SUBSTATION GROUNDING OPTIMIZATION

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MASTER OF SCIENCE
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by

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SUBSTATION GROUNDING OPTIMIZATION

A Project

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Preetham B. Kumar

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Date

Department of Electrical and Electronic Engineering
Abstract

of

SUBSTATION GROUNDING

by

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Statement of problem

Substation grounding is a critical part of the overall electric power system. It is designed to not only provide a path to dissipate electric currents into the earth without exceeding the operating limits of the equipment, but also provide a safe environment for any people that are in the vicinity. Design of a proper grounding system will be discussed as well as performing of calculations necessary to ensure a safe design.

Aspects of soil resistivity measurements, area of the ground grid, calculation of tolerable limits of current to the body, typical shock situations, tolerable touch and step voltages, maximum fault current grid resistance, grid current, ground potential rise, and benefits of surface materials will be discussed. Simulation software will also be discussed and its functionality in a step-by-step manner.

Sources of Data

IEEE Std. 80-2000 was used as the primary source of information.
Conclusions Reached

An adequate grounding grid has been designed using concepts outlined in IEEE Std.80-2000 and applied into programming and simulating results in MATLAB.

_______________________, Committee Chair
[Dr.Turan Gonen]

_______________________
Date
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CHAPTER 1 - INTRODUCTION

1.1 Overview

The scope of this project will be concerned with safe grounding practices and designs for ac substations. An effective grounding system has objectives as follows:

It ensures that any human personnel walking within the boundaries of the grounded facilities are not exposed to the dangers of critical electric shock. Both the touch and step voltages produced in an abnormal system conditions must be within the safe values. Safe values are defined as values that do not produce enough current to cause ventricular fibrillation. Dissipation of electric currents into the earth must occur under both normal and faulted conditions without exceeding the operational and equipment limits or the continuity of service. Grounding must be provided for lightning impulses and switching related surges. Low resistance for protective relays to see and clear ground faults.

It is necessary that the entire grounding system is designed in a way that under reasonable conditions, personnel are not exposed to potentials that are hazardous to the human body.

Design of a proper substation grounding system is very involved as many variables affect the design. It is also difficult at times to obtain accurate values for some parameters. For obtaining values of ground resistivity, the effects of moisture conditions and temperature can cause extreme variations in the values. These variables need to be taken into account using various methods of approximations and exercising engineering judgment.
A good grounding system is one that provides low resistance to earth which in turn minimizes the ground potential rise. The design procedures presented in this project are primarily based on the IEEE Std. 80 in which a design procedure is outlined that meets the required safety criteria without using expensive computer software.

1.2 Key Terms
Key terms of the commonly used terms throughout this text along with their definitions are presented below as follows:

1. DC Offset: Difference between the symmetrical current wave and the actual current wave during a transient condition.

2. Earth Current: The current that is being circulated between the grounding system and the ground fault current source that uses the earth as the return path.

3. Ground Fault Current: Current that flows into or out of the earth or conductive path during a faulted condition involving the ground.

4. Ground Potential Rise (GPR): The maximum voltage that the ground grid may attain relative to a distant point assumed to be at the potential of remote earth. GPR is equal to the product of the earth current and the equivalent impedance of the grounding system.

5. Mesh Voltage: The maximum touch voltage within a mesh of a ground grid.

6. Soil Resistivity: The electrical characteristics of the soil in regards to conductivity.

7. Step Voltage: The difference in surface potential that one may experience by bridging a distance of 1 meter with his feet without contacting any other grounded object.
8. Touch Voltage: The potential difference between the ground potential rise and the surface potential at the point where a person is standing while at the same time having the hands in contact with a grounded structure.
CHAPTER 2 - LITERATURE SURVEY

2.1 Grounding Overview

Electric power systems are grounded or connected to earth for several reasons. The main reasons for grounding are as follows: provide safety during normal and faulted conditions, to assure correct operation of electrical devices, stabilize the voltage during transient conditions and minimize flashover during transients, as well as dissipate lightning strikes [7].

When a system is said to be grounded, it is electrically connected to an earth-embedded metallic structure. The earth embedded metallic structures will be called the grounding system and provide a conducting path of electricity to earth [2]. A typical substation grounding system consists of a driven ground rods, buried interconnecting grounding cables or grid, equipment ground mats, connecting cables which connect the buried grounding grid to the metallic parts of structures and equipment, connections to the grounded system neutrals, as well as the material insulating the surface [2].

A grounding system provides low-impedance electrical contact between the neutral of the electrical system and the earth. The potential of the neutral in a 3-phase system should be the same as that of the earth. When this is the case humans and other living beings are safe to make contact with metallic structures connected to the neutral of the system. The impedance of the grounding system to earth always has some finite value, however, and as a result the potential of the grounding structures may become different at various
points during an abnormal condition. These abnormal conditions may be considered as unbalances or faulted conditions.

The level of the potential difference between the earth and the grounded structures can present various hazardous conditions for human beings. This condition has 2 main possibilities: 1. A person touching a grounded structure which has a potential that is different from that of the point of earth at which the person is standing. In this case, the person is subjected to a voltage that will generate an electric current through his or her body. The voltage to which the human body is subjected to is called the touch voltage. 2. A person walking on the surface of the earth will experience a voltage between their feet. This voltage will generate electric body currents. This case is called the step voltage.

The flow of electric current through the human body is the source of danger. Grounding systems should be designed in a way that it is possible for the electric body current in an person that should not exceed the limit under any foreseeable adverse events. In this respect, the objective of analysis procedures for grounding systems is to answer the following two questions: What are the reasonable assumptions in the definition of foreseeable adverse conditions and what is the highest possible body current during the worst conditions? Once these questions are answered, those values are used in creating an adequate grounding design.

### 2.2 Conditions of danger

During a condition involving a ground fault, the flow of current to earth will produce gradients not only in the boundaries of the substation, but around it as well. Without the
proper ground system design, dangerous voltages can develop between the grounded structures, equipment frames and nearby earth. The IEEE standard 80-2000 describes conditions that accidental shock may develop as follows:

a. Relatively high fault current to ground in relation to the area of ground system and its resistance to remote earth.

b. Soil resistivity and distribution of ground currents such that high potential gradients may occur at points at the earth’s surface.

c. Presence of an individual at such a point, time, and position that the body is bridging two points of high potential difference.

d. Absence of sufficient contact resistance or other series resistance to limit current through the body to a safe value under circumstances a) through c).

e. Duration of the fault and body contact, and hence, of the flow of current through a human body for a sufficient time to cause harm at the given current intensity.

2.3 Limits of Current Tolerable by the Human Body

The magnitude as well as the duration at 50-60 Hz of the current needs to be below the threshold for ventricular fibrillation for 99.5% of the population. The threshold for ventricular fibrillation can be as low as 60 mA [3]. Extensive experiments on animals having body and heart weights comparable to humans were conducted as they were subjected to the maximum shock durations of 3 seconds [2]. Currents in the range of 1-6mA are commonly referred to as let-go currents. Currents in this range are unpleasant, however they do not affect the ability of the person to let go of the energized object.
Currents ranging from 9-25 mA are painful and affect the muscles and make it difficult or impossible to release the object. However, if currents are above the threshold for ventricular fibrillation, they can cause heart paralysis, inhibition of breathing, and burns.

2.4 Tolerable Voltages

There are five voltages that a person can be exposed to inside of a substation. These situations are shown in the figure below which include: metal-to-metal voltage, $E_{mm}$, step voltage, $E_s$, touch voltage, $E_t$, mesh voltage, $E_m$, and transferred voltage, $E_{trd}$ [2,7]. Substation metal-to-metal touch voltages may be present when a person is standing on or touching a grounded object or structure comes into contact with a metallic object or structure within the substation site that is not bonded to the ground grid. This can be avoided by bonding potential danger points to the substation grid. The step voltage is considered as the difference in surface potential that is experienced by a person bridging a distance of 1 meter without contacting any other grounded object [1,2]. The touch voltage is the difference of potential between the GPR and the surface potential at the point where a person is standing while having a hand in contact with a grounded structure [1,2]. Mesh voltage can be described as the maximum touch voltage within a mesh of a ground grid [1,2]. A special case of the touch voltage where a voltage is transferred into or out of the substation from a remote or external substation site is called the transferred voltage [2,7]. Figure 2-1 graphically shows scenarios of the different shock situations that can occur in the vicinity of the substation.
2.4.1 Tolerable Touch and Step Voltages

Touch and Step voltages are a criteria that needs to be met for ensuring a safe design. The lower the maximum touch and step voltages, the harder it is to fulfill an adequate design. The faster the clearing time, the less exposure of the fault current there is to the person. In Figure 2-2 and 2-3, the exposure to the touch and step voltages are shown in a graphical manner.

Figure 2-1: Basic Shock Situations.
(From IEEE Std. 80-2000, Figure 12. Copyright © 2000 IEEE. All rights reserved)
Figure 2-2: Exposure to Touch Voltage.
(From IEEE Std. 80-2000, Figure 6. Copyright © 2000 IEEE. All rights reserved)

Figure 2-3: Exposure to Step Voltage.
(From IEEE Std. 80-2000, Figure 9. Copyright © 2000 IEEE. All rights reserved)
2.5 Reclosing

Reclosing the circuit is a common practice in today's industry. This can be of concern as the person may have not had enough time to recover from the first shock when he gets hit with another one in a short period of time. These cumulative effects of closely spaced shocks have not been thoroughly evaluated, but a reasonable allowances can be made by summing the shock durations as the time of a single exposure [2,3].

2.6 High-Speed Fault Clearing

There is great importance in high-speed fault clearing of ground faults and it has great advantages for two reasons: 1. Probability of exposure to electric shock is greatly reduced by fast fault clearing time, 2. Tests and experience show that the chance of severe injury or death is significantly reduced if the duration of the current going through the body is brief [8].

2.7 Soil Resistivity Measurements

Before design can begin, soil resistivity measurements need to be taken at the site of the substation. Soil resistivity is done in order to determine the soil structure at a particular site as it can vary greatly depending on the type of terrain. For example, silt on a river bank may have resistivity of 1.5 ohm-meters, while dry sand or granite may have values of 10,000 ohm-meters[6]. Factors that affect the resistivity of soil include: type of soil (clay, sandstone, granite, etc), moisture content, temperature, chemical composition,
presence of metal and concrete pipes, and topology of the soil. As a result, each individual site is unique and measurements need to be made specifically at each location. Measurements are to be made at a number of places throughout the property as it is rare to find the entire area to have uniform soil resistivity [2]. In many cases, there are many layers of soil at the site and the resistivity of each layer varies. When at the site, the measurements need to be made at various locations to determine if there are significant changes with depth. The number of measurements should be greater in areas with greater variations. There are several methods of getting the resistivity measurements.

2.7.1 Wenner Four-Pin Method

The Wenner four-pin method is the most commonly used method. The concept behind this method includes driving four probes into the earth along a straight line at equal distances and a certain depth[2,8]. The voltage between the two inner electrodes is then measured and divided by the current between the two outer electrodes. This will give the value of resistance, R. This method can be observed in Figure 2-4 and Figure 2-5 below, where a is the equal distances apart and depth is, b.

There are a number of reasons for the popularity of this method. There are no heavy equipment required for the testing [8]. The four-pin method obtains the resistivity data for the deeper layers without having to drive the test pins to the deeper layers. The results do not vary greatly due to the pin resistance or the holes created while driving the test pins into the soil.
Resistivity measurements need to include the temperature and moisture content of the soil at time of the measurement. Any additional known buried conductive objects should be noted as well, as they can create false reading measurements if they are close enough.

Disadvantages of the Wenner method are the rapid decrease in magnitude of potential between the two inner electrodes when their spacing is increased to somewhat large values. In the past, instruments were incapable of measuring such low potential values. An additional disadvantage of the Wenner method is that it requires all four probes to be repositioned for each measured depth and is inefficient in terms of operational standpoint.

Figure 2-4: Wenner Four-Pin Method.

(From IEEE Std. 80-2000, Figure 19. Copyright © 2000. IEEE. All rights reserved)
2.7.2 Unequally Spaced or Schlumberger-Palmer Method

This method involves the inner probes to be placed closer together and the outer probes further apart. Unlike the Wenner method where all of the probes need to be repositioned whenever testing needs to be done at the particular location, the Schlumberger method only requires that outer probes to be repositioned for varying measurements. As a result, measurements from the tests can be performed quicker and economy of manpower is gained [2,6]. Figure 2-6 graphically illustrates the Schlumberger-Palmer method below as follows:
2.7.3 Driven Rod (3-pin) Method

The driven rod or 3-pin method is suitable for cases such as those involving transmission line structure earths, or areas that have difficult terrain due to shallow penetration or localized measurement areas. This method, the depth of the driven-rod located in the soil tested is varied. The other two rods remain as reference rods and are driven to a shallow depth in a straight line. The location of the voltage rod is varied between the test rod and the current rod [2]. Figure 2-7, shows the setup of the driven rod method as follows:
2.7.4 Interpretation of Resistivity Measurements

The interpretation of the measured results from the field is the difficult part of the process. The basic objectives are to obtain a good approximation soil model compared to the actual soil. Soil resistivity will vary due to type of soil, depth and seasonal variations. An equivalent is created based on the factors as follows: accuracy and extent of measurements, method applied, complexity of the mathematics and purpose of the measurements [2]. In power engineering, the two-layer equivalent model is accurate enough in many cases and is usually not too involved mathematically.
Methods of analyzing soil include curve matching and analytical procedures to identify the presence of resistivity layering. Figure 2-8 shows several apparent resistivity curves. Graphical curve matching is useful for field personnel for detecting any anomalies and identifying areas that may need a more thorough examination and testing. Graphical curve matching is limited to soils that contain three or less layers [6]. Computer based solutions are also available and this technique can be used to estimate the multilayer soil if needed. Weighted averaging is another technique used to determine an equivalent homogeneous soil model for each probe spacing that is not mathematically sound. The best approach is to firstly obtain a resistivity model for each traverse and make a decision upon which information to base the grounding system design.

Figure 2-8: Typical Resistivity Curves Curve (A) - Homogeneous resistivity, Curve (B) - Low resistivity layer overlaying higher resistivity layer, Curve (C) - High resistivity layer between two low resistivity layer, Curve (D) - High resistivity layer overlaying a lower resistivity layer, Curve (E) - Low resistivity layer over high resistivity layer with a vertical discontinuity (typically a fault line).

(From Substation Earthing Guide. Figure 5.2: Typical Resistivity Curves)
2.8 Area of the Ground Grid

The ground grid area should be as large as possible and preferable covering the entire substation site. The concept behind this is that this provides the greatest effect in lowering the grid resistance. Adding additional grid conductor does not provide a decrease in grid ground resistance to the same level as increasing the area does. The outer grid conductor area should be placed on the boundary of the substation site. The substation fence needs to be placed at a minimum of 3 feet inside of the outer conductors [2]. As a result, this provides the lowest grid resistance and protects anyone outside of the fence from hazardous touch voltages.

The design equations require a square, rectangular, triangular, T-shaped, or L-shaped grids [2]. In design stages, on the layout drawing of the substation site, the largest of the shapes are to be drawn that will fit within the site. This will represent the outer grid conductors and will define the area of the grid that will be used in the calculations. For sites having one of the shapes mentioned above, they do not require any additional conductors once the design is complete. For irregular sites, additional conductors need to be run along the perimeter of the site that were not included in the original grid design.

2.9 Protective Surface Material

A thin layer of resistive surface material is put in a substation in order to reduce the available shock current at the substation. The surface material increases the contact resistance between the soil and the feet of the people in the vicinity of the substation. The surface material is put throughout the boundary of the substation with a depth of
about 3-6 inches and the depth increases to 3-4 feet outside of the substation fence [2,5].

The reason to the surface material extending outside of the substation fence is to reduce the touch voltages as they may become dangerously high. A range of factors can influence the resistivity values of the surface material. These include: the type of stone, size, condition of the stone, amount of moisture content, atmospheric contamination, etc.

Table 2-1, below, shows the resistivity is considerable different between wet and dry surface materials [2].

<table>
<thead>
<tr>
<th>Number</th>
<th>Description of surface material (U.S. state where found)</th>
<th>Resistivity of sample $\Omega \cdot m$</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Dry</td>
</tr>
<tr>
<td>1</td>
<td>Crushed run granite with fines (N.C.)</td>
<td>$140 \times 10^6$</td>
</tr>
<tr>
<td>2</td>
<td>1.5 in (0.04 m) crushed run granite (Ga.) with fines</td>
<td>4000</td>
</tr>
<tr>
<td>3</td>
<td>0.75-1 in (0.02-0.025 m) granite (Calif.) with fines</td>
<td>$-\ldots$</td>
</tr>
<tr>
<td>4</td>
<td>#4 (1.2 in) (0.025-0.05 m) washed granite (Ga.)</td>
<td>$1.5 \times 10^6$ to $4.5 \times 10^6$</td>
</tr>
<tr>
<td>5</td>
<td>#3 (2-4 in) (0.05-0.1 m) washed granite (Ga.)</td>
<td>$2.6 \times 10^6$ to $3 \times 10^6$</td>
</tr>
<tr>
<td>6</td>
<td>Size unknown, washed limestone (Mich.)</td>
<td>$7 \times 10^6$</td>
</tr>
<tr>
<td>7</td>
<td>Washed granite, similar to 0.75 in (0.02 m) gravel</td>
<td>$2 \times 10^6$</td>
</tr>
<tr>
<td>8</td>
<td>Washed granite, similar to pea gravel</td>
<td>$40 \times 10^6$</td>
</tr>
<tr>
<td>9</td>
<td>#57 (0.75 in) (0.02 m) washed granite (N.C.)</td>
<td>$190 \times 10^6$</td>
</tr>
<tr>
<td>10</td>
<td>Asphalt</td>
<td>$2 \times 10^6$ to $30 \times 10^6$</td>
</tr>
<tr>
<td>11</td>
<td>Concrete</td>
<td>$1 \times 10^6$ to $1 \times 10^9$ a</td>
</tr>
</tbody>
</table>

aOven dried concrete (Hammond and Robson [B75]). Values for air-cured concrete can be much lower due to moisture content.

Table 2-1: Typical Surface Material Resistivity.
(From IEEE Std. 80, Table 7. Copyright © 2000 IEEE. All rights reserved)
2.10 Ground Conductor

The most commonly used materials for ground in United States are copper and copper-clad steel [2]. Both have pros and cons. Copper is commonly the most used material for grounding. Copper has an advantage of being resistant to most underground corrosion as copper is cathodic with respect to most other metals that could be buried in the vicinity. Meanwhile, Copper-clad steel is usually used for underground rods and in some occasions for grounding grids. It is also an option to be used for areas where copper theft is a problem.

Other materials that can be used are aluminum and steel. Aluminum is a good conductor however, copper conducts better. Advantages of Aluminum are that theft is less of an issue and it is less expensive than copper [4]. The fusing temperature of aluminum is about half of copper, while the thermal capacity is about two thirds. Steel is another available option for ground grid conductors and rods. Theft is not much of an issue as well. The temperature characteristics and thermal capacity are very good for steel.

2.11 Design of a Substation Grounding System

The design of the substation grounding system is followed using the outline in the IEEE STD 80-2000.

2.11.1 General Concepts

The common practice for a grounding system in the United States and other countries is the use of buried horizontal conductors in the form of a grid, which are then
supplemented by a number or ground rods connected to the grid. The idea behind using horizontal (grid) conductors is that they are effective in reducing the danger of high step and touch voltages on the surface of the earth. For vertical ground rods, they allow the penetration to lower resistivity soil which makes it more effective in dissipating fault currents in the case of encountering two or more layered soil. The upper layer of soil in many cases has the higher resistivity than the lower layer. This is of importance as the lower-layer soil maintains a nearly constant resistivity and is far less dynamic compared to upper-layer. Throughout the seasons, the soil conditions change due to freezing or drying.

2.11.2 Design Procedures

1. The grounding system needs to consist of a network of bare conductors that are buried in the earth to provide for grounding connections to ground neutrals, equipment ground terminals, equipment housings, and structures as well as to limit the maximum possible shock current in an event of a ground fault. Once the mesh and step voltages of the grid are calculated and are below the maximum values for touch and step voltages, the grounding design is considered adequate. This does not mean that in an event of an abnormal condition, personnel will not experience a shock, however, the shock will not be high enough to cause ventricular fibrillation.

2. The ground grid needs to encompass all of the area within the substation fence and extend 3 feet outside of the substation fence. A perimeter grid conductor
should extend 3 feet around the entire substation fence and including the gates in any position. A perimeter grid conductor shall also surround any substation equipment and structure cluster in cases where the fence is located far from the cluster.

3. Soil resistivity tests will need to be done in order to determine the soil resistivity profile and the soil model needed. Estimates of preliminary resistance in uniform soil can be determined by taking the average of the measurements. In the final design, more accurate estimates for resistance may be needed and various techniques are available for getting for higher accuracy.

4. The fault current, $3I_0$, should be the maximum expected fault current that can be conducted by any conductor in the grounding system. The time, $t_C$, should reflect the maximum possible clearing time and including the backup.

5. The tolerable touch and step voltages will then need to be determined using equations available in chapter 3. The choice of time, $t_s$, is left to the judgment of the engineer designing the system with the guidance of the IEEE std. 80. If the assumptions are made using the worst-case scenario conditions at the time of the fault, the worst-case primary clearing time for the substation can be used for time, $t_s$. A very conservative design would use the time, $t_s$, of the backup clearing time.

6. The ground conductor size shall be determined using concepts in section 3.3.

7. The entire area inside of the fence including the minimum of 3.3 feet outside of the fence needs to have a layer that covers the area with 4 inches of protective
surface material. This material can include crushed rock or other material that will have a minimum resistivity of 3,000 ohm-meters in both wet and dry conditions.

8. The ground grid will consist of horizontal conductors placed on the ground that will produce a square mesh. One row of the horizontal conductors is equally spaced 9.8 to 49.2 feet apart. In the second row of equally spaced horizontal conductors running in the perpendicular direction to the first row is spaced in a 1:1 to 1:3 ratio of the first row's spacing. If the first row has a spacing of 9.8 feet, the second row should be spaced between 9.8 to 29.5 feet. The crossover point between the first and the second row of conductors should be bonded securely. The bonding of conductors will ensure an adequate control of surface potential, secure multiple paths for fault currents, minimize the drop in voltage in the grid and provide a measure of redundancy in an event of conductor failures. The size of grid conductors can range from 2/0 AWG to 500 kcmil.

9. The burial depth of the grid conductors should be a minimum of 18 inches to 59.1 inches below the final earth grade, not including the crushed rock covering and may be plowed in or placed in trenches. In soils that are normally dry near the surface, the burial depth may need to be deeper to obtain the needed values of grid resistance.

10. The vertical rods may be placed at grid corners or junction points along the perimeter. Ground rods can also be installed at major equipment and especially
close to surge arresters. In soils with many layers, or high-resistivity, it may be useful to use rods of longer length or install rods at additional junction points. Vertical rods should be 5/8 inch in diameter and at least 8 foot long copper, steel or any other approved type of conductor in the approved list of materials. A minimum of 1.97 inches should be below grade and bonded to the ground grid connectors. It is good practice to not space the rods closer than their length. Another determinant is to ensure that there are enough rods so that their average fault current pickup will not exceed 300 amps, assuming all ground system current will enter the grid through the rods.

11. If it is found the calculated GPR in the preliminary design is below the tolerable touch voltage, than no further analysis is necessary. The design may only need to undergo refinements.

12. Calculating the mesh and step voltage for the grid as designed can be done using techniques in sections 3.6.1 and 3.10.

13. In the case that the computed mesh voltage is below the tolerable touch voltage, the design may be complete. However, if the computed mesh voltage is greater than the tolerable touch voltage, the preliminary design should be refined.

14. If the computed touch and step voltages are not below the tolerable voltages, the preliminary design is to be revised.
15. If the step or touch tolerable limits are greater than allowed, the design will be required to undergo a revision. In the revision, items such as smaller conductor spacing or additional ground rods may be changed.

16. Once the step and touch voltage requirements are met, additional grid and ground rods may still be required. This is the case if the site is irregular or if the grid design does not include conductors near equipment to be grounded. Adding additional ground rods may be required at the base of surge arresters, transformer neutrals and other equipment. Hazards due to transferred potentials need to be taken into account as well.

2.11.3 Preliminary Design

The design criteria in the preliminary design are the tolerable touch and step voltages. In a preliminary design, the grid chosen will consist of a uniform square or rectangular mesh. This is the case in order to calculate the touch and step voltages using simplified design equations and are valid for every location within the ground grid. When the safe preliminary design is achieved, the ground grid can be further modified. Upon modification of the design, special precautions need to be made that they do not result in mesh that is larger than the one used in the preliminary design as it could result in unsafe touch and step voltages. Adding additional ground conductors to the preliminary design will allow for a more conservative design, while subtracting conductors from the preliminary design can result in an unsafe design.

The following steps are used in the preliminary design:
1. Using the layout drawing of the substation site, draw the largest square, rectangle, triangle, T-shape, or L-shape grid that will fit within the site.

2. Place the grid conductors to produce a square mesh of approximately 20 to 40 feet on a side.

3. The grid depth will be set equal to 18 inches.

4. Set the thickness of the surface material to equal 4 inches.

5. The ground rods are then to be placed around the perimeter of the substation. In general, place a ground rod at every other perimeter grid connection and at corners of the substation. Ground rods discharge most of their current through their lower portion and they are effective in controlling the large current densities that are present in the perimeter conductors during fault conditions.
Figure 2-9: Design Procedure Block Diagram.

(From IEEE Std. 80-2000 Figure 33. Copyright © 2000 IEEE. All rights reserved)
3.1 Soil Resistivity Measurements

Soil resistivity measurements are taken at the site in a number of different places. It is very uncommon to find uniform resistivity throughout the entire substation area. The measuring techniques are described in Chapter 2. Weiner four-pin method is the most common method [2]. The typical values of $D_f$ are shown in the table below.

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

The decremental factor, $D_f$, can be calculated using the following formula:

$$D_f = \sqrt{1 + \frac{T_u}{t_f} \left(1 - e^{-\frac{2t_f}{T_u}}\right)}$$

(3.1)
where

\[ t_f : \text{ time duration of the fault in seconds} \]

and

\[ T_o = \frac{X}{\omega R} \]

The value of symmetrical current is found by the following formula, if the dc offset is needed:

\[ I_f = I_f \cdot D_f \quad (3.2) \]

The soil resistivity, \( \rho \), is calculated using the formula below:

\[ \rho = \frac{4\pi aR}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}} \quad (3.3) \]

where

\[ \rho : \text{ apparent soil resistivity in } \Omega \cdot \text{m} \]

\[ R : \text{ measured resistance in ohms} \]

\[ a : \text{ distance between adjacent electrodes in meters} \]

\[ b : \text{ depth of the electrodes in meters} \]

If \( b \) is small compared to \( a \) using equation (3.3) as in a case where the probes penetrate the ground a short distance, the equation can be simplified as follows:

\[ \rho = 2\pi aR \quad (3.4) \]
Current tends to flow near the surface for small probe spacing, however more current penetrates deeper soils in large spacing. In this case the assumption is made the resistivity measure from the probe of spacing \( a \) is equal to the apparent soil resistivity of a depth \( a \).

### 3.2 Fault Currents

There are different types of faults that can occur on the system. The most probable types are given a greater consideration. These include the single-line to ground fault and the double-line to ground fault.

For double-line to ground faults, the zero-sequence fault current is:

\[
I_0 = \frac{E \cdot (R_2 + jX_2)}{(R_1 + jX_1) \cdot [(R_0 + R_1 + 3R_f + j(X_0 + X_2)] + (R_2 + jX_2) \cdot (R_0 + 3R_f + jX_0)}  \tag{3.5}
\]

where

- \( I_0 \): symmetrical rms value of zero sequence fault current in Amps
- \( E \): phase-to-neutral voltage in volts
- \( R_f \): estimated resistance of the fault. It is normally assumed to be 0 in ohms
- \( R_2 \): negative sequence equivalent system resistance in ohms
- \( R_f \): positive sequence equivalent system resistance ohms
- \( R_0 \): zero sequence equivalent system resistance in ohms
- \( X_2 \): negative sequence equivalent system reactance in ohms
- \( X_f \): positive sequence equivalent system reactance ohms
For a single–line to ground fault, the zero-sequence fault current is as follows:

\[ I_0 = \frac{E}{3R_f + R_1 + R_2 + R_0 + j(X_1 + X_2 + X_0)} \]  

(3.6)

The resistances and reactances in the equation above are calculated at the location of the fault. However, in many circumstances, the resistances are neglected, thus simplifying the equation above as follows:

The zero-sequence fault current equation for double-line to ground is as follows:

\[ I_0 = \frac{E \cdot X_2}{X_1 \cdot (X_0 + X_2) + (X_2 + X_0)} \]  

(3.7)

The zero-sequence fault current equation for single-line to ground is as follows:

\[ I_0 = \frac{E}{X_1 + X_2 + X_0} \]  

(3.8)

### 3.3 Ground Conductor Sizing

The most common materials used in for grounding are copper and copper-clad-steel as mentioned in Chapter 2.

#### 3.3.1 Conductor Sizing - Symmetrical currents

The ground conductor for the grid and equipment connections should be sized according the equation as follows:

\[ I = A_{mm^2} \sqrt[4]{\frac{TCAP \cdot 10^{-4}}{t_c \alpha_\rho}} \ln \left( \frac{K_0 + T_m}{K_0 + T_a} \right) \]  

(3.9)
where

\[ I \] : rms current in kA

\[ A_{\text{mm}^2} \] : conductor cross section in mm\(^2\)

\[ A_{\text{kcmil}} \] : conductor cross section in kcmil

\[ T_m \] : maximum allowable temperature in \(^\circ\)C

\[ T_a \] : ambient temperature in \(^\circ\)C

\[ \alpha_r \] : thermal coefficient of resistivity at reference temperature in \(T_r(1/\circ\)C\)

\[ \rho_r \] : resistivity of the ground conductor at reference temperature in \(T_r(\mu\Omega\text{-cm})\)

\[ t_c \] : duration of current in seconds

\[ K_0 \] : equals \(1/\alpha_0\) or \((1/\alpha_r) - T_r(\circ\)C\)

\[ TCAP \] : thermal capacity per unit volume in \(\text{J/cm}^2 \cdot \circ\)C

Common values of \(\alpha_r, K_0, T_m, \rho_r,\) and \(TCAP\) values can be found in Table 3-2.
Table 3-2: Constants for Typical Materials.
(From IEEE Std 80-2000 Table 3.2. Copyright © 2000. IEEE. All rights reserved)

<table>
<thead>
<tr>
<th>Description</th>
<th>Material conductivity (%)</th>
<th>$\alpha_T$ factor at 20 °C (1°C)</th>
<th>$K_0$ at 0 °C (0 °C)</th>
<th>Fusing$^a$ temperature $T_m$ (°C)</th>
<th>$\rho_20$ 20 °C (µΩ·cm)</th>
<th>TCAP thermal capacity $[J/(cm^2·°C)]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper, annealed soft-drawn</td>
<td>100.0</td>
<td>0.003 93</td>
<td>234</td>
<td>1083</td>
<td>1.72</td>
<td>3.42</td>
</tr>
<tr>
<td>Copper, commercial hard-drawn</td>
<td>97.0</td>
<td>0.003 81</td>
<td>242</td>
<td>1084</td>
<td>1.78</td>
<td>3.42</td>
</tr>
<tr>
<td>Copper-clad steel wire</td>
<td>40.0</td>
<td>0.003 78</td>
<td>245</td>
<td>1084</td>
<td>4.40</td>
<td>3.85</td>
</tr>
<tr>
<td>Copper-clad steel wire</td>
<td>30.0</td>
<td>0.003 78</td>
<td>245</td>
<td>1084</td>
<td>5.86</td>
<td>3.85</td>
</tr>
<tr>
<td>Copper-clad steel rod$^b$</td>
<td>20.0</td>
<td>0.003 78</td>
<td>245</td>
<td>1084</td>
<td>8.62</td>
<td>3.85</td>
</tr>
<tr>
<td>Aluminum, EC grade</td>
<td>61.0</td>
<td>0.004 03</td>
<td>228</td>
<td>657</td>
<td>2.86</td>
<td>2.56</td>
</tr>
<tr>
<td>Aluminum, 5005 alloy</td>
<td>53.5</td>
<td>0.003 53</td>
<td>263</td>
<td>652</td>
<td>3.22</td>
<td>2.60</td>
</tr>
<tr>
<td>Aluminum, 6201 alloy</td>
<td>52.5</td>
<td>0.003 47</td>
<td>268</td>
<td>654</td>
<td>3.28</td>
<td>2.60</td>
</tr>
<tr>
<td>Aluminum-clad steel wire</td>
<td>20.3</td>
<td>0.003 60</td>
<td>258</td>
<td>657</td>
<td>8.48</td>
<td>3.58</td>
</tr>
<tr>
<td>Steel, 1020</td>
<td>10.8</td>
<td>0.001 60</td>
<td>605</td>
<td>1510</td>
<td>15.90</td>
<td>3.28</td>
</tr>
<tr>
<td>Stainless-clad steel rod$^c$</td>
<td>9.8</td>
<td>0.001 60</td>
<td>605</td>
<td>1400</td>
<td>17.50</td>
<td>4.44</td>
</tr>
<tr>
<td>Zinc-coated steel rod</td>
<td>8.6</td>
<td>0.003 20</td>
<td>293</td>
<td>419</td>
<td>20.10</td>
<td>3.93</td>
</tr>
<tr>
<td>Stainless steel, 304</td>
<td>2.4</td>
<td>0.001 30</td>
<td>749</td>
<td>1400</td>
<td>72.00</td>
<td>4.03</td>
</tr>
</tbody>
</table>
Given a conductor size in kcmil, the following equation is applied:

\[
I = 5.07 \cdot 10^{-3} A_{\text{kcmil}} \sqrt{\frac{TCAP}{t_c \alpha_r \rho_r}} \ln \left( \frac{K_0 + T_m}{K_0 + T_a} \right)
\]  

(3.10)

The conductor area can be calculated as follows for mm\(^2\) and kcmil respectively:

\[
A_{\text{mm\(^2\)}} = I \frac{1}{\sqrt{\left( \frac{TCAP \cdot 10^{-4}}{t_c \alpha_r \rho_r} \right) \ln \left( \frac{K_0 + T_m}{K_0 + T_a} \right)}}
\]  

(3.11)

or

\[
A_{\text{kcmil}} = I \frac{197.4}{\sqrt{\left( \frac{TCAP}{t_c \alpha_r \rho_r} \right) \ln \left( \frac{K_0 + T_m}{K_0 + T_a} \right)}}
\]  

(3.12)

Equation 3.12 where conductor area is found in kcmil, the formula can be simplified with the following equation using the \(K_f\) constant found in Table 3-3:

\[
A_{\text{kcmil}} = I \cdot K_f \sqrt{I_c}
\]  

(3.13)

where

\(K_f\), constant is based on the ambient and fusing temperatures of material commonly used for ground conductors.
The size conversion from kcmil to mm$^2$ is calculated using the following formula:

$$A_{mm^2} = \frac{A_{kcmil} \cdot 1000}{1973.52}$$  \hspace{1cm} (3.14)

The diameter of a conductor can be determined by the following formula:
A thin layer of resistive surface material can be applied throughout the substation area which can greatly reduce the available shock current at the substation [2].

The equation for calculating the new ground resistance, $R_f$, that includes the added layer or resistive surface material is calculated as follows:

$$ R_f = \left( \frac{\rho_s}{4b} \right) C_s $$

(3.16)

The reduction factor can be calculated in the equation as follows:

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

(3.17)

where

the reflection factor, $K$, is calculated as follows:

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

(3.18)

$C_s$ is considered as a corrective factor to compute the effective foot resistance with a finite amount of surface material thickness. $C_s$ is tedious to calculate without using computational software, therefore a graph with pre-calculated values for $b=0.08m$ are given in Figure 3-1:
3.5 Tolerable Body Current Limits

The effects of ventricular fibrillation are very dangerous. If not treated quickly, than the effects of ventricular fibrillation can cause death [3]. Therefore, the threshold of fibrillation needs to be established as accurately as possible. Currents that the human body can withstand, without ventricular fibrillation, are assumed for 99.5% of the population. Based on Danziel's work, the body current, $I_B$, is defined as follows:
\[ I_B = \frac{k}{\sqrt{t_s}} \]  

(3.19)

where \( k = \sqrt{S_B} \)

t\(_s\) is the duration of current in seconds,

\( I_B \) is the rms magnitude of the current through the body.

k: is related to the energy that is absorbed by the body during an electric shock. K varies with respect with the person's body weight.

For a person weighing 50 kg (110 lbs), \( k = 0.116 \)

For a person weighing 70 kg (155 lbs), \( k = 0.157 \)

Equation 3.19 is based on tests limited to a range of between 0.03 and 3.0 s, and is not valid for very short or long durations. Utilizing equation 3.19, for a person weighing 50 kg and a fault duration of 1s, the non-fibrillation current equal to 116 mA. When the same equation is applied for a person weighing 70 kg for a duration 1s, the non-fibrillation current is equal to 157 mA. It can be observed that the higher the weight of the person, the more current they can withstand. Figure 3-2 below demonstrates a graphical representation of body current vs time. The time duration of current, \( t_s \), is equal to the high-speed clearing time of ground fault by the primary protection, however, if even more conservative measures are to be used, than the duration of the back-up relay clearing time can be used.
3.6 Tolerable Step and Touch voltages

The tolerable touch as step voltages need to be met in order ensure that a safe design is in place. The lower the maximum touch voltages are, the more challenges are presented in creating a design that fulfills the necessary requirements.
3.6.1 Step Voltage

Per IEEE Std, the resistance of a human body is \( R_B = 1000 \ \Omega \).

For step voltage the limit is:

\[
E_{step} = (R_B + 2 \cdot R_f) \cdot I_B
\]  

(3.20)
For a body weighing 50kg

\[ E_{step50} = (1000 + 6 \cdot C \cdot \rho) \frac{0.116}{\sqrt{t_s}} \]  \hspace{1cm} (3.21)

For a body weighing 70kg

\[ E_{step70} = (1000 + 6 \cdot C \cdot \rho) \frac{0.157}{\sqrt{t_s}} \]  \hspace{1cm} (3.22)

3.6.2 Touch Voltage

![Figure 3-5: Exposure to Touch Voltage.](From IEEE Std. 80, Figure 6. Copyright © 2000. IEEE. All rights reserved)

![Figure 3-6: Impedances in Touch Voltage Circuit.](From Substation Design6-2001. Figure 9-31. Copyright © 2001. IEEE. All rights reserved)
For touch voltage, the limit is

\[ E_{\text{touch}} = \left( R_B + \frac{R_f}{2} \right) \cdot I_B \]  

(3.23)

For a body weighing 50kg

\[ E_{\text{touch50}} = (1000 + 1.5 \cdot C_s \cdot \rho_s) \cdot \frac{0.116}{\sqrt{t_s}} \]  

(3.24)

For a body weighing 70kg

\[ E_{\text{touch70}} = (1000 + 1.5 \cdot C_s \cdot \rho_s) \cdot \frac{0.157}{\sqrt{t_s}} \]  

(3.25)

If no protective surface layer is used in the substation, \( C_s = 1 \) and \( \rho_s = \rho \).
If there is metal-to-metal contact, both hand-to-hand and hand-to-feet contact, $\rho_s=0$ since the ground is not included in this situation. In this case, the touch voltage limit equations are:

For a body weighing 50kg

$$E_{mm-touch50} = \frac{116}{\sqrt{I_s}}$$

(3.26)

For a body weighing 70kg

$$E_{mm-touch70} = \frac{157}{\sqrt{I_s}}$$

(3.27)

3.7 Ground Resistance

For uniform soil, the minimum value of the grounding resistance is approximated using the following formula:

$$R_g = \frac{\rho}{4 \sqrt{\pi A}}$$

(3.28)

where

- $A$ : area occupied by the ground grid in $m^2$
- $\rho$ : soil resistivity in $\Omega$-m
- $R_g$ : substation ground resistance in $\Omega$

Using the following formula developed by Laurent and Niemann for calculating the substation ground resistance, the upper limit can be calculated as follows:
\[ R_g = \frac{\rho}{4} \sqrt{\frac{\pi}{A}} + \frac{\rho}{L_T} \]  
(3.29)

where

\[ L_T : \text{total burial length of conductors in meters.} \]

The total burial length is the sum of horizontal, vertical conductors, and ground rods. The total burial length, \( L_T \), is calculated using the following formula:

\[ L_T = L_C + L_R \]  
(3.30)

where

\[ L_C : \text{total length of grid conductor in meters} \]
\[ L_R : \text{total length of ground rods in meters}. \]

In the equation below, it can be observed that a larger area, \( A \), in combination with a large total conductor length, \( L_T \), will result in a smaller grid resistance. Conversely, a smaller area, \( A \), in conjunction with a smaller total conductor length, \( L_T \), will result in a greater grid resistance.

If a more accurate grounding resistance approximation is desired, the following equation can be used:

\[ R_g = \rho \left[ \frac{1}{L_T} + \frac{1}{\sqrt{20}A} \left(1 + \frac{1}{1 + h\sqrt{20/A}}\right) \right] \]  
(3.31)

where

\[ h : \text{depth of the grid in meters}. \]
3.8 Maximum Grid Current

Some part of the fault current will flow to the earth through the grounding grid. This current is called the grid current. The grid current is defined using the following equation:

\[ I_G = D_f \cdot I_g \]  \hspace{1cm} (3.32)

where

- \( I_G \): is the maximum grid current in Amps
- \( D_f \): decrement factor for the duration of the fault is found in Table 5
- \( I_g \): rms symmetrical grid current in Amps

The symmetrical grid current, \( I_g \), which is used in calculating the grid current in the equation above is defined as follows:

\[ I_g = S_f \cdot I_f \]  \hspace{1cm} (3.33)

where

- \( I_g \): rms symmetrical grid current in Amps
- \( I_f \): rms symmetrical grid fault current in Amps
- \( S_f \): fault current division factor

3.9 Ground Potential Rise (GPR)

GPR - Ground potential rise is “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.” GPR is equal to the maximum grid current times the grid resistance as defined in the equation below:

\[ GPR = I_G \cdot R_g \]  \hspace{1cm} (3.34)

where

- \( R_g \): substation ground resistance in ohms
- \( I_G \): maximum grid current in Amps

### 3.10 Computing Maximum Mesh and Step Voltages

#### 3.10.1 Mesh Voltage (\(E_m\))

The mesh voltage is the highest possible touch voltage within a substations grounding grid. The basis of a safe grounding grid system is the mesh voltage. This includes the grounding grid inside the substation and outside of the substation fence. For a safe grounding grid system, the mesh voltage needs to be less than the touch voltage.

The mesh voltage is calculated using the formula as follows:

\[ E_m = \frac{\rho \cdot I_G \cdot K_m \cdot K_i}{L_M} \]  \hspace{1cm} (3.35)

where

- \( \rho \): resistivity of earth in ohm meters
- \( L_M \): effective burial length in meters
- \( K_m \): geometrical spacing factor
- \( K_i \): irregularity factor
$K_m$ is the geometrical spacing factor for the mesh voltage and is defined as:

$$K_m = \frac{1}{2 \cdot \pi} \left[ \ln \left( \frac{D^2}{16 \cdot h \cdot d} + \frac{(D + 2 \cdot h) - h}{8 \cdot D \cdot d} \right) + \frac{K_{ii}}{K_h} \cdot \ln \left( \frac{8}{\pi (2 \cdot n - 1)} \right) \right]$$  \hspace{1cm} (3.36)

where

- $D$ : spacing between parallel conductors in meters
- $d$ : diameter of grid conductors in meters
- $h$ : depth of ground grid conductors in meters
- $K_{ii}$ : corrective weighting that adjusts effects of inner conductors on the corner mesh
- $K_h$ : corrective weighting factor emphasizing the grid depth effects

The corrective weighting factor, $K_h$, is defined as follows:

$$K_h = \sqrt{1 + \frac{h}{h_0}}$$  \hspace{1cm} (3.37)

where

- $h_0$ : is the grid reference at depth equivalent to 1

The corrective weighting factor, $K_{ii}$, varies with different situations. In the case of the ground rods being along the perimeter of the site as well as throughout the substation grid and corners, $K_{ii}$ is defined as follows:

$$K_{ii} = 1$$
In the case of grounding grids with no or insignificant amount of rods and the rods not being located about the perimeter or corners, the corrective weighting factor, $K_{ii}$, is defined as follows:

$$K_{ii} = \frac{1}{(2 \cdot n)^{\frac{1}{n}}}$$  \hspace{1cm} (3.38)

The geometric factor, $n$, is defined below as follows:

$$n = n_a \cdot n_b \cdot n_c \cdot n_d$$  \hspace{1cm} (3.39)

meanwhile the equivalents of the factors are as follows,

$$n_a = \frac{2 \cdot L_c}{L_p}$$  \hspace{1cm} (3.40)

$n_b$= 1 for square grids

$n_c$= 1 for square and rectangular grids

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

If the factors do not meet criteria above, they can be calculated below as follows:

$$n_p = \frac{L_p}{\sqrt{4 \cdot \sqrt{A}}}$$  \hspace{1cm} (3.41)

$$n_c = \left[ \frac{L_x \cdot L_y}{A} \right]^{0.7 \cdot \frac{A}{L_x \cdot L_y}}$$  \hspace{1cm} (3.42)

$$n_d = \frac{D_m}{\sqrt{L_x^2 + L_y^2}}$$  \hspace{1cm} (3.43)

where
$L_C$ : total length of conductor in the horizontal grid in meters

$L_p$ : peripheral length of grid in meters

$D$ : spacing between parallel conductors in meters

d : diameter of grid conductors in meters

$h$ : depth of ground grid conductors in meters

$A$ : area of grid in squared meters

$L_x$ : maximum length of grid in the x-direction in meters

$L_y$ : maximum length of grid in the y-direction in meters

$D_m$ : maximum distance between any two points on the grid in meters

The irregularity factor, $K_i$, can be calculated as follows:

$$K_i = 0.644 + 0.148 \cdot n$$  \hspace{1cm} (3.44)

In the case of the grids with no or few ground rods with no rods being along the perimeter or corners, the effective buried length, $L_M$, is calculated as follows:

$$L_M = L_C + L_R$$  \hspace{1cm} (3.45)

where

$L_C$ : total length of conductor in the horizontal grid in meters

$L_R$ : total length of all ground rods in meters

In the case of ground grids with ground rods located throughout the grid and at the perimeter and corners, the effective buried length, $L_M$, is calculated as follows:

$$L_M = L_C + \left[ 1.55 + 1.22 \left( \frac{L_x}{\sqrt{L_x^2 + L_y^2}} \right) \right] L_R$$  \hspace{1cm} (3.45)
where

\[ L_r : \text{ total length of each ground rods in meters.} \]

### 3.10.2 Step Voltage \((E_s)\)

In order for the step voltage to be within tolerable limits, the system has to be designed for safe mesh voltages and less than the tolerable step voltage. Usually, step voltages are lower than touch voltages. This is because the feet are in series. The human body is able to withstand a larger current through the foot-to-foot path; this is because the current does not pass through the heart.

The mesh voltage is defined as follows:

\[ E_s = \frac{D \cdot K_s \cdot K_i \cdot I_G}{L_s} \tag{3.47} \]

The effective buried conductor length \(L_s\) is defined as follows:

\[ L_s = 0.75 \cdot L_c + 0.85 \cdot L_r \tag{3.48} \]

The step factor, \(K_s\), is defined as follows

\[ K_s = \frac{1}{\pi} \left[ \frac{1}{2 \cdot h} + \frac{1}{D + h} + \frac{1}{D} (1 - 0.5^{n-2}) \right] \tag{3.49} \]

where

\[ D : \text{ spacing between parallel conductors in meters} \]

\[ h : \text{ depth of ground grid conductors in meters} \]

\[ n : \text{ geometric factor composed of factors } n_a, n_b, n_c, \text{ and } n_d \]
CHAPTER 4 - APPLICATION

4.1 Initial Parameters

Initial Design of Elk-Grove Florin 12kV substation grounding case study

parameters are given below in Table 4-1 as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Soil resistivity</td>
<td>57.4 $\Omega$.m</td>
</tr>
<tr>
<td>Fault current split Factor</td>
<td>0.6</td>
</tr>
<tr>
<td>Fault Current</td>
<td>13785A</td>
</tr>
<tr>
<td>Crushed rock layer inside sub</td>
<td>0.1016m</td>
</tr>
<tr>
<td>Resistivity of crushed Rock layer</td>
<td>2500$\Omega$.m</td>
</tr>
<tr>
<td>Grid buried 18”</td>
<td>0.4572m</td>
</tr>
<tr>
<td>Switch Yard operator</td>
<td>&gt;50kg</td>
</tr>
<tr>
<td>Current Division Factor $S_f$</td>
<td>0.6</td>
</tr>
<tr>
<td>Soil location Type</td>
<td>Uniform</td>
</tr>
<tr>
<td>Length in X direction</td>
<td>100 m</td>
</tr>
<tr>
<td>Projection Factor</td>
<td>20%</td>
</tr>
<tr>
<td>Length in Y direction</td>
<td>90 m</td>
</tr>
<tr>
<td>Shock Duration</td>
<td>0.5s</td>
</tr>
<tr>
<td>Ambient Temperature</td>
<td>40°C</td>
</tr>
<tr>
<td>Fault duration</td>
<td>0.5s</td>
</tr>
<tr>
<td>Grid Shape</td>
<td>Rectangular</td>
</tr>
</tbody>
</table>

4.2: Field Data (Step 1)

The Area for the substation is given as 100m x 90m, with assumption of average soil resistivity of 57.4 $\Omega$.m.
4.3: Obtaining the Conductor Size (Step 2)

Calculation of ground fault as given in the table given

\[ I_f = 3I_0 = 13785 \text{ A} \]  \hspace{1cm} (4.1)

where \( X/R \) is assumed to be 10.

Adding the current protection factor with growth factor of 20\%, the ground fault current is computed as follows:

\[ I_f = 3I_0 = 16542 \text{ A}. \]

Using Table 3-1 for the \( X/R \) ratio and fault duration given in Table 3-1, it is found that the decrement, \( D_f = 1.026 \).

Now finding the rms symmetrical fault current is calculated as follows:

\[ I_f = I_f \cdot D_f \]  \hspace{1cm} (4.2)

\[ = 16972.092 \text{ A} \]

Assuming the use of copper-clad steel wire at ambient temperature (\( T_a \)) of 30\(^\circ\) C with melting temperature of 1084\(^\circ\) C, \( K_f = 10.45 \) using Table 3.1

The required cross-sectional area in circular mils is computed as follows:

\[ A_{kcml} = I \cdot K_f \cdot \sqrt{I_c} \]  \hspace{1cm} (4.3)

\[ = 16972.092 \times 10.45 \times \sqrt{0.5} \]

\[ = 83.21 \ \text{Kcmil} \]

Converting to \( A_{kcml} \) to \( \text{mm}^2 \) is computed below as follows:
\[ A_{mm^2} = \frac{A_{kcmil} \cdot 1000}{1973.52} = 75.6534 mm^2 \]  \hfill (4.4)

Thus the conductor diameter is equivalent to

\[ d = \sqrt{\frac{4 \cdot A_{mm^2}}{\pi}} \]  \hfill (4.5)

\[ d = \sqrt{\frac{4 \cdot 30.5788}{\pi}} = 9.8145 \text{ mm or 0.0098145 m} \]

Table 4-2: Computed Value of d for use of Best Material for Optimization

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity</th>
<th>T (°c)</th>
<th>K_f</th>
<th>A_{kcmil}</th>
<th>A_{mm^2}</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper, annealed soft drawn</td>
<td>100.00</td>
<td>1083.00</td>
<td>7.00</td>
<td>84.01</td>
<td>42.57</td>
<td>7.36</td>
</tr>
<tr>
<td>Copper, commerical hard drawn</td>
<td>97.00</td>
<td>1084.00</td>
<td>7.06</td>
<td>84.73</td>
<td>42.93</td>
<td>7.40</td>
</tr>
<tr>
<td>Copper, commerical hard drawn</td>
<td>97.00</td>
<td>250.00</td>
<td>11.78</td>
<td>141.37</td>
<td>71.63</td>
<td>9.55</td>
</tr>
<tr>
<td>Copper-clad steel wire</td>
<td>40.00</td>
<td>1084.00</td>
<td>10.45</td>
<td>125.41</td>
<td>63.55</td>
<td>9.00</td>
</tr>
<tr>
<td>Copper-clad steel wire</td>
<td>30.00</td>
<td>1084.00</td>
<td>12.06</td>
<td>144.73</td>
<td>73.34</td>
<td>9.67</td>
</tr>
<tr>
<td>Copper-clad steel rod</td>
<td>20.00</td>
<td>1084.00</td>
<td>14.64</td>
<td>175.70</td>
<td>89.03</td>
<td>10.65</td>
</tr>
<tr>
<td>Aluminum EC grade</td>
<td>61.00</td>
<td>657.00</td>
<td>12.12</td>
<td>145.45</td>
<td>73.70</td>
<td>9.69</td>
</tr>
<tr>
<td>Aluminum 5005 Alloy</td>
<td>53.50</td>
<td>652.00</td>
<td>12.41</td>
<td>148.93</td>
<td>75.47</td>
<td>9.80</td>
</tr>
<tr>
<td>Aluminum 6201 Alloy</td>
<td>52.50</td>
<td>654.00</td>
<td>12.47</td>
<td>149.65</td>
<td>75.83</td>
<td>9.83</td>
</tr>
<tr>
<td>Aluminum-clad steel wire</td>
<td>20.30</td>
<td>657.00</td>
<td>17.20</td>
<td>206.42</td>
<td>104.59</td>
<td>11.54</td>
</tr>
<tr>
<td>Steel 1020</td>
<td>10.80</td>
<td>1510.00</td>
<td>15.95</td>
<td>191.42</td>
<td>96.99</td>
<td>11.12</td>
</tr>
<tr>
<td>Stainless Clad steel rod</td>
<td>9.80</td>
<td>1400.00</td>
<td>14.92</td>
<td>179.06</td>
<td>90.73</td>
<td>10.75</td>
</tr>
<tr>
<td>Zinc-coated steel rod</td>
<td>8.60</td>
<td>419.00</td>
<td>28.96</td>
<td>347.55</td>
<td>176.11</td>
<td>14.98</td>
</tr>
<tr>
<td>Stainless steel 304</td>
<td>2.40</td>
<td>1400.00</td>
<td>30.05</td>
<td>360.63</td>
<td>182.74</td>
<td>15.26</td>
</tr>
</tbody>
</table>

As shown in the calculation, we now can pick the wire we may want to use biased on cost and reliability.
4.4: Touch and Step Criteria (Step 3)

For a crushed rock-surfacing layer of 0.01268m, having resistivity of 2500Ω m and with the computed soil resistivity of 57.4Ω m, the reflection factor K is computed as:

\[
K = \frac{\rho - \rho_s}{\rho + \rho_s} = \frac{57.4 - 2500}{57.4 + 2500} = -0.9511
\]  

(4.6)

For the \( K = -0.93548 \). The crushed rock is to be de-rated by a factor of approximately, \( C_s \), which is computed as:

\[
C_s = 1 - \frac{0.09(1 - \frac{\rho}{\rho_s})}{2 \cdot h_s + 0.09}
\]  

\[
= 1 - 0.09(1 - \frac{57.4}{2500})
\]

\[
= \frac{1 - 0.09(1 - \frac{57.4}{2500})}{2 \cdot 0.1016 + 0.09} = 0.70
\]  

(4.7)

Now optimizing the crushed rock layer thickness

Table 4-3: Calculated Resistivity De-rating Factor for Crushed Rock

<table>
<thead>
<tr>
<th>Crushed Rock Layer</th>
<th>Resistivity De-rating Factor</th>
<th>Surface Layer Resistivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>No crushed rock</td>
<td>1</td>
<td>120</td>
</tr>
<tr>
<td>0.10</td>
<td>0.70</td>
<td>2500</td>
</tr>
<tr>
<td>0.15</td>
<td>0.77</td>
<td>2500</td>
</tr>
<tr>
<td>0.20</td>
<td>0.82</td>
<td>2500</td>
</tr>
<tr>
<td>0.25</td>
<td>0.85</td>
<td>2500</td>
</tr>
</tbody>
</table>

This also could be found in Table 3-1.
In the design criteria, the switch operator or the maintenance would be approximate 50kg or heavier.

The step and touch voltages are calculated as follows:

\[ E_{\text{step}} = (1000 + 6 \cdot C_s \cdot \rho_s) \frac{0.116}{\sqrt{t_s}} \]  \hspace{1cm} (4.8)

\[ E_{\text{step}} = (1000 + 6 \cdot 0.7 \cdot 2500) \frac{0.116}{\sqrt{t_s}} = 1866.56 \text{V} \]

\[ E_{\text{touch}} = (1000 + 1.5 \cdot C_s \cdot \rho_s) \frac{0.116}{\sqrt{t_s}} \]  \hspace{1cm} (4.9)

\[ E_{\text{touch}} = (1000 + 1.5 \cdot 0.7 \cdot 2500) \frac{0.116}{\sqrt{t_s}} \]

\[ = 594.67 \text{ V} \]

Table 4- 4: Prospective touch and step voltage with crushed rock thickness

<table>
<thead>
<tr>
<th>Location</th>
<th>Crushed Rock Layer Thickness (m)</th>
<th>Prospective Touch Voltage (V)</th>
<th>Prospective Step Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substation</td>
<td>No Crushed Rock</td>
<td>779.2316</td>
<td>2624.7808</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>594.6768</td>
<td>1886.5609</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>637.7396</td>
<td>2058.8121</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>668.4988</td>
<td>2181.8486</td>
</tr>
</tbody>
</table>

4.5: Initial Design (Step 4)

The design is based on the minimum amount of conductor needed that fulfills the requirements.
Figure 4- 1: 4 Cases Demonstrating Varying Conductor Amounts.

Case A - showing no ground rods, Case B - 4 ground rods, Case C - 8 ground rods and
Case D - 10m spacing with 8 ground rods.

Configuration options are presented as follows:
Table 4-5: Optimization of Different Cases.

<table>
<thead>
<tr>
<th>Option case</th>
<th>Horizontal Mesh conductor spacing</th>
<th>Vertical Electrode Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>10x30</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>10x30</td>
<td>4</td>
</tr>
<tr>
<td>C</td>
<td>10x30</td>
<td>8</td>
</tr>
<tr>
<td>D</td>
<td>20x30</td>
<td>8</td>
</tr>
</tbody>
</table>

Assuming any given area for 100m x 90m with equally spaced conductors shown in the Figure 4-1 having spacing 5m and the grid burial depth h=3m.

Thus the grid conductor combined length is

\[ L_c = L_1 \cdot L_x + L_2 \cdot L_y \]  
\[ = 4 \cdot 100 + 11 \cdot 90 \]
\[ = 1390 \] (4.10)

Assuming 4 ground rods of 3 meters long are used:

\[ L_R = 4 \times 3 = 12 \text{m} \]  
(4.11)

The total length of buried conductor would be computed as

\[ L_T = L_c + L_R \]  
\[ = 1390 + 12 \text{m} \]
\[ = 1402 \text{m} \] (4.12)
Table 4-6: Total length in buried in all cases

<table>
<thead>
<tr>
<th>Case Options</th>
<th>Grid conductor combined length (m)</th>
<th>Buried conductor length (m)</th>
<th>Total length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1390</td>
<td>0</td>
<td>1390</td>
</tr>
<tr>
<td>B</td>
<td>1390</td>
<td>12</td>
<td>1402</td>
</tr>
<tr>
<td>C</td>
<td>1390</td>
<td>24</td>
<td>1414</td>
</tr>
<tr>
<td>D</td>
<td>1210</td>
<td>24</td>
<td>1234</td>
</tr>
</tbody>
</table>

4.6: Determination of Grid Resistance (Step 5)

From the previous computations, the length of buried conductor is known to be 1,402 m, having an area $A=9000m^2$.

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

$$= 57.4 \left[ \frac{1}{1402} + \frac{1}{\sqrt{20\cdot9000}} \left( \frac{1}{1 + \frac{1}{1+0.4572\sqrt{20/9000}}} \right) \right]$$

$$= 0.30867 \, \Omega$$

(4.13)

4.7: Maximum Grid Current $I_G$ (Step 6)

Calculating, $I_G$, using IEEE Std.80-2000 is done as follows:

$$I_g = I_f \cdot S_f$$

(4.14)
= 16542 x 0.6 A

and

\[ I_G = D_f \cdot I_g \]
\[ = D_f \cdot 3 \cdot I_0 \cdot S_f \]
\[ = (1.026) \cdot (16542) \cdot (0.6) \]
\[ = 10183.26 \text{ A} \]  

(4.15)

4.8: Calculating GPR (Step 7)

To calculate the GPR and compare with touch voltage.

\[ GPR = I_G \cdot R_v = 3142.26 \text{ v} \]  

(4.16)

Comparing with the touch voltage computed in step 3 which was 594.67 V. The GPR is far exceeds the safe touch voltage. But to optimize cost, rods can be reduced to ensure no overspending occurs.

4.9: Mesh Voltage and Step Voltages (Step 8)

\[ n_u = \frac{2 \cdot L_C}{L_p} \]
\[ = \frac{2 \cdot 1390}{2 \cdot 100 + 2 \cdot 90} \]
\[ = 7.32 \]  

(4.17)

Since there is a rectangular grid,
\[ n_b = \sqrt{\frac{L_p}{4 \cdot \sqrt{A}}} = \frac{380}{\sqrt{4 \cdot \sqrt{9000}}} = 1.00693 \]  
(4.18)

\[ n_c = 1 \]

\[ n_d = 1. \]

Now we calculate the geometric factor,

\[ n = n_a \cdot n_b \cdot n_c \cdot n_d = 7.32 \cdot 1.006 \cdot 1 \cdot 1 = 7.363 \]  
(4.19)

With the value of \( n \) found, the irregularity factor \( K_i \) is calculated as

\[ K_i = 0.644 + 0.148 \cdot n = 0.644 + 0.148 \cdot 7.363 = 1.733 \]  
(4.20)

Since the ground rods are in corners and around the perimeter, the corrective weighting factor is:

\[ L_M = L_c + \left[ 1.55 + 1.22 \left( \frac{L_p}{\sqrt{L_x^2 + L_y^2}} \right) \right] L_R \\
= 1390 + \left[ 1.55 + 1.22 \left( \frac{3}{\sqrt{(4 \cdot 100)^2 + (11 \cdot 90)^2}} \right) \right] 12 \\
= 1408.64 \text{m} \]  
(4.21)
Now computing for the corrective weighted factor $K_h$, for a ground grid conductor buried at the depth of 0.4572 m

$$K_h = \sqrt{1 + \frac{h}{h_b}}$$

$$= \sqrt{1 + \frac{0.4572}{1}}$$

$$= 1.2329$$ \hspace{1cm} (4.22)

Calculating the geometrical spacing factor, $K_m$, for the mesh voltage:

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

$$= \frac{1}{2 \cdot \pi} \ln \left[ \frac{5^2}{16 \cdot 0.4572 \cdot 0.01168} + \frac{(5 + 2 \cdot 0.4572)}{8 \cdot 5 \cdot 0.01168} - \frac{0.4570}{4 \cdot 0.011672} \right]$$

$$+ \frac{1}{2 \cdot \pi} \cdot \frac{1}{1.225} \ln \left( \frac{8}{\pi(2 \cdot 7.363 - 1)} \right)$$

$$= 0.736$$ \hspace{1cm} (4.23)

Finally the mesh voltage, $E_m$, is computed as follows

$$E_m = \frac{\rho \cdot I_G \cdot K_m \cdot K_i}{L_m}$$

$$= \frac{57.4 \cdot 10183.26 \cdot 0.736 \cdot 1.733}{1408.64}$$

$$= 529.29 \text{ V}$$ \hspace{1cm} (4.24)
Now to calculate the step voltage for the effective buried conductor length, \( L_s \), for this design, the following formula is applied:

\[
L_s = 0.75 \cdot L_c + 0.85 \cdot L_r \\
= 0.75 \cdot 1390 + 0.85 \cdot 12 \\
= 1052.7 \text{m} \tag{4.25}
\]

With the height \( h = 0.472 \text{m} \) and spacing between conductors \( D = 5 \text{ m} \) and \( n = 7.363 \).

In computing the step factor is now computed:

\[
K_s = \frac{1}{\pi} \left[ \frac{1}{2 \cdot h} + \frac{1}{D + h} + \frac{1}{D} \left(1 - 0.5^{n-2}\right) \right] \\
= \frac{1}{\pi} \left[ \frac{1}{2 \cdot 0.4571} + \frac{1}{5 + 0.4571} + \frac{1}{5} \left(1 - 0.5^{7.363-2}\right) \right] \\
= 0.46856 \tag{4.26}
\]

Now the, \( E_s \), is computed as follows

\[
E_s = \frac{\rho \cdot K_s \cdot K_e \cdot I_G}{L_s} \\
= \frac{57.4 \cdot 0.46856 \cdot 1.733 \cdot 10183.26}{1052.7} \\
= 450.87 \text{V} \tag{4.27}
\]

**4.10: \( E_m \) vs \( E_{touch} \) (Step 9)**

Once all computations are completed, the calculation results are compared in order to see if the touch voltage is below the mesh voltage

\[
E_{touch,50} = 594.67 \text{ V} \\
E_m = 529.29 \text{ V V}
\]

Clearly, we can see that the mesh voltage is smaller than the tolerable touch voltage.
4.11: $E_s$ vs. $E_{step}$ (Step 10)

Comparing step voltages to the tolerable step voltage is done below:

$$E_{touch_{50}} = 1886.56 \text{ V}$$

$$E_s = 450.87 \text{ V}$$

In comparing the step voltage, it is lower than the tolerable step voltage. However, in this case there are only 4 ground rods which saves costs of over implementation.

4.12: Modification (Step 11)

In this case, modification was not necessary but using a software application would have produced a better-optimized design, choosing different layouts.

4.13: Detailed design (Step 12)

Here all additional ground rods for surge arrestors should be added to complete the design.
CHAPTER 5 - CONCLUSION

In a substation, design of grounding is very important, not only should the design be able to comply with IEEE safety standards, but also be cost effective at the same time. This project has presented the design and optimization of a substation while maintaining flexibility of working around limitations based on land availability and materials.

Different conductors have different properties and costs. The selection of ideal conductor needs to be based on location, temperature, availability and reliability.

This report follows the design and implementation as described in IEEE Std 80-2000 and all steps are explained with sample calculations presented. As seen in the project, the grounding grid could be optimized in several ways which include: the size of the grid, total number of grounding rods place, and the depth at which the grounding is placed. There are few values that can be adjusted and they are explored in order to achieve the most cost-effective solution. It is practical for utilities needing a cost-effective solution while meeting the grounding needs.
Sample interface for calculating tolerable step and touch voltage.

APPENDIX A

USING GUI MATLAB to optimize substation grounding
Sizing of conductor Size

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault current</td>
<td>13785</td>
</tr>
<tr>
<td>DF</td>
<td>1.026</td>
</tr>
<tr>
<td>Ambient</td>
<td>30</td>
</tr>
<tr>
<td>tc</td>
<td>0.5</td>
</tr>
<tr>
<td>KF</td>
<td>10.45</td>
</tr>
</tbody>
</table>

Result:
- $63.547 \text{ mm}^2$
- $125.411 \text{ Kcmil}$
- $8.99503 \text{ d}$
Using Interactive GUI Method to compute interactive solution

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lx</td>
<td>100</td>
<td>h</td>
<td>0.4572</td>
</tr>
<tr>
<td>Ly</td>
<td>90</td>
<td>ho</td>
<td>1</td>
</tr>
<tr>
<td>Rows</td>
<td>4</td>
<td>D</td>
<td>5</td>
</tr>
<tr>
<td>column</td>
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<td>d</td>
<td>0.011368</td>
</tr>
<tr>
<td>grnd L</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>grndNz</td>
<td>4</td>
<td>Mesh Em</td>
<td>450.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mesh Es</td>
<td>529.29</td>
</tr>
</tbody>
</table>
% matlab code for substation design

Lx=90
Ly=100
Io=18470
P=57.4
P1=2500
hs=0.1016
wt=80
numrws=4
numcolm=11
numgrnd=4
rodlength=3
h=0.4572
Sf=0.6
ho=1
D=5

A= Lx*Ly % area of the grid

% calculating ground fault

If= Io*3
If growth = 1.2 * If% using growth factor 20% (*1.2)

Df = 1.026

IF = Df * Ifgrowth% Df = Decrement factor

Kf = 7.06

tc = 0.5

Akcmil = IF * Kf * sqrt(tc) * (1/1000) % finding the cross section area in k

Ammsq = Akcmil * 1000 / 1973.52 % converting to kcmil to mm^2

d = sqrt(4 * Ammsq / pi) % finding the conductor Diameter

% touch and step Criteria

K = (P - P1) / (P + P1) % Reflection factor K

Cs = 1 - ((0.09 * (1 - P / P1)) / (2 * hs + 0.09)) % computing the reduction factor

if (wt > 70)

Estep70 = (1000 + 6 * Cs * P1) * 0.157 / sqrt(tc) % finding the step @ 70kg

Etouch70 = (1000 + 1.5 * Cs * P1) * 0.157 / sqrt(tc) % finding the touch voltage.

else

Estep50 = (1000 + 6 * Cs * P1) * 0.116 / sqrt(tc) % finding the step @ 50kg

Etouch50 = (1000 + 1.5 * Cs * P1) * 0.116 / sqrt(tc) % finding the touch voltage.
end

% finding total length of the area 90*100

Lc = (numrws*Lx) + (numcolm*Ly) % finding total length rods used

Lr = numgrnd*rodlength% numer of ground rod used.

Lt = Lc+Lr% total length of rods used

% Determination of grid resistance

Rg = P*((1/Lt)+((1/(sqrt(20*A)))*(1/(1+h*sqrt(20/A))))))

%maximum grid Current Ic

Ig = If*Sf IG = Df*Ig

GPR = IG*Rg

% Mesh Voltage ans step voltage

Lp = 2*Lx+2*Ly

na = 2*Lc/Lp% geometric Factor

nb = sqrt(Lp/(4*sqrt(A)))

nc = 1
\[ \text{nd}=1 \]

\[ n=\text{na} \times \text{nb} \times \text{nc} \times \text{nd} \]

\[ \text{ki}=0.644 + 0.148 \times n \]

\% calculating corrective weighting factor

\[ \text{Ki}=1 \]

\[ \text{Lm}= \text{Lc}+(1.55+1.22 \times \left( \frac{\text{Lr}}{\sqrt{(\text{Lx}^2+\text{Ly}^2)}} \right)) \]

\% corrective weighted factor

\[ \text{Kh}= \sqrt{1 + \left( \frac{\text{h}}{\text{ho}} \right)} \]

\% calculating step factor

\[ \text{Ks}= \left( \frac{1}{\pi} \right) \times \left( \frac{1}{2 \times \text{h}} \right) + \left( \frac{1}{\text{D}+\text{h}} \right) + \frac{1}{\text{D}} \times (1-0.5^{(n-2)}) \]

\% step voltage

\[ \text{Es}= \text{P} \times \text{Ks} \times \text{Ki} \times \text{IG} \]
REFERENCES


