gradients and step potentials is to bury two or more parallel conductors around the perimeter at successively greater depth as distance from the substation is increased. Another approach is to vary the grid conductor spacing with closer conductors near the perimeter of the grid (AIEE Working Group [B4]; Biegelmeier and Rotter [B10]; Laurent [B100]; Sverak [B136]).

c) *Diverting a greater part of the fault current to other paths:* By connecting overhead ground wires of transmission lines or by decreasing the tower footing resistances in the vicinity of the substation, part of the fault current will be diverted from the grid. In connection with the latter, however, the effect on fault gradients near tower footings should be weighed (Yu [B155]).

d) *Limiting total fault current:* If feasible, limiting the total fault current will decrease the GPR and all gradients in proportion. Other factors, however, will usually make this impractical. Moreover, if accomplished at the expense of greater fault clearing time, the change may be increased rather than diminished.

e) *Barring access to limited areas:* Barring access to certain areas, where practical, will reduce the probability of hazards to personnel.

f) *Increase the tolerable touch and step voltages:* The tolerable touch and step voltages can be increased by reducing the fault clearing time, use a surface material with a higher resistivity or increase the thickness of the surface material. See Table 7.

16.7 Application of equations for E_m and E_s

Several simplifying assumptions are made in deriving the equations for E_m and E_s. The equations were compared with more accurate computer results from cases with various grid shapes, mesh sizes, numbers of ground rods, and lengths of ground rods, and found to be consistently better than the previous equations. These cases included square, rectangular, triangular, T-shaped, and L-shaped grids. Cases were run with and without ground rods. The total ground rod length was varied with different numbers of ground rod locations and different ground rod lengths. The area of the grids was varied from 6.25 m^2 to 10 000 m^2. The number of meshes along a side was varied from 1 to 40. The mesh size was varied from 2.5 m to 22.5 m. All cases assumed a uniform soil model and uniform conductor spacing. Most practical examples of grid design were considered. The comparisons found the equations to track the computer results with acceptable accuracy.

16.8 Use of computer analysis in grid design

Dawalibi and Mukhedkar [B43]; EPRI TR-100622 [B64]; and Heppe [B81] describe computer algorithms for modeling grounding systems. In general, these algorithms are based on

a) Modeling the individual components comprising the grounding system (grid conductors, ground rods, etc.).

b) Forming a set of equations describing the interaction of these components.

c) Solving for the ground-fault current flowing from each component into the earth.

d) Computing the potential at any desired surface point due to all the individual components.

e) The accuracy of the computer algorithm is dependent on how well the soil model and physical layout reflect actual field conditions.

There are several reasons that justify the use of more accurate computer algorithms in designing the grounding system. These reasons include

- Parameters exceed the limitations of the equations.
- A two-layer or multilayer soil model is preferred due to significant variations in soil resistivity.
- Uneven grid conductor or ground rod spacings cannot be analyzed using the approximate methods of 16.5.
- More flexibility in determining local danger points may be desired.
- Presence of buried metallic structures or conductor not connected to the grounding system, which introduces complexity to the system.

17. Special areas of concern

Before the final ground grid design calculations are completed, there still remains the important task of investigating possible special areas of concern in the substation grounding network. This includes an investigation of grounding techniques for substation fence, switch operating shafts, rails, pipelines, and cable sheaths. The effects of transferred potentials should also be considered.

17.1 Service areas

The problems associated with step and touch voltage exposure to persons outside a substation fence are much the same as those to persons within fenced substation areas.

Occasionally, a fence will be installed to enclose a much larger area than initially utilized in a substation and a ground grid will be constructed only in the utilized area and along the substation fence. The remaining unprotected areas within the fenced area are often used as storage, staging, or general service areas. Step and touch voltages should be checked to determine if additional grounds are needed in these areas.

A reduced substation grid, which does not include the service area, has both initial cost advantages and future savings resulting from not having the problems associated with “working around” a previously installed total area grid system when future expansion is required into the service area. However, a reduced grid provides less personnel protection compared to a complete substation grid that includes the service area. Also, because of the smaller area and less conductor length, a service area grid and reduced substation grid will have a higher overall resistance compared to a complete substation grid that includes the service area.

The service area might be enclosed by a separate fence that is not grounded and bonded to the substation grid. Possible transfer voltage issues are addressed in 17.3.

17.2 Switch shaft and operating handle grounding

Operating handles of switches represent a significant concern if the handles are not adequately grounded. Because the manual operation of a switch requires the presence of an operator near a grounded structure, several things could occur that might result in a fault to the structure and subject the operator to an electrical shock. This includes the opening of an energized circuit, mechanical failure, electrical breakdown of a switch insulator, or attempting to interrupt a greater value of line-charging current or transformer magnetizing current than the switch can safely interrupt.

It is relatively easy to protect against these hazards when the operating handle is within a reasonably extensive substation ground grid area. If the grounding system has been designed in accordance with this standard, touch and step voltages near the operating handle should be within safe limits. However, quite often additional means are taken to provide a greater safety factor for the operator. For example, the switch operating shaft can be connected to a ground mat (as described in 9.1) on which the operator stands when operating the switch. The ground mat is connected directly to the ground grid and the switch operating shaft. This technique provides a direct bypass to ground across the person operating the switch. The grounding path from the switch shaft to the ground grid must be adequately sized to carry the ground fault current for the required duration. Refer to Figure 33 for a typical switch shaft grounding practice.

The practices for grounding switch operating shafts are varied. The results of a worldwide survey conducted in 2009 indicated that 82% of the utilities that responded required grounding of substation air switch operating shafts to the grounding grid. The survey also showed 100% of the respondents took extra precautions to reduce surface gradients where the switch operator stands. The methodology to ground the operating shaft was almost equally divided among those responding to the questionnaire. Approximately half of the utilities provided a direct jumper between the switch shaft and the ground mat, while the other half provided a jumper from the switch shaft to the adjacent grounded structural steel. The steel is used as part of the conducting path. Approximately 90% of the utilities utilized a braid for grounding the switch shaft. The remaining 10% utilized a braidless grounding device. A typical braided ground is shown in Figure 34 and a braidless grounding device is shown in Figure 35. The methodology for reducing the surface gradients where the switch operator would be standing was divided between utilizing: a grounded platform, a closely spaced wire mesh under the surface material, or closer spacing of the primary grid.

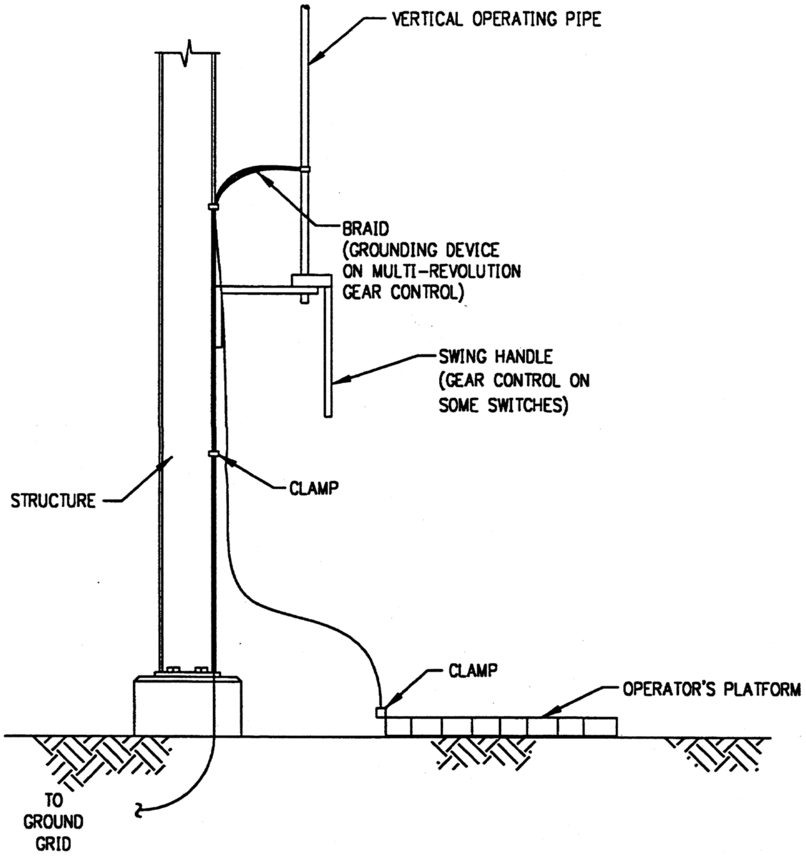

Figure 33—Typical switch shaft grounding

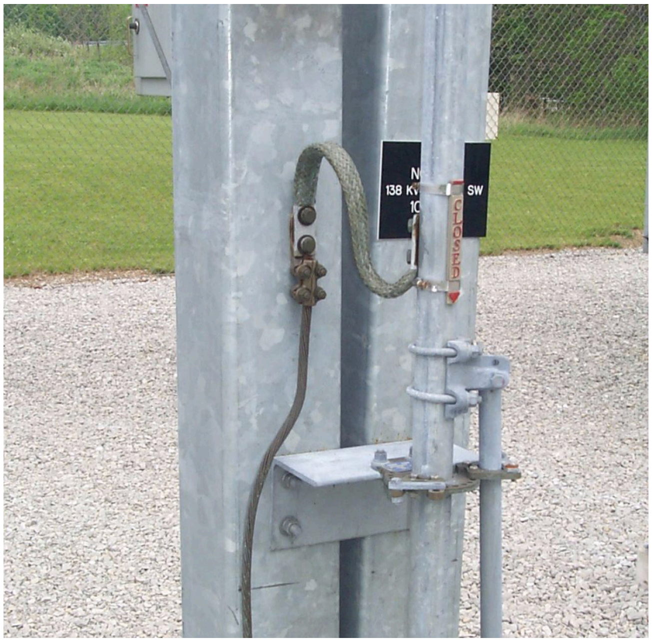

Figure 34—Typical braided ground

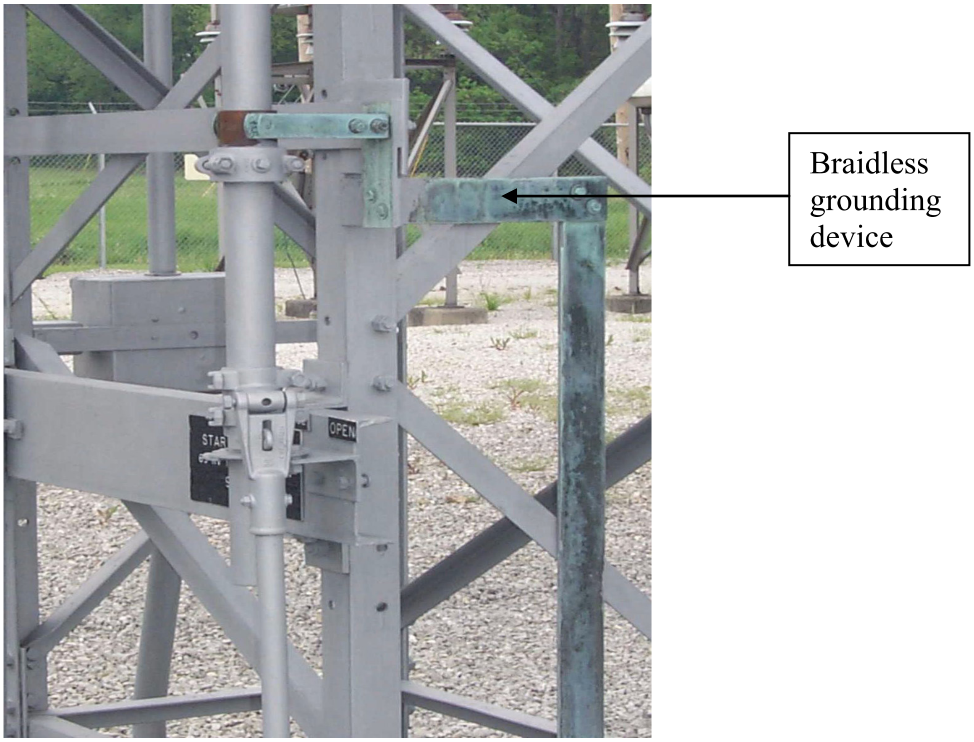

Figure 35—Typical braidless grounding device

17.3 Grounding of substation fence

Fences around substations are usually metallic. In some cases, the fence might be made of masonry materials or non-conductive materials. For those cases, the fence is not grounded, except possibly at exposed metallic hardware or sections, such as gates. The following discussion pertains to metallic fence grounding.

Fence grounding is of major importance because the fence is usually accessible to the general public. The substation grounding design should be such that the touch voltage on the fence is within the calculated tolerable limit of touch voltage. Step voltage should also be checked to verify that a problem does not exist, though step voltage is rarely a problem when the touch voltage is below the tolerable level.

Several philosophies exist with regard to grounding of substation fence. As an example, the National Electrical Safety Code® (NESC®) [B3] requires grounding metal fences used to enclose electric supply substations having energized electrical conductors or equipment. This metal fence grounding requirement may be accomplished by bonding the fence to the substation ground grid or to a separate ground electrode(s), which might consist of one or more ground rods and a buried conductor inside or outside the fence using the methods described in the NESC. The various fence grounding practices are:

- Fence is within the substation ground grid area and is connected to the substation ground grid.
- Fence is outside of the substation ground grid area and is connected to the substation ground grid.
- Fence is outside of the substation ground grid area, but is not connected to the substation ground grid. The fence is connected to a separate grounding electrode.
- Fence is outside of the substation ground grid area, but is not connected to the substation ground grid. The fence is not connected to a separate grounding electrode. The contact of the fence post through the fence post concrete to earth is relied on for an effective ground.

If the latter two practices on fence grounding are to be followed, i.e., if the fence and its associated grounds are not to be coupled in any way to the main ground grid (except through the soil), then three factors require consideration:

Is the falling of an energized line on the fence a danger that must be considered?

Construction of transmission lines over private fences is common and reliable. The number of lines crossing a substation fence may be greater, but the spans are often shorter and dead-ended at one or both ends. Hence, the danger of a line falling on a fence is usually not of great concern. If one is to design against this danger, then very close coupling of the fence to adjacent ground throughout its length is necessary. Touch and step potentials on both sides of the fence must be within the acceptable limit for a fault current of essentially the same maximum value as for the substation. This is somewhat impractical because the fence is not tied to the main ground grid in the substation and the adjacent earth would be required to dissipate the fault current through the local fence grounding system. In addition, the fault current would cause significant damage to the fence, and predicting the actual clearing time and touch and step voltages might be impossible.

May hazardous potentials exist at the fence during other types of faults because the fence line crosses the normal equipotential contours?

Fences do not follow the normal equipotential lines on the surface of the earth which result from fault current flowing to and from the substation ground grid. If coupling of the fence to ground is based solely on the contact between the fence posts and the surrounding earth, the fence might, under a fault condition, attain the potential of the ground where the coupling was relatively good, and thereby attain a high voltage in relation to the adjacent ground surface at locations where the coupling was not as good. The current flowing in the earth and fence, and the subsequent touch voltage on the fence are less than would result from an energized line falling on the fence; however, the touch voltage may exceed the allowable value and would, hence, be unsafe.

In practice, can complete metallic isolation of the fence and substation ground grid be assured at all times?

It may be somewhat impractical to expect complete metallic isolation of the fence and the substation ground grid. The chance of an inadvertent electrical connection between the grid and the fence areas may exist. This inadvertent electrical connection may be from metallic conduits, water pipes, etc. These metallic items could transfer main grid potential to the fence and hence dangerous local potential differences could exist on the fence during a fault. If the fence is not closely coupled to the nearby ground by its own adequate ground system then any such inadvertent connections to the main grid could create a hazard along the entire fence length under a fault condition. This hazard could be only partially negated by utilizing insulated joints in the fence at regular intervals. However, this does not appear to be a practical solution to the possible hazard.

Several different practices are followed in regard to fence grounding. Some ground only the fence posts, using various types of connectors as described elsewhere in this guide and depend on the fence fabric fasteners (often simple metallic wire ties) to provide electrical continuity along the fence. Others ground the fence posts, fabric, and barbed wire. The ground grid should extend to cover the swing of all substation gates. The gate posts should be securely bonded to the adjacent fence post utilizing a flexible connection.

To illustrate the effect of various fence grounding practices on fence touch potential, five fence grounding examples were analyzed using computer analysis. The fence grounding techniques analyzed were

- Case 1: Inclusion of fence within the ground grid area. The outer ground wire is 0.91 m (3 ft) outside of the fence perimeter. The fence is connected to the ground grid. Refer to Figure 36 and Figure 37 for grid layout.
- Case 2: Ground grid and fence perimeter approximately coincide. The outer ground wire is directly alongside the fence perimeter. The fence is connected to the ground grid. Refer to Figure 38 and Figure 39 for grid layout.
- Case 3: The outer ground grid wire is 0.91 m (3 ft) inside the fence perimeter. The fence is connected to the ground grid. Refer to Figure 40 and Figure 41 for grid layout.
- Case 4: Ground grid is inside of fence area. The outer ground grid wire is 6.7 m (22 ft) inside the fence perimeter. The fence is connected to the ground grid. Refer to Figure 42 and Figure 43 for grid layout.
- Case 5: Ground grid is inside of fence area. The outer ground grid wire is 6.7 m (22 ft) inside the fence perimeter. The fence is locally grounded but not connected to the ground grid. Refer to Figure 44 and Figure 45 for grid layout.

The fenced area for each case is a square having sides of 43.9 m (144 ft). The test calculations are based on the following parameters:

$\rho = 60\ \Omega\text{-m}$

$I_G = 5000$ A

$h_s = 0.076$ m

$\rho_s = 3000\ \Omega\text{-m}$, extending 0.91 m (3 ft) beyond the fence

$R = 0.66\ \Omega$ for cases 1 through 4

$R = 0.98\ \Omega$ for case 5

$t_s = 0.5$ s

$D_f = 1.0$

The factor C_s for derating the nominal value of surface layer resistivity is dependent on the thickness and resistivity of the surface material and the soil resistivity, and is computed using Equation (27) or Figure 11:

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

$$K = \frac{60 - 3000}{60 + 3000} = -0.961$$

$$C_s = 0.636$$

The allowable step and touch voltages are calculated using Equation (29) and Equation (32). For test cases 1 through 5:

$$E_{step50} = (1000 + 6C_s \times \rho_s)0.116/\sqrt{t_s} = 2042\ \text{V}$$

$$E_{touch50} = (1000 + 1.5C_s \times \rho_s)0.116/\sqrt{t_s} = 634\ \text{V}$$

The actual step voltage E_s and actual mesh voltage E_m are calculated as a function of the GPR in percent, using the following equations:

$$E_S = R_g \times I_g \frac{E_S(\%)}{100} D_f$$

$$E_m = R_g \times I_g \frac{E_m(\%)}{100} D_f$$

where

$E_s(\%)$ is the step voltage in terms of percent of GPR
$E_m(\%)$ is the mesh voltage in terms of percent of GPR

Equating the actual step and mesh voltage equations to the tolerable step and touch voltage values ($E_{step} = E_s$ and $E_{touch} = E_m$) and solving for E_s (%) and E_m (%), the equations become

$$E_s(\%) = \frac{E_{step}(100)}{R_g \times I_g \times D_f}$$

$$E_m(\%) = \frac{E_{touch}(100)}{R_g \times I_g \times D_f}$$

Substituting the assumed parameters for these test cases yields the following:

For cases 1 through 4

$$E_s(\%) = 61.9$$

$$E_m(\%) = 19.2$$

For case 5

$$E_s(\%) = 41.7$$

$$E_m(\%) = 12.9$$

The actual step and mesh voltages as a percent of GPR must be less than 61.9% and 19.2%, respectively, for cases 1 through 4 and less than 41.7% and 12.9%, respectively, for case 5.

For each test case, two voltage profiles were computed at the following locations:

- A line parallel to and 0.91 m (3 ft) outside of fence
- A line through the grid from one side to the other, parallel to the grid wires

17.4 Results of voltage profiles for fence grounding

The results of the voltage profiles along the surface of the earth for test case 1 are shown in Figure 36 and Figure 37. The results for both profiles indicate that the touch voltage on the fence for a person standing 0.91 m (3 ft) from the fence (approximately one arm's length) is less than the tolerable touch voltage and hence safe. The voltage profiles illustrate how the voltage above remote earth decreases rapidly as one leaves the substation ground grid area. As seen in Figure 36, the step voltage is no greater than 3% to 4% and is far below the tolerable step voltage percent of 61.9% of GPR. Because step voltage is usually not the concern in regard to fence grounding, it will not be analyzed in the remaining test cases.

The results of the voltage profiles for test case 2 are shown in Figure 38 and Figure 39. The voltage profile in Figure 39 for a line through the grid from one side to the other indicates that the touch voltage 0.91 m (3 ft) outside of the fence is very nearly equal to the allowable touch voltage. However, as seen in Figure 38 for a voltage profile along the fence and 0.91 m (3 ft) away from it, it is clear that the touch voltages on certain areas of the fence are not safe for a person to contact. By comparing Figure 36 and Figure 38, one can clearly see the effect of having a ground grid wire 0.91 m (3 ft) outside of the fence and around the fence perimeter.

The results of the voltage profiles for test case 3 are shown in Figure 40 and Figure 41. These results are very similar to those of test case 2 and illustrate that the touch voltage on the fence is generally not safe in several areas for a person to contact.

The results of the voltage profiles for test case 4 are shown in Figure 42 and Figure 43. These results again illustrate that the touch voltage on the fence during a fault condition is not safe to contact. It can be seen by comparing Figure 36, Figure 38, Figure 40, and Figure 42 that the touch voltage along the length of the fence increases as the outer ground grid wire is moved inward toward the substation.

The results of the voltage profiles for test case 5 are shown in Figure 44 and Figure 46. The tolerable touch voltage has decreased from 19.2% to 12.9% because of an increase in the substation grid resistance. The grid resistance increase is a result of less wire and reduced area in the grid for test case 5. According to the computer program results, the potential rise on the isolated, separately grounded fence during a ground fault condition is 43.7% of GPR, which is shown as a horizontal line on the graphs. The potential rise on the fence is caused by the coupling through the earth from the ground grid to the fence. As shown in Figure 44, the potential rise on the earth 0.91 m (3 ft) beyond the fence corner caused by a ground fault condition is 30.5% of GPR. The largest difference in voltage between the fence and the earth occurs at the corner and is 13.2% of GPR, which is 0.3% greater than the allowable touch voltage of 12.9%. It is also important to note that if the fence should ever inadvertently become metallically connected to the ground grid, the potential on the fence could reach 100% of GPR and the results would be similar to those shown in case 4 (Figure 42 and Figure 43).

Test cases studied for an isolated ungrounded fence yield very similar results as the test cases run for an isolated, separately grounded fence shown in Figure 44 and Figure 46.

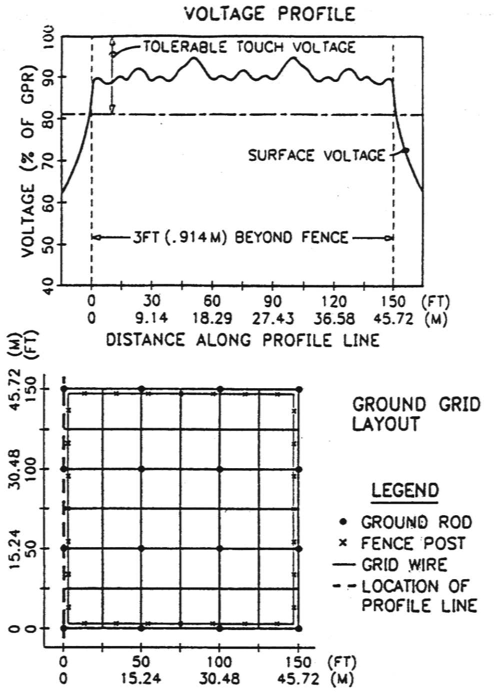

Figure 36—Case 1, plot 1

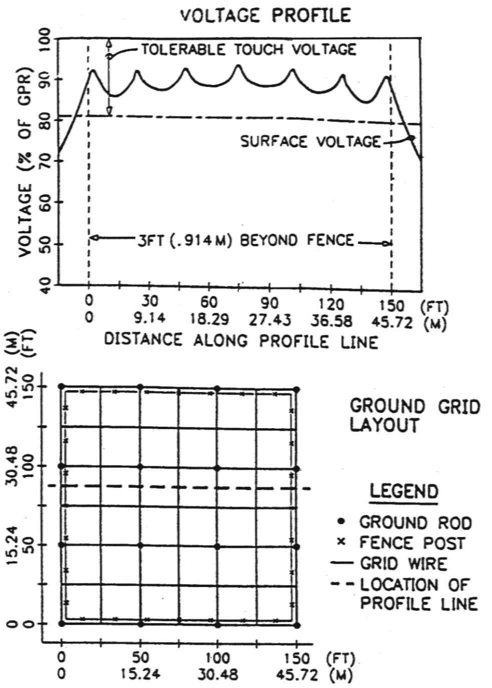

Figure 37—Case 1, plot 2

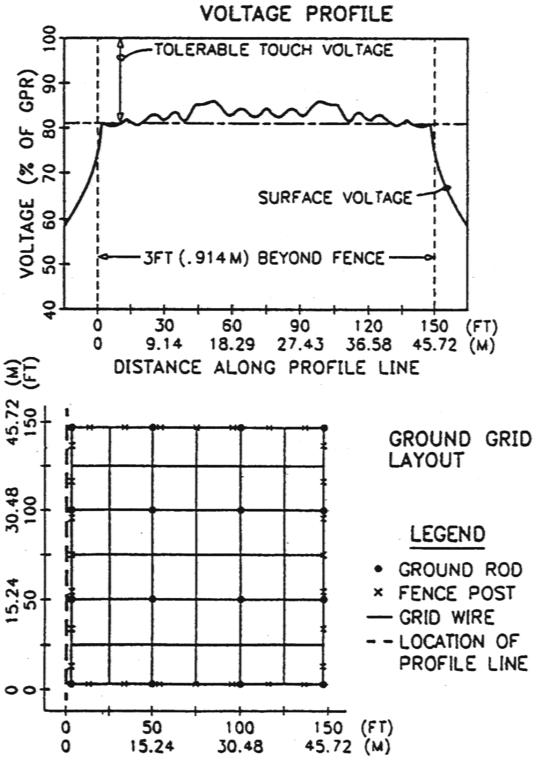

Figure 38—Case 2, plot 1