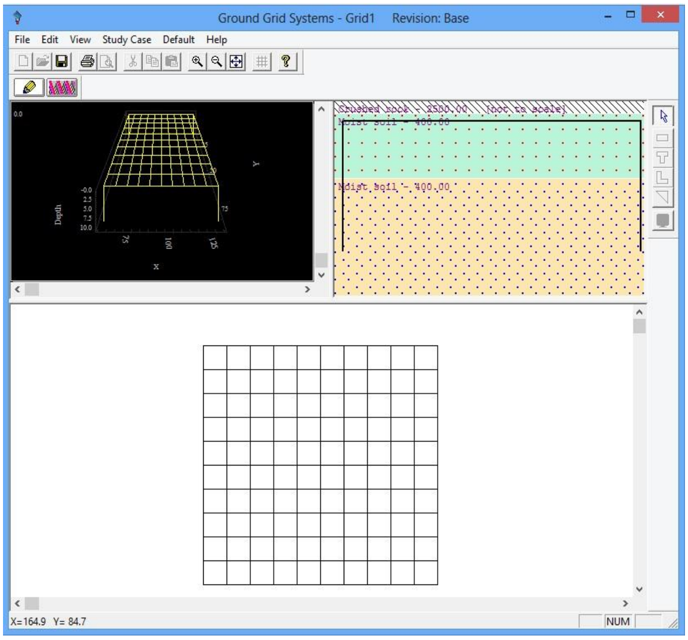




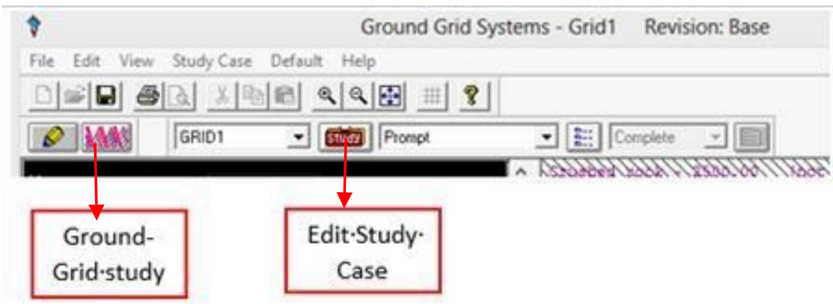
6. Go to Rods page and select the Arrangement from the drop down button as shown below.

Ground Grid Studies

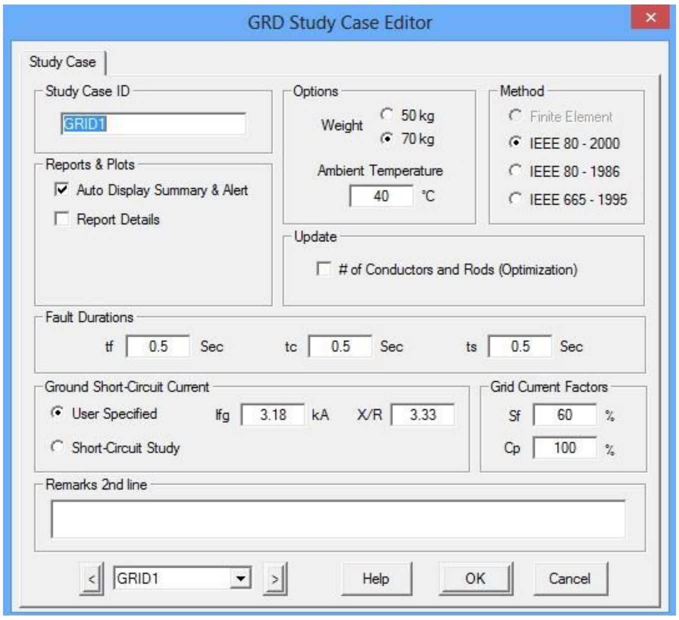




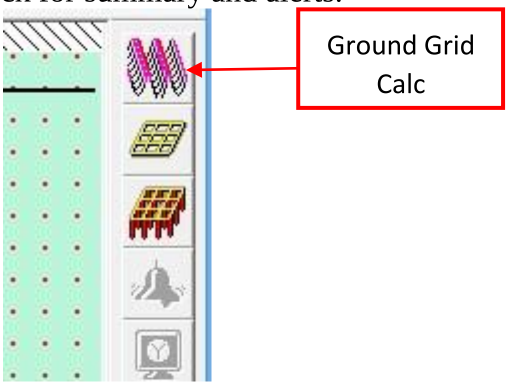
7. Click on Ground-Grid Study, go to Edit Study Case and enter the data shown below.

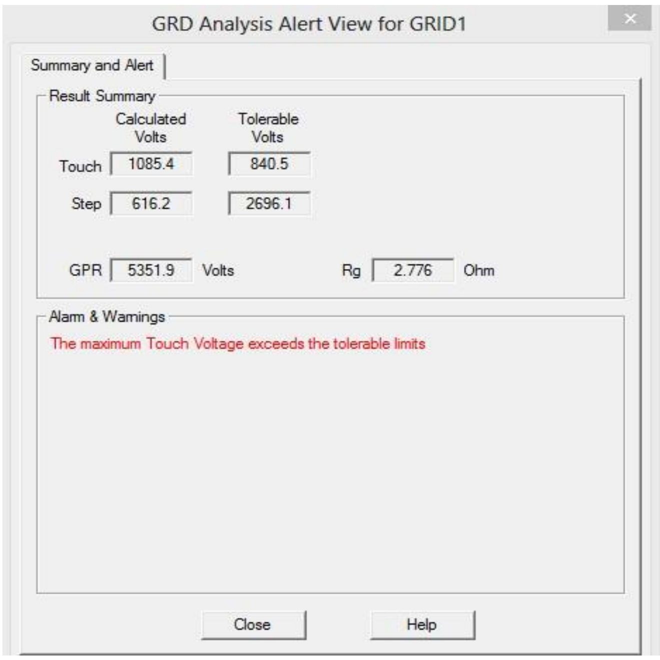


Ground Grid Studies



8. Run Ground Grid Calc and check for summary and alerts.





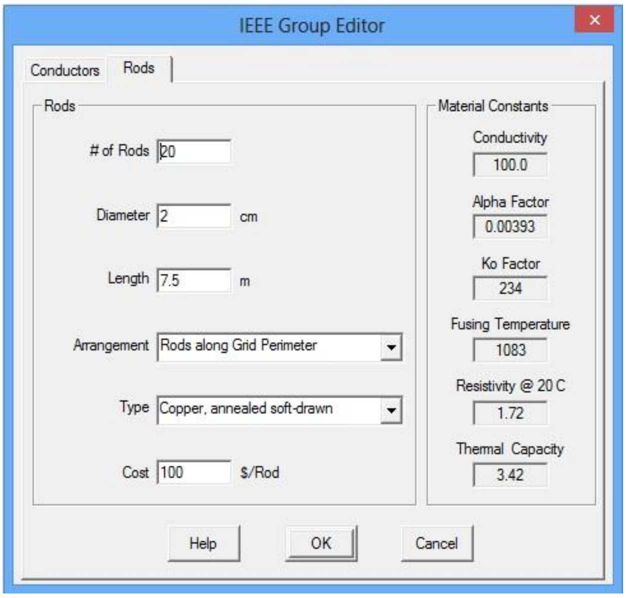
Ground Grid Studies

9. Comparison of results obtained with IEEE 80 standard results for Example1 attached as input data is shown in table below.

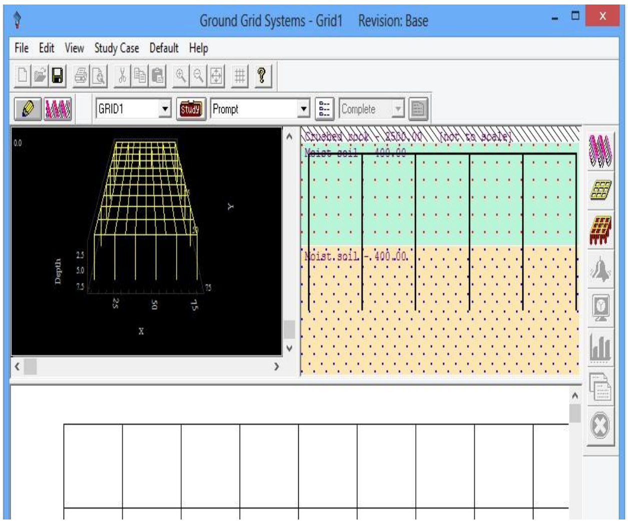
	IEEE-80 standard		ETAP results using IEEE method	
	Tolerable volts	Calculated volts	Tolerable volts	Calculated volts
Touch Potential in volts	838.2	1002.1	840.5	1085.4
Step Potential in volts	2686.6	Not calculated	2696.1	616.2
GPR in volts	5304		5351.9	
Ground resistance R_g (ohms)	2.78		2.776	

Case 2- Square grid with ground rods (input data as per Example-2).

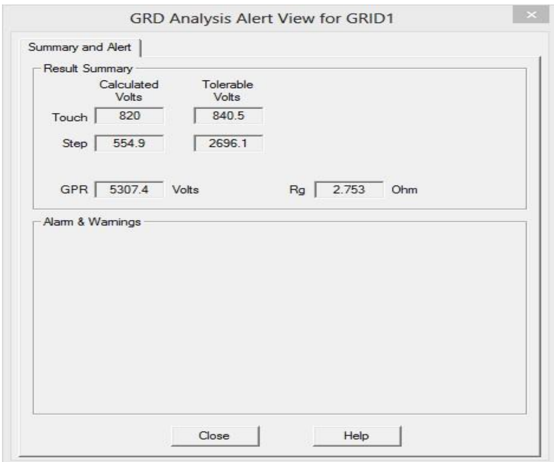
1. Double click on Top view and enter the data in IEEE Group Editor as shown in Rod page. Conductor data being same as in case 1.



Ground Grid Studies



2. Run Ground-Grid Calc and check for alerts.



3. Comparison of results obtained with IEEE 80 standard results for Example2 attached as input data is shown in table below.

	IEEE-80 standard		ETAP results using IEEE method	
	Tolerabl e volts	**Calculated volts**	**Tolerable volts**	**Calculated volts**
Touch Potential in volts	838.2	1002.1	840.5	820
Step Potential in volts	2686.6	548.9	2696.1	554.9
GPR in volts	5304		5307.4	
Ground resistance R_g (ohms)	2.75		2.752	

As per Example1 & Example2 given in the input data, IEEE considers decrement factor to be unity for calculations and ETAP computes decrement factor according the equation given below.

$$Df = \sqrt{1 + \frac{Ta}{tf}\left(1 - e^{-2tf/Ta}\right)}$$

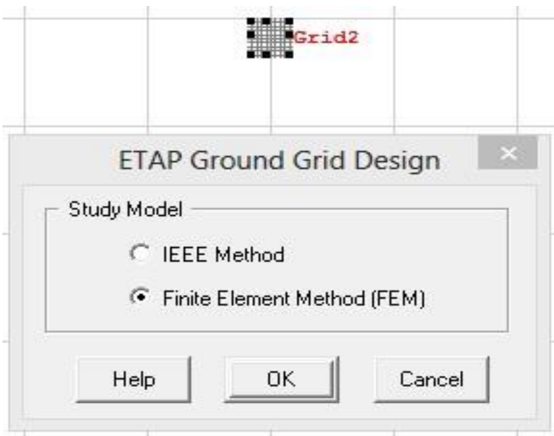
Ground Grid Studies

Considering inputs as X/R=3.33 for a 50Hz system for a fault duration of 0.5s, decrement factor obtained as per the equation is 1.011 as shown in table below.
Therefore, ETAP results of GPR deviate with that of IEEE calculations.

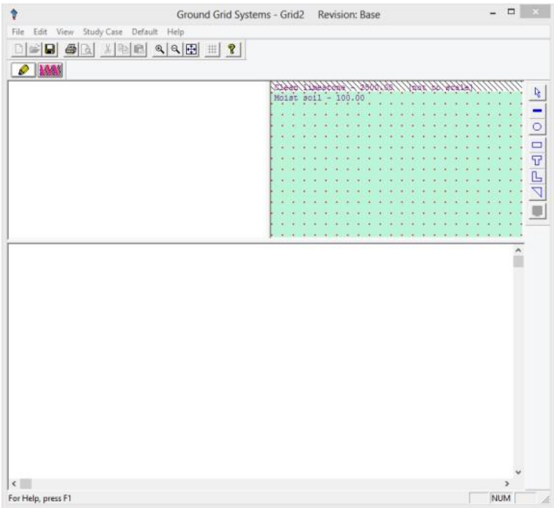
X/R		3.33	
Frequency in Hz		50	
D_f	**T_a=wL/R**	**T_f**	**Calculated D_f**
1	0.010599719	0.1	1.052
1	0.010599719	0.2	1.026
1	0.010599719	0.3	1.018
1	0.010599719	0.4	1.013
1	0.010599719	0.5	1.011
1	0.010599719	0.6	1.009
1	0.010599719	0.7	1.008
1	0.010599719	0.8	1.007
1	0.010599719	0.9	1.006
1	0.010599719	1	1.005

Study Model- Finite Element Method (FEM) Case 1- Square grid without ground rods (input data as per Example-1)

1. Drag and drop another Grid on OLV, double click on Grid2 & select Study Model as Finite Element Method (FEM) to get Ground Grid Systems Revision: Base page as shown below.



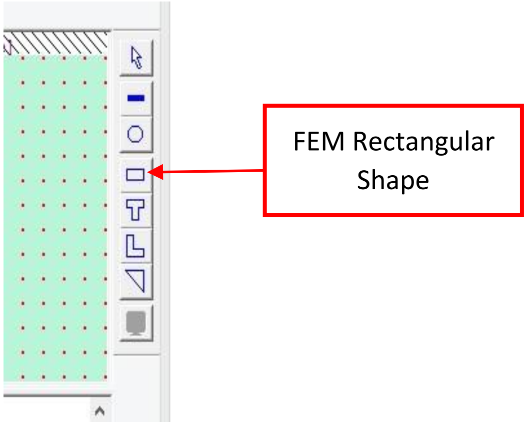
Ground Grid Studies

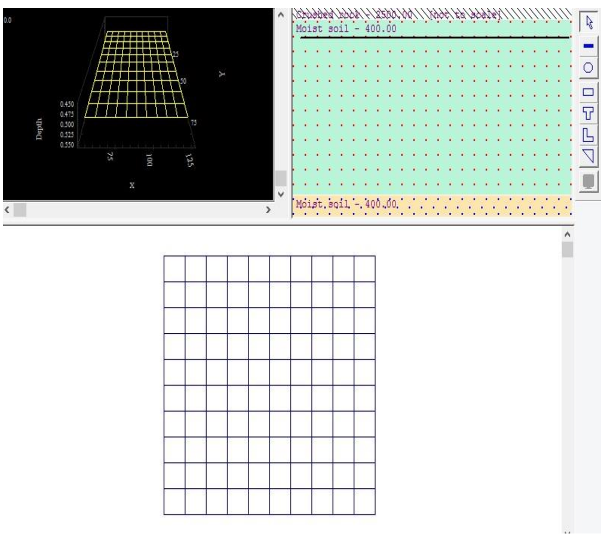


2. Double click on Soil View to enter data shown below.

3. Select FEM Rectangular Shape from FEM Edit Toolbar and place it in top view, double click on Top View to enter data in Group Conductors page shown below.

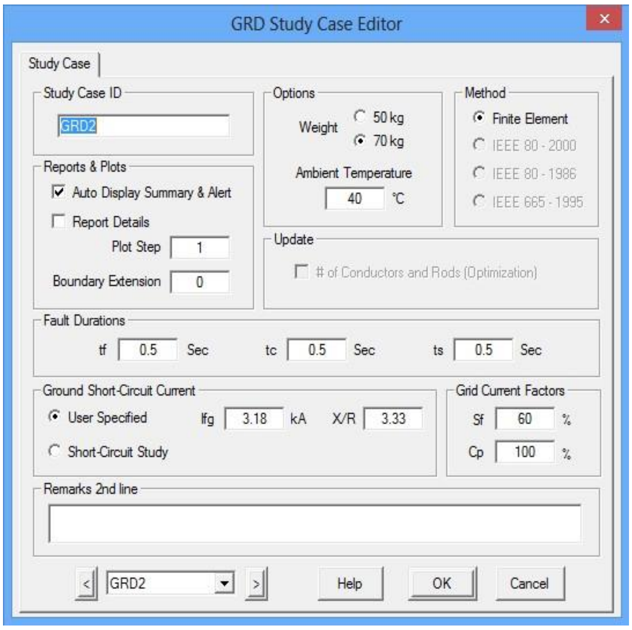
Ground Grid Studies



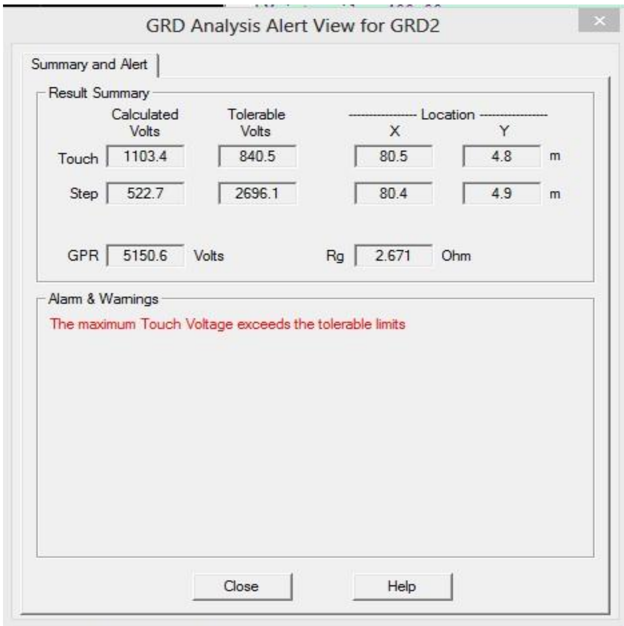


4. Click on Ground-Grid Study and then select Edit study Case and enter the data shown below.

Ground Grid Studies



5. Run Ground Grid Calc and check for alerts.

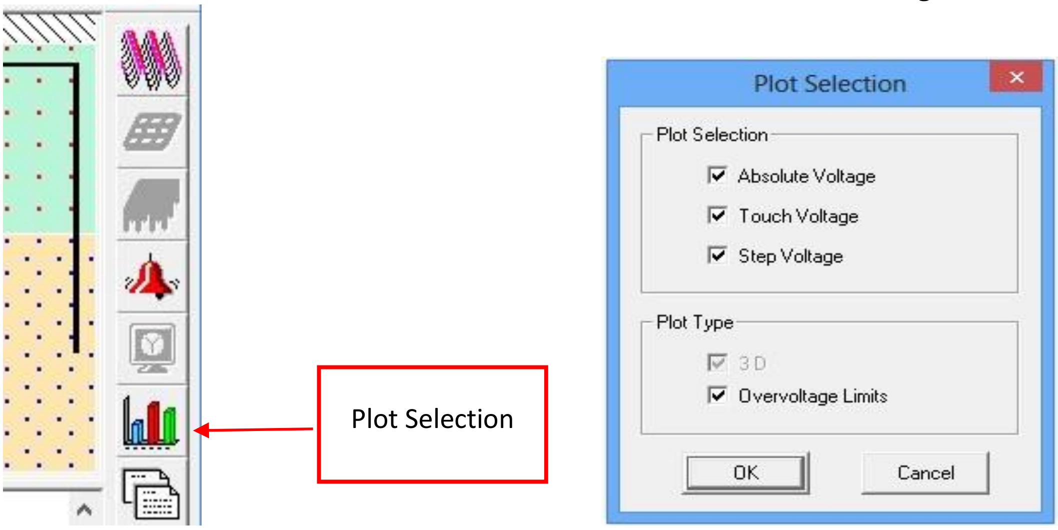


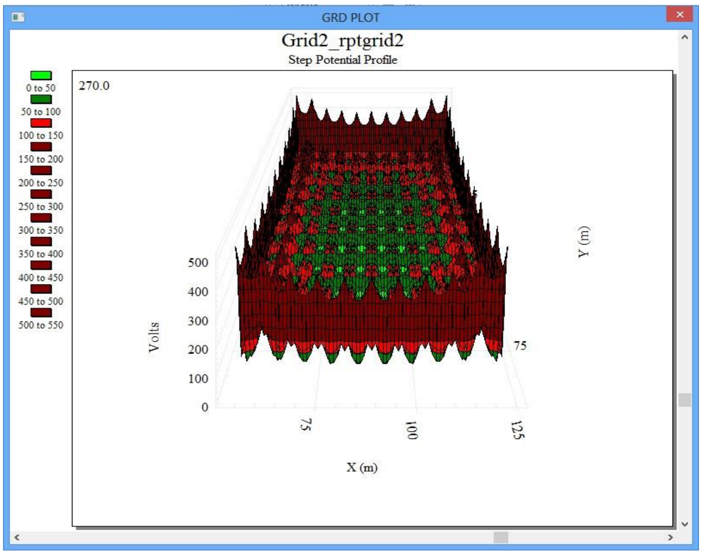
6. Comparison of results obtained with IEEE 80 standard results for Example1 attached as input data is shown in table below.

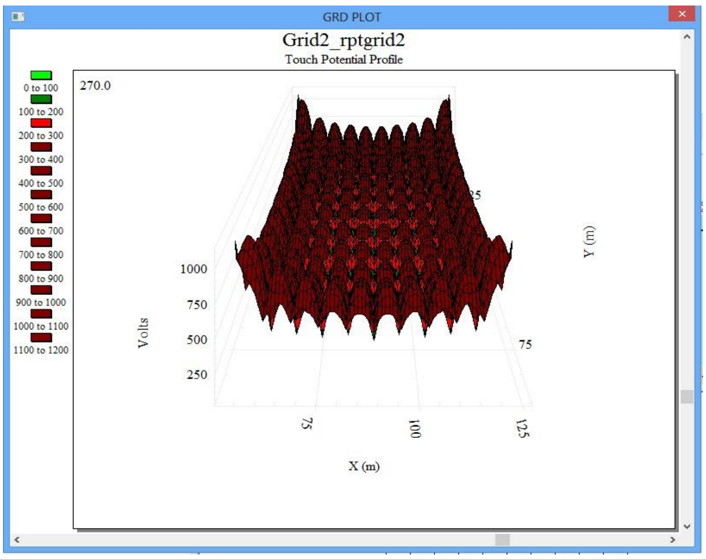
	IEEE-80 standard		**ETAP results using FEM method**	
	Tolerable volts	**Calculated volts**	**Tolerable volts**	**Calculated volts**
Touch Potential in volts	838.2	1002.1	840.5	1103.4
Step Potential in volts	2686.6	Not calculated	2696.1	522.7
GPR in volts	5304		5150.6	
Ground resistance R_g (ohms)	2.78		2.671	

Ground Grid Studies

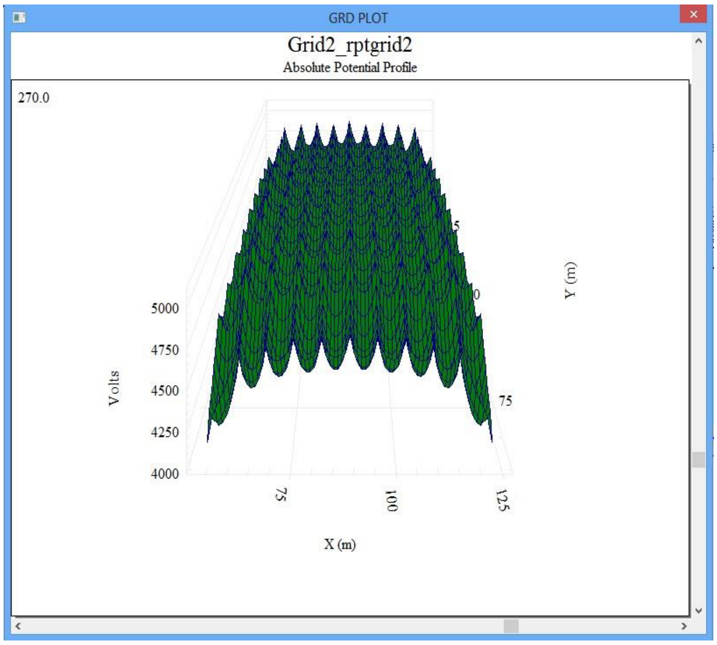
7. Click on Plot Section in the FEM Edit Toolbar and check for the following as shown below.







Ground Grid Studies

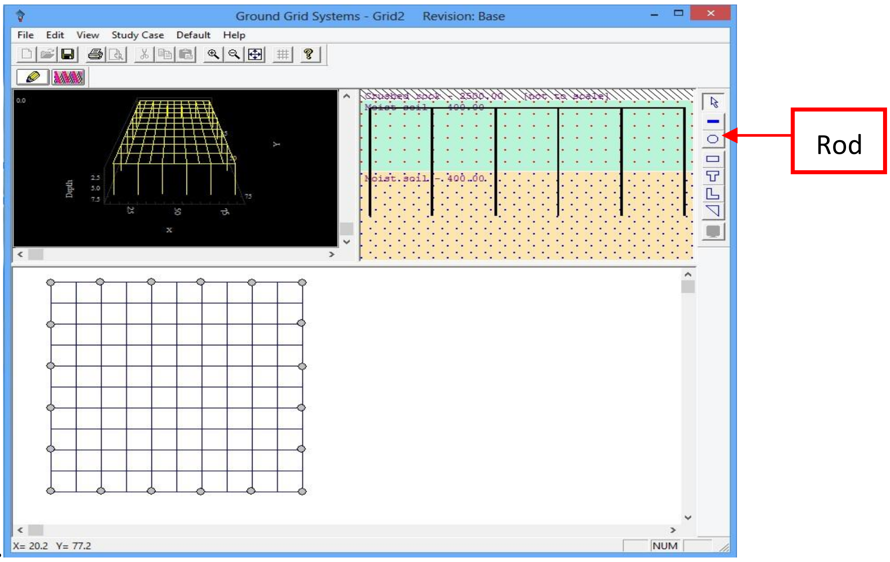


Case 2- Square grid with ground rods (input data as per Example-2)

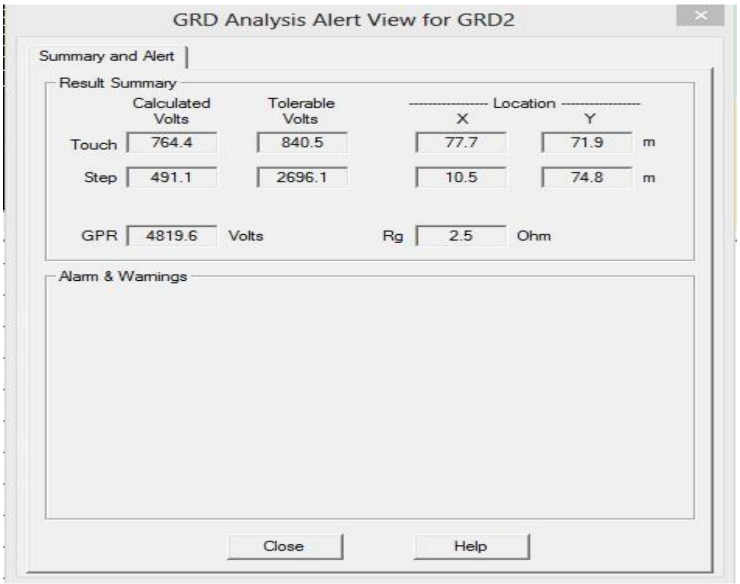
1. Click on Default, select Rod option and enter data in Rod Editor as shown below.

2. Go to Edit mode, select rod from FEM Edit Toolbar and place the rods in the top view as shown below.

Ground Grid Studies



3. Run Ground Grid Calc and check for alerts.



4. Comparison of results obtained with IEEE 80 standard results for Example2 attached as input data is shown in table below.

	IEEE-80 standard		**ETAP results using IEEE method**	
	Tolerable volts	**Calculated volts**	**Tolerable volts**	**Calculated volts**
Touch Potential in volts	838.2	1002.1	840.5	764.4
Step Potential in volts	2686.6	548.9	2696.1	491.1
GPR in volts	5304		4819.6	
Ground resistance R_g (ohms)	2.75		2.5	

Ground Grid Studies

5. Click on Plot Section in the FEM Edit Toolbar and plot ground voltage profiles.