DESIGN OF A GROUNDING GRID FOR A 230/69kV SWITCHYARD

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Department of Electrical and Electronic Engineering
Abstract

of

DESIGN OF A GROUNDING GRID FOR A 230/69kV SWITCHYARD

by

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A grounding system is required for a switchyard that contains two 230/69kV step down transformers and other equipments. The design of a grounding system will help with the safety of personnel and protection of equipments within the substation, if a fault were to occur in the switchyard.

The design of the grounding system in this project is heavily referenced to Institute of Electrical and Electronics Engineers (IEEE) 80 Std-2000. Other standards and textbooks are also used for the design of this grounding system.

Equations obtained from cited references were entered in an excel sheet for calculations. Hand calculations were also done for a second verification of solutions obtained. A third solution is provided by a computer program called WinIGS.

________________________________, Committee Chair
Turan Gonen, Ph.D

_________________________________

Date

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Chapter 1

INTRODUCTION

Grounding is one of the most important steps when designing a switchyard. Switchyards usually contain equipments that distribute high amounts of currents and potential to other areas. It is empirical to have a grounding system that would help lower the current and potential to a safe level during a fault. Grounding provides safety for personnel by preventing dangerous levels of shock. It also prevents or reduces electrical equipment damage, which helps cut cost to buying new equipments if it was beyond repair.

In this project, a grounding system will need to be designed for a switchyard. The switchyard contains high voltage equipments such as two 230/69kV step-down transformers, breakers for protection, instrument transformers and many more. The purpose of this power system will not be a concern as the grounding system is the main concentration. The grounding system will be designed to meet standards for the protection of personnel and the electrical equipments in the vicinity of the fault.

The next chapter will provide general considerations when designing a grounding system. Definitions of terms that are commonly used will be provided for a better understanding of this subject. Chapter 3 will provide the mathematical equations used in this project along with the definitions of each variable associated with each equation. Chapter 4 applies the equations described in Chapter 3 according to the parameters given or calculated for this project. The results shown on Chapter 4 will also be analyzed and compared to a computer simulation.
Chapter 2

TERMINOLOGIES AND BASICS OF GROUNDING

2.1 Introduction

Designing a grounding system is an important step when an engineer is given a project to design a switchyard. The purpose of a grounding system is to provide a less hazardous area for electrical equipments and personnel located within the faulted area. In general, personnel should be safe from electrical shocks and electrical equipments are protected from high currents that can cause major damages.

A grounding system is may look like a simple design to be considered important when someone with little or no experience see nothing but conductors and soil. In truth, there are more involved in designing a grounding system than what is in front of the eyes. A grounding system consist of many components, such as the soil for which the ground grid is to be installed, ground rods, a surface layer for increasing the resistance for a human body, bare conductors, and ground enhancing materials if the soil is highly resistive. The next few sections in this chapter will discuss the preparation necessary for the initial design.

2.2 Definitions

Definitions are provided below to help better understand the terms used when designing and discussing with others about grounding system. It is important to understand these terms and not have any confusion with similar terms that are used. For example, the terms grounding conductor and grounding electrode conductor have similar definitions.
**Ground** – A conducting connection which electrical equipment is connected to the earth or a large body that takes place of earth.

**Grounding Electrode** – A conductor buried into the earth that is mainly used for dissipating ground currents into the earth.

**Ground Potential Rise** – Maximum potential that exist within a substation grounding grid relative to a remote earth.

**Grounding Grid** – Horizontal grounding conductors, buried at a certain depth below the switchyard in a grid shape, which provides a common ground for dissipating current and decreasing potential gradient.

**Mesh Voltage** – “The maximum touch voltage within a mesh of a ground grid” [3].

**Step Voltage** – The voltage between two feet that are 1 meter apart with no contact by any part of a person’s body on any grounded objects.

**Touch Voltage** – “The potential difference between the ground potential rise (GPR) and the surface potential at the point where a person is standing while at the same time having a hand in contact with a grounded structure” [3].

### 2.3 Purpose of Grounding

As mentioned above, the general idea behind a grounding system is to provide safety for personnel and protection of electrical equipments. Turan Gonen gives five specific reasons for having a grounding system [1]:

1. To provide the ground connection for the grounded neutral for transformers, reactors, and capacitors.
2. To provide the discharge path for lightning rods, arresters, gaps, and similar devices.

3. To ensure safety to operating personnel by limiting potential differences than can exist in a substation.

4. To provide a means of discharging and de-energizing equipment in order to proceed with the maintenance of the equipment.

5. To provide a sufficiently low resistance path to ground to minimize rise in ground potential with respect to remote ground.

The reasons mentioned above gives a general idea that a fault in a switchyard will provide high currents. The high current is brought to a safe level by providing a path to ground, where it will be safer for personnel and equipments.

2.4 Measuring Soil Resistivity

The grounding system, specifically the ground grid, is installed underground at a certain depth. Therefore, the soil where the grounding system is installed is taken into consideration as part of the design. Soil will need to be considered as part of the design because, depending on what type of soil, it can vary in resistivity. The resistivity of the soil affects the path currents will take during ground fault.

Based on IEEE Std 81-1983, there are currently three methods in measuring soil resistivity. The third method, which is considered to be the most accurate, consists of two sub methods that can be used to measure soil resistivity. Each sub methods will produce similar results. The three methods are [2]:

1. Variation of Depth Method (Three Point Method).
2. Two-Point Method.

3. Four-Point Method
   a. Equally Spaced or Wenner Arrangement.
   b. Unequally-spaced or Schlumberger-Palmer Arrangement.

Although the procedure of measurement and interpretation of soil resistivity data is out of the scope of this project, it is highly recommended for a designer to take a look at IEEE Std 80 and IEEE Std 81.

Ideally, an engineer would like the soil to be uniform to make analyzing of the soil easier. In practical situations, however, soil tends to vary horizontally and vertically. It also varies due to temperature and moisture content of the soil. The soil resistivity data can be treated as uniform, two-layer, or multi-layer model.

2.5 Ground Grid Area

The area allowable for construction could determine the size of the ground grid. Typically, the ground grid could have a vast amount of area to be considered during designing, but that would not be economically feasible. More construction for a wide area with more conductors may not be necessary when a smaller area could be used.

There are also other reasons why the size of the ground grid could be limited. For example, a pumping station that is sitting next to a reservoir could have a limited amount of ground space beneath the plant because one side will be filled with water and the other side is just air.

The grounding system does not necessarily have to be in a form of a square or rectangle. Depending on the layout of the switchyard or whichever the ground system is
protection, the grounding system could very well end up being an L-shaped or T-shaped grid. Fences are usually installed along the switchyard to prevent access to the public. These fences will need to be grounded and bonded to the grid or an underground conductor because of its ability to conduct electricity. According to IEEE Std 80, the switchyard grounding design “should be such that the touch potential on the fence is within the calculated tolerable limit of touch potential”[3].

2.6 Ground Faults

Basic circuit theory tells us that currents take the path of least resistance. During a ground fault, most of the currents will take the path of least resistance. However, there will be some currents that could take other path as well. These paths could be anywhere from the surface layer of the switchyard to the equipments, but a good design of the grounding system should provide a high concentration of current on the ground grid.

An engineer should perform a short circuit study on the system that is installed in the switchyard. This analysis should include a worst-case situation where the system would produce the maximum fault current. The maximum fault current is used to determine other variables such as ground conductors. The usage of the ground fault value will be shown in later chapters.

2.7 Conductors and Grounding Equipments

The size and type of conductor that is used on grounding systems are not arbitrarily selected. According to the IEEE Std 80-2000, the type and size of the conductor are based on the following listed below [3]:
1. Have sufficient conductivity, so that it will not contribute substantially to local voltage differences.

2. Resist fusing and mechanical deterioration under the most adverse combination of a fault magnitude and duration.

3. Be mechanically reliable and rugged to a high degree.

4. Be able to maintain its function even when exposed to corrosion or physical abuse.

Other materials, such as ground rods and grounding plates are also used in a grounding system.

### 2.7.1 Conductors

There are different materials used for conductors. The most common materials that are used for grounding conductors are copper, copper-clad steel, aluminum, and steel. Different reasons are given for the usage of one of these mentioned materials. For example, copper would be good for the ground grid because copper is highly conductive and highly resistant to corrosion. Copper-clad steel, on the other hand, is commonly used for ground rods.

As mentioned before, the conductor size is not selected arbitrarily. The size of the conductor depends on the amount of fault current is available. Sizing of the conductor could also be sized a certain percentage over the amount of the fault due to possible safety codes, such as the National Electrical Code (NEC) or National Electrical Safety Code (NESC).
2.7.2 **Ground Rods**

Ground rods are just another addition to the ground system that would help with dissipating the ground fault current and the ground potential rise. The ground rods are installed vertically while being connected to the horizontal system of grid conductors. Depending on the soil’s resistivity, ground rods may be encased with concrete for lowering the resistivity value. The reason a ground rod encased with concrete has less resistance than a ground rod without concrete is that concrete have the ability to absorb moisture.

Although ground rods sounds like a simple addition to the ground system, there are also regulations that engineers will need to abide by when choosing the type of rod to install. Standards and codes such as NEC, provides a minimum size a designer would have to meet for ground rods and other equipment. For example, the NEC states that, “Rod and pipe electrodes shall not be less than 2.44 m (8 ft) in length…shall be at least 15.87 mm (5/8 in.) in diameter, unless listed and not less than 12.70 mm (1/2 in.) in diameter)”[4]. These rules are made to provide the best safety measure for the public and personnel incase of abnormal conditions. Therefore, it is important that grounding system designers know the codes and regulations very well to design a safe grounding system.

2.8 **Current and Body Limits**

The human body is one of the most important aspects a design engineer would have to consider when designing a grounding system. Gonen agrees by mentioning “it is important to understand the electrical characteristics of the most important part of the
circuit, the human body” [1]. It is important to understand the amount of current and shock a human body can handle and how the body reacts under a certain amount of current and shock. Table 2.1 below provides a study of the effect of electrical current on men and women.

<table>
<thead>
<tr>
<th>Effect of Electric Current (in mA) on Men and Women</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Effect</strong></td>
</tr>
<tr>
<td><strong>Men</strong></td>
</tr>
<tr>
<td>1. No sensation on hand</td>
</tr>
<tr>
<td>2. Slight tingling; per caption threshold</td>
</tr>
<tr>
<td>3. Shock – not painful and muscular control not lost</td>
</tr>
<tr>
<td>4. Painful shock – painful but muscular control not lost</td>
</tr>
<tr>
<td>5. Painful shock – let-go threshold*</td>
</tr>
<tr>
<td>6. Painful and severe shock, muscular contractions, breathing difficulty</td>
</tr>
<tr>
<td>7. Possible ventricular fibrillation from short shocks:</td>
</tr>
</tbody>
</table>
### Effect of Electric Current (in mA) on Men and Women

<table>
<thead>
<tr>
<th></th>
<th>Direct Current</th>
<th>Alternating Current (60 Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Effects</strong></td>
<td>Men</td>
<td>Women</td>
</tr>
<tr>
<td>(a) Shock duration 0.03 sec</td>
<td>1300</td>
<td>1300</td>
</tr>
<tr>
<td>(b) Shock duration 3.0 sec</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>(c) Almost certain ventricular fibrillation (if shock duration over one heart beat interval)</td>
<td>1375</td>
<td>1375</td>
</tr>
</tbody>
</table>

*Threshold for 50% of the males and females tested

**Table 2.1 Effect of Electric Current [1]**

There are two main things to consider when considering the interaction between the human body and current. One of the things is the amount of current a body can take, which was mentioned earlier. The amount of current a body can take can depend on the weight of a person. Supposedly, the more a person weighs the more resistance a body carries. This will allow the body to handle more current. The second thing to consider is the duration a body can handle given a certain amount of current. A research done by Dalziel and Lee led them to a formula that relates how much current a body of a certain weight can handle given a certain amount of time. The test range that they used in terms of time was 0.03 seconds and 3.0 seconds. Based on various weights and time duration, IEEE Std 80 suggests basing calculations on either a person weighing 50 kg or 70 kg.
2.9 Human Body Resistance

The human body resistance can be approximated based on the type of currents and the frequency the power system is running. Different parts of the body are different in resistance and depending on the shock situation, the equivalent resistance of the body can change significantly. For example, a scenario provided by IEEE 80 gives a resistance of a certain body considering hand-to-hand contact as 2330 ohms, while a hand to feet contact is equal to 1130 ohms. To make things easier when designing a switchyard, IEEE 80 suggest the general usage of 1000 ohms for the resistance of a human body.

The human body resistance gives rise to the typical shock situations a person can have in a given switchyard. The typical shock situations are

1. Metal-to-Metal Touch Voltage.
2. Step Voltage.
3. Touch Voltage.
5. Transferred Voltage.

Each of these shock situations produces different amounts of potential from each other. The reason for the difference is because of the arrangement of the body during a fault. For example, a step voltage situation would only involve the ground a person is standing on and the person’s two feet. The amount of shock is produced by the current flowing from one leg and down to the other. Although in practice, a person would be wearing shoes on both feet that would provide a high resistivity through the dielectric medium between the ground and the body. On the other hand, a different amount of shock is
produced if a person has one hand on electrical equipment while having their legs on the ground. The current will have to travel from the arm, through the body, and down to the legs. This also brings up a good point where a certain path the current takes will determine whether it may be lethal. Any path a current takes that involves going through the body, which involves currents flowing near the human heart, may be lethal to a person. A person experiencing shock from a step voltage may not be in danger compared to a person experiencing a touch voltage because the current is likely to travel from only one leg and down the other.

2.10 Grounding System Surface Materials

Typically grounding systems in switchyards include a layer of surface material for further protection of shock during a fault. The most common surface material that is used is the crushed rock. The surface layer usually surrounds the same area as the ground grid and the thickness of the layer is usually 0.08 m to 0.15 m. Table 2-2 provides a list of surface materials and their resistivity, depending on whether it is a wet or dry situation.

<table>
<thead>
<tr>
<th>Number</th>
<th>Description of Surface Material (U.S. State where found)</th>
<th>Resistivity of Sample, Ω-m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Dry</td>
</tr>
<tr>
<td>1</td>
<td>Crusher run granite with fines (N.C)</td>
<td>140 x 10^6</td>
</tr>
<tr>
<td>2</td>
<td>1.5 in (0.04 m) crusher 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>-</td>
</tr>
<tr>
<td>4</td>
<td>#4 (1 – 2 in) (0.025-0.05 m) washed granite (Ga.)</td>
<td>1.5 x 10^6 to 4.5 x 10^6</td>
</tr>
</tbody>
</table>
Table 2.2 Typical Surface Material Resistivities. [3]

It is recommended that the surface layer taken into account during calculations be considered as the wet values rather than the dry values. The surface layer material used should be tested for the resistivity for accurate measurements.

2.11 Design Route

Unlike many other power system designs, IEEE 80 actually provides a recommended procedure a grounding system design engineer should follow for designing a safe grounding system. The procedure is in the form of a block diagram that takes the designer in a step-by-step process. Certain criteria are required or certain criteria are calculated before moving onto the next step in the process. Figure 2-1 shows the block diagram provided by IEEE 80.

<table>
<thead>
<tr>
<th></th>
<th>Material Description</th>
<th>Resistivity Range</th>
<th>Resistivity Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>#3 (2-4 in) (0.05-0.1 m) washed granite (Ga.)</td>
<td>2.6 x 10⁶ to 3 x 10⁶</td>
<td>10 000 (Rain water, 100 Ω-m)</td>
</tr>
<tr>
<td>6</td>
<td>Size unknown, washed limestone (Mich.)</td>
<td>7 x 10⁵</td>
<td>2000-3000 (ground water, 45 Ω-m)</td>
</tr>
<tr>
<td>7</td>
<td>Washed granite, similar to 0.75 in (0.02 m) gravel</td>
<td>20 x 10⁶</td>
<td>10 000</td>
</tr>
<tr>
<td>8</td>
<td>Washed granite, similar to pea gravel</td>
<td>40 x 10⁶</td>
<td>5000</td>
</tr>
<tr>
<td>9</td>
<td>#57 (0.75 in) (0.02 m) washed granite (N.C.)</td>
<td>190 x 10⁶</td>
<td>8000 (ground water, 45 Ω-m)</td>
</tr>
<tr>
<td>10</td>
<td>Asphalt</td>
<td>2 x 10⁶ to 30 x 10⁶</td>
<td>10 000 to 6 x 10⁶</td>
</tr>
<tr>
<td>11</td>
<td>Concrete</td>
<td>1 x 10⁶ to 1 x 10⁹ᵃ</td>
<td>21 to 100</td>
</tr>
</tbody>
</table>

Oven dried concrete (Hammond and Robson [B78]). Values for air-cured concrete can be much lower due to moisture content.
Figure 2.1 Design Procedure Block Diagram [3]
Chapter 3
GROUND GRID DESIGN FORMULAS

3.1 Introduction

The purpose of a substation is to step-up or step-down voltage during the transmission or distribution of electricity. Due to this potential hazardous nature of electricity, a grounding grid has to be designed and built at every substation. The purpose of the grounding grid is to safely conduct electric currents into the earth during normal and fault conditions, without exceeding equipment operational limits. This purpose serves to ensure that any person in the vicinity of a substation is not exposed to the danger of critical electric shock [3]. Because electricity flows through the path of least resistance, a properly designed ground grid ensures a safe and controlled flow of electricity into the ground.

Some necessary preliminary steps required before designing the grounding grid include; gathering data pertaining substation, measuring the soil resistivity of the substation soil, measuring the ground impedance, getting a detailed model of the substation for fault and grounding grid computer analysis, getting information on the transmission lines feeding the substation and the power system (source) beyond this transmission lines. Using IEEE Std. 80 as guide the following formulas can be used to design a grounding grid.

3.2 Soil Resistivity

Determining the resistivity of the soil at the substation is an important aspect of designing a substation grounding grid. The substation soil resistivity is directly
proportional to the resistance of the earth and it can impact the total impedance of the grounding grid. Soil resistivity varies widely from site to site, point to point at the same site and even at different depths at the same site. For this reason actual measurement using industry standards rather than using approximate values is recommended.

There are several ways of measuring the soil’s resistivity, but a typical way of measuring the resistivity of the soil is by the Wenner four-pin method. The Wenner four-pin method involves four rods driven to the ground as shown in Figure 3-1 and a machine that uses equation 3-1 to calculate the resistivity of the soil.

\[
\rho_a = \frac{4\pi a R}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}} \tag{3.1}
\]

where

- \(\rho_a\) = Apparent resistivity of the soil in W-m
- \(R\) = Measured resistance in ohms
- \(a\) = Distance between adjacent electrodes in meters
- \(b\) = Depth of the electrodes in meters

**Figure 3.1** Wenner Four-Pin Method. Ref. IEEE Std. 80, January 30 2000,
Equation (3.1) can be reduced to equation (3.2) if the b is small compared to a \( a \)

\[
\rho_a = 2\pi a R
\]  

(3.2)

3.3 Interpretation of Soil Resistivity Measurements

After measuring the soil’s resistivity, the next important step to do is to understand the data that is collected. There are several models that can be used to describe the soil’s resistivity, but the two practical models that are considered here is the uniform soil model and the two-layer model. The uniform soil model should only be considered when the soil resistivity is slightly different for each reading. This is, however, a rare case, but the approximate uniform soil resistivity can be calculated by,

\[
\rho_{a(\text{av})} = \frac{\rho_{a(1)} + \rho_{a(2)} + \rho_{a(3)} + \ldots + \rho_{a(n)}}{n}
\]  

(3.3)

where

\( \rho_{a(1)}, \rho_{a(2)}, \rho_{a(3)} \ldots \rho_{a(n)} \) = Measured apparent resistivity data obtained at different spacing in the four-pin method or at different depths in the driven ground rod method in W-m

\( n \) = Total number of measurements

3.4 Ground Fault Currents

It is hard to figure out which fault type and location will result in the greatest flow of current between the grounding grid and the surround earth. IEEE Std. 80-2000
recommends that for practical reasons, investigation of the maximum/worst ground fault be confined to single-line-to-ground and line-to-line-to-ground faults. For practical purposes, the zero sequence fault current of a line-to-line-to-ground fault should be used. It should be noted that there are situations when the value of a single-line-to-ground fault will exceed the value of a line-to-line-to-ground faults.

In addition to readily available commercial and academic software for these calculations, hand calculations can also be used to determine the available double-line-to-ground and single-line-to-ground faults as follows.

### 3.4.1 Double-Line-To-Ground Faults

The double-line-to-ground fault can be calculated as follows as provided by IEEE Std. 80-2000,

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

(3.4)

where

\[I_0\] = the symmetrical rms value of zero sequence fault current in A

\[E\] = the phase-to-neutral voltage in V

\[R_f\] = the estimated resistance of the fault in \(\Omega\) (normally it is assumed \(R_f = 0\))

\[R_1\] = the positive sequence equivalent system resistance in \(\Omega\)

\[R_2\] = the negative sequence equivalent system resistance in \(\Omega\)

\[R_0\] = the zero sequence equivalent system resistance in \(\Omega\)

\[X_1\] = the positive sequence equivalent system reactance (sub-transient) in \(\Omega\)

\[X_2\] = the negative sequence equivalent system reactance in \(\Omega\)
$X_0 =$ the zero sequence equivalent system reactance in $\Omega$

The values of $R_0$, $R_1$, $R_2$ and $X_0$, $X_1$, $X_2$ are determined by looking into the system from the point of fault [3].

Often, however, the resistance quantities given in the above equation are negligibly small. Hence, a simplified equation for calculating the zero sequence current for a single line to ground fault is recommended in IEEE 80-2000 as follows,

$$I_0 = \frac{E \times X_2}{X_1(X_0 + X_2) + (X_0 + X_2)} \quad (3.5)$$

### 3.4.2 Single-Line-To-Ground Faults

The single-line-to-ground fault can be calculated as follows as provided by IEEE Std. 80-2000,

$$I_0 = \frac{E}{3R_f + R_0 + R_1 + R_2 + j(X_0 + X_1 + X_2)} \quad (3.6)$$

where

$I_0 =$ the symmetrical rms value of zero sequence fault current in A

$E =$ the phase-to-neutral voltage in V

$R_f =$ the estimated resistance of the fault in $\Omega$ (normally it is assumed $R_f = 0$)

$R_1 =$ the positive sequence equivalent system resistance in $\Omega$

$R_2 =$ the negative sequence equivalent system resistance in $\Omega$

$R_0 =$ the zero sequence equivalent system resistance in $\Omega$

$X_1 =$ the positive sequence equivalent system reactance (sub-transient) in $\Omega$

$X_2 =$ the negative sequence equivalent system reactance in $\Omega$
\( X_0 \) = the zero sequence equivalent system reactance in \( \Omega \)

The values of R0, R1, R2 and X0, X1, X2 are determined by looking into the system from the point of fault [3].

Often, however, the resistance quantities given in the above equation are negligibly small. Hence, a simplified equation for calculating the zero sequence current for a single line to ground fault is recommended in IEEE 80-2000 as follows,

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

(3.7)

### 3.5 Split Factor

The split factor, \( S_f \) is used to determine the approximate amount of current that flows through the ground as follows

\[
I_g = S_f \times I_f
\]

(3.8)

where

- \( I_g \) = the rms symmetrical grid current in A
- \( S_f \) = split factor
- \( I_f \) = the rms value of the symmetrical ground fault current in A

One of the methods used to figure out the value of the split factor is through current division. Using an equivalent system representation current division can be used to determine the value of the current that flows through the ground and other paths. Among the different available methods, the tabulations and curves of IEEE Std. 80-2000 Annex C are the most prevalent.
3.6 Decrement Factor

The decrement factor, \( D_f \), is used to determine the effective current during a given time interval after inception of a fault as follows,

\[
I_a = D_f \times I_g
\]  

(3.9)

where

\( I_a = \) the maximum grid fault current in A

\( D_f = \) the decrement factor for the entire fault duration of \( t_f \)

\( I_g = \) the rms symmetrical grid current in A

The decrement factor can be calculated as follows [3],

\[
D_f = \sqrt{1 + \frac{T_a}{t_f} \left( 1 - e^{-\frac{2t_f}{T_a}} \right)}
\]  

(3.10)

where

\( t_f = \) time duration of fault in seconds

\( T_a = X / (\omega R) = \) DC offset time constant in seconds

\( t_f \) should be chosen where the fastest clearing time. The fastest clearing time and \( t_f \) includes breaker and relay time for transmission substations. In this equation, it is assumed that the ac components do no decay with time.
3.7 Maximum Grid Current

The maximum grid current flowing between the grounding system and surrounding earth, taking into account the DC component of the initial fault current, is calculated as follows,

\[ I_G = D_f \times I_g \]  \hspace{1cm} (3.11)

where

- \( I_G \) = the maximum grid fault current in A
- \( D_f \) = the decrement factor for the entire fault duration of \( t_f \)
- \( I_g \) = the rms symmetrical grid current in A

3.8 Ground Conductor

The ground conductor sizing should be based on the maximum rms current the fault clearing time among other things. The required size of the grounding conductors can be computed with the aid of the equations in the IEEE Std. 80-2000 assuming a specific maximum permissible temperature rise,

\[ A_{kcmil} = I \left( \frac{197.4}{\sqrt{\frac{TCAP}{t_\alpha \alpha \rho_r}}} \cdot \ln \left( \frac{K_o + T_m}{K_o + T_a} \right) \right) \]  \hspace{1cm} (3.12)

where

- \( I \) = rms fault current in kA
- \( A_{kcmil} \) = Area of conductor in kcmil
- \( T_m \) = Maximum allowable temperature in °C
$T_a =$ Ambient temperature in °C

$T_r =$ Reference temperature for material constants in °C

$\alpha_r =$ Thermal coefficient of resistivity at reference temperature $T_r$ in $1/°C$

$\rho_r =$ Resistivity of the ground conductor at reference temperature $T_r$ in mW-cm

$K_o =$ $1/\alpha o$ or $(1/ar) - T_r$ in °C

$t_c =$ Fault current duration in seconds

$TCAP =$ Thermal capacity per unit volume from, in $J/(cm^3·°C)$

### 3.9 Current Through the Human Body

As per Gonen, for 99.5% of the population, the 60-Hz minimum required body current, $I_B$, leading to possible fatality through ventricular fibrillation can be expressed as follows,

$$I_B = \frac{k}{\sqrt{t_s}} \quad (3.13)$$

where

$I_B =$ rms magnitude of the current through the body in A

$t_s =$ Duration of the current exposure in seconds ranging between 8.3 ms and 5 s

$k =$ Constant related to electric shock energy

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

For a person weighing 70 kg (155 lbs), $k = 0.157$
3.10 Tolerable Step and Touch Voltages

Tolerable step and touch voltages have to be met to guarantee the safety of the people in and around the Substation. Figure 3-2 below illustrates exposure to touch voltage.

![Diagram](image)

**Figure 3.2** Exposure to Touch Voltage. Ref. IEEE Std. 80, January 30, 2000, Figure 6. Copyright © 2000. IEEE. All rights reserved [3].

The equation used to derive the tolerable touch voltage is as follows,

\[
V_{\text{touch}} = (R_B + \frac{R_f}{2})I_B
\]  

(3.14)

where

\[ R_f = \text{ground resistance of one foot in } \Omega \]

\[ R_B = \text{resistance of the human body in } \Omega, \text{ typically } 1000\Omega \text{ for 50-Hz and 60-Hz} \]
$I_B = \text{the rms magnitude of the current through the body in A}$

An illustration of the exposure to step voltage is shown in Figure 3-3.

\[ V_{\text{Step}} = (R_B + 2R_f)I_B \quad (3.15) \]

In equation (3.14) and (3.15), $R_f$ is found with equation,

\[ R_f = C_s \cdot 3 \rho_s \quad (3.16) \]

where

$C_s = \text{the surface layer derating factor based on the thickness of the protective surface layer spread above the earth grade at the substation. If no protective surface layer is used, } C_s = 1$ \[3].
\( \rho_s \) = the resistivity of the protective layer used at the substation in \( \Omega \cdot \text{m} \). If no layer is used, then \( \rho_s = \rho \) = the resistivity of Earth [3].

For a human body with a mass of 70Kg, the \( V_{\text{Touch}} \) and \( V_{\text{Step}} \) are calculated as follows,

\[
V_{\text{Touch}70} = (1000 + 1.5C_s \cdot \rho_s) \frac{0.157}{\sqrt{T_s}} \tag{3.17}
\]

\[
V_{\text{Step}70} = (1000 + 6C_s \cdot \rho_s) \frac{0.157}{\sqrt{T_s}} \tag{3.18}
\]

And for human body with a mass of 50Kg, the \( V_{\text{Touch}} \) and \( V_{\text{Step}} \) are calculated as follows,

\[
V_{\text{Touch}50} = (1000 + 1.5C_s \cdot \rho_s) \frac{0.116}{\sqrt{T_s}} \tag{3.19}
\]

\[
V_{\text{Step}50} = (1000 + 6C_s \cdot \rho_s) \frac{0.116}{\sqrt{T_s}} \tag{3.20}
\]

### 3.11 Reduction of Factor \( C_s \)

“A thin layer of highly resistive protective surface material such as gravel spread across the earth at a substation greatly reduces the available shock current at a substation” [3]. The equation for the ground resistance of one foot on a thin layer of surface material is obtained calculated using the following equation,
\[ C_S = 1 + \frac{1.6 \times b}{\rho_S} \sum_{n=1}^{\infty} K^n R_{m(2n\rho_s)} \]  

\[ C_S = 1 - \frac{0.09(1 - \frac{\rho}{\rho_S})}{2h_s + 0.09} \]  

\[ K = \frac{\rho - \rho_S}{\rho + \rho_S} \]  

where

\( C_s \) = Surface layer derating factor

\( \rho_s \) = Surface material resistivity in \( \Omega \)-m

\( K \) = Reflection factor between different material resistivity

\( \rho \) = Resistivity of Earth beneath the substation in \( \Omega \)-m

\( h_s \) = Thickness of the surface material in meters

\( b \) = Radius of the circular metallic disc representing the foot in meters

\( R_{m(2n\rho_s)} \) = Mutual ground resistance between two similar, parallel, coaxial plates, separated by a distance \( 2n\rho_s \) in \( \Omega \)-m

Application curves for \( C_s \) are illustrated in Figure 3-4 shown below.
3.12 Mesh Voltage

In the event that the GPR exceeds the tolerable touch and step voltages, mesh voltage design calculations are done to determine whether the design of a substation is safe. If the design is again unsafe, conductors in the form of ground rods are added to the design until the design is considered safe.

The mesh voltage values can be calculated using the following equation,
\[ E_m = \frac{\rho \cdot K_m \cdot K_i \cdot I_G}{L_M} \]  \hfill (3.24) 

where

\( \rho \) = Soil Resistivity in \( \Omega\)-m  

\( K_m \) = Mesh coefficient or  

\( K_i \) = Correction factor for grid geometry  

\( I_G \) = Maximum grid current that flows between ground grid and surrounding earth in amperes.  

\( L_m \) = Length of \( L_c + L_R \) for mesh voltage in meters  

\( L_c \) = Total length of grid conductor in meters  

\( L_R \) = Total length of ground rods in meters

The geometrical factor \( K_m \) is expressed as the follows,

\[
K_m = \frac{1}{2\pi} \left[ \ln \left( \frac{D^2}{16d} + \frac{(D + 2h)^2}{8D} - \frac{h}{4d} \right) + \frac{K_{ii}}{K_h} \cdot \ln \left( \frac{8}{\pi(2n-1)} \right) \right] \]  \hfill (3.25) 

where

\( D \) = Spacing between parallel conductors in meters  

\( d \) = Diameter of grid conductors in meters  

\( h \) = Depth of ground grid conductors in meters  

\( n \) = Geometric factor  

\( K_h \) = Corrective weighting factor that highlight the effects of grid depth  

\( K_{ii} \) = Corrective weighting factor that adjusts for the effects of inner conductors on the corner mesh. [3]
For grounding grids with ground rods in grid corners as well as on the perimeter,

\[ K_{ii} = 1 \]

For grids with no or few ground rods with none in corners and none on the perimeter,

\[ K_a = \frac{1}{(2n)^{3/2}} \quad (3.26) \]

\[ K_h = \sqrt{1 + \frac{h}{h_0}} \quad (3.27) \]

where

\[ h_0 = 1 \text{m (grid reference depth)} \]

The effective number of parallel conductors in a given grid are \( n \) and is given as follows,

\[ n = n_a * n_b * n_c * n_d \quad (3.28) \]

Where

\[ n_a = \frac{2 * L_c}{L_p} \quad (3.29) \]

\( n_b = 1 \) for square grids

\( n_c = 1 \) for square and rectangular grids

\( n_d = 1 \) for square, rectangular, and L-shaped grids

Otherwise,
\[ n_b = \frac{L_p}{\sqrt{4 \cdot \sqrt{A}}} \]  
(3.30)

\[ n_c = \left[ \frac{L_x \cdot L_y}{A} \right]^{0.744} \]  
(3.31)

\[ n_d = \frac{D_m}{\sqrt{L_x^2 + L_y^2}} \]  
(3.32)

where

\( L_c = \) Total length of the conductor in the horizontal grid in meters

\( L_p = \) Peripheral length of the grid in meters

\( A = \) Area of the grid in \( m^2 \)

\( L_x = \) Maximum length of the grid in the x direction in meters

\( L_y = \) Maximum length of the grid in the y direction in meters

\( D_m = \) Maximum distance between any two points on the 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

The irregularity factor \( K_{ii} \) is expressed as follows,

\[ K_n = 0.644 + 0.148n \]  
(3.33)
For grids with little or no ground rods but none located in the corners or along the perimeter of the grid, the effective buried length, $L_{m}$, is expressed as follows [3]

$$L_{M} = L_{C} + L_{R}$$  \hspace{1cm} (3.34)

where

$L_{R} = \text{Total length of all ground rods in meters.}$

For grids with ground rods in corners and along the perimeter and throughout the grid, the following equation is applied:

$$L_{M} = L_{C} + \left[ 1.55 + 1.22 \left( \frac{L_{R}}{\sqrt{L_{x}^2 + L_{y}^2}} \right) \right] L_{R}$$  \hspace{1cm} (3.35)

where

$L_{R} = \text{Length of each ground rod in meters}$

3.13 Step Voltage

In order for the ground system to be safe, step voltage has to be less than the tolerable step voltage. In addition, step voltages within a grid system designed for safe mesh voltages will be well within the tolerable limits [3]. This is because both feet and legs are in series rather than in parallel and the current takes the path from one leg to the other rather than through vital organs. The step voltage values are obtained as follows:

$$E_{S} = \frac{\rho \cdot K_{S} \cdot K_{I} \cdot I_{G}}{L_{S}}$$ \hspace{1cm} (3.36)

where
\( K_s \) = Step coefficient

\( L_s \) = Buried conductor length in meters

As before, for grids with or without ground rods, \( L_s \) is expressed as:

\[
L_s = 0.75L_c + 0.85L_g \tag{3.37}
\]

The step coefficient is expressed as:

\[
K_s = \frac{1}{\pi} \left[ \frac{1}{2h} + \frac{1}{D + h} + \frac{1}{D} \left( 1 - 0.5^n - 2 \right) \right] \tag{3.38}
\]

where:

\( h \) = Depth of ground grid conductors in meters, usually between 0.25 m < h < 2.5 m

All other variables are as defined before.

3.14 **Ground Resistance**

Several methods/formulations are available for this calculation. The available methods as per IEEE Std. 80-2000, include the Laurent-Niemann Method, Sverak Method, and Schwarz Method. For this study, we will use the Sverak Method which uses the following equation,

\[
R_g = \rho \left[ \frac{1}{L_T} + \frac{1}{\sqrt{20A}} \left( 1 + \frac{1}{1 + h\sqrt{20/A}} \right) \right] \tag{3.39}
\]

where

\( R_g \) = Grounding/Grid resistance in Ohms
\[ \rho = \text{Soil resistivity in Ohms} \ast \text{m} \]

\[ L_T = \text{Total buried length of conductors in m} \]

\[ A = \text{Area occupied by the ground grid in m}^2 \]

\[ h = \text{Depth of the grounding grid in m}. \]

### 3.15 Ground Potential Rise (GPR)

Ground potential rise is the maximum electrical potential that a substation grounding grid may attain. This voltage, GPR, is expressed as follows,

\[
GPR = I_G \ast R_g
\]  \hspace{1cm} (3.40)

where

- \( GPR \) = Ground potential rise in volts
- \( R_g \) = Ground grid resistance in \( \Omega \)
- \( I_G \) = the maximum grid fault current in A

### 3.16 Total Length of the Ground Conductor

The total length of the ground conductor can be found using the following equation,

\[
L_T = L_C + L_R
\]  \hspace{1cm} (3.41)

where

- \( L_T \) = Total length of the ground conductor
- \( L_C \) = Total grid conductor length
- \( L_R \) = Total length of all ground rods
Alternatively if the grid resistance is known, Sverak’s Method can be used to calculate the total length, $L_T$, of the ground conductor using the following equation and solving for $L_T$,

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

where

- $R_g = \text{Grounding/Grid resistance in Ohms}$
- $\rho = \text{Soil resistivity in Ohms*m}$
- $L_T = \text{Total buried length of conductors in m}$
- $A = \text{Area occupied by the ground grid in m}^2$
- $h = \text{Depth of the grounding grid in m}$.
4.1 Introduction

As mentioned in the previous chapters, it is important that a good grounding system is design. In this case, the grounding system is designed for a switchyard. The reason that this is mentioned so often is because it deals with safety. A good grounding system would provide adequate protection for people and it will save companies a significant amount of money on electrical equipments. Damages on electrical equipment are costly to replace and there is nothing to replace a lost of life.

The grounding system that we have to design for consists of a three phase, 230 kV source, provided by the utility. The lines are connected to a bus where it feeds two transformers that steps down the voltage from 230 kV to 69 kV. These two step-down transformers are connected in parallel with each other. One transformer feeds another switchyard. The other is connected to a 3-4 MVA transformer that steps down the voltage from 69 kV to 13.8 kV. Its main purpose is to provide power to a nearby fish facility.

There are other parameters about the system that were given. These parameters are mentioned later and will provide the information necessary for the equations that were given in the previous chapter. As a grounding system designer, standards and regulations will need to be followed. For this project, IEEE Std 80-2000 will be used as a guide for the design of this grounding system.
4.2 Design Procedure

The IEEE 80 standard provides a logic flow diagram to assist with the design of a grounding system for a switchyard. A logic flow diagram is a step-by-step instruction that shows a certain path a switchyard grounding design engineer have to take to complete the design. Depending on whether a certain step is met, the logic flow diagram will guide the engineer to a certain path to make the necessary correction to get to the right step. There could be many iterations before going to the next step.

4.3 Given Parameters

Table 4.1, below, was assumed parameters of the system described earlier. These parameters help start the initial design process that is required by IEEE 80.

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area of ground grid</td>
<td>A</td>
<td>4204.6 m$^2$ (84.6m x 49.6m)</td>
</tr>
<tr>
<td>Soil Resistivity</td>
<td>$\rho$</td>
<td>50 $\Omega$-m</td>
</tr>
<tr>
<td>Fault Current</td>
<td>$3I_0$</td>
<td>17,000 A</td>
</tr>
<tr>
<td>Fault Time Duration for Conductor Sizing</td>
<td>$t_c$</td>
<td>1 s</td>
</tr>
<tr>
<td>Grid Conductor Diameter</td>
<td>$d$</td>
<td>0.018 m (for 500 kcmil)</td>
</tr>
<tr>
<td>Fault Time Duration for Shock</td>
<td>$t_s$</td>
<td>0.5 s</td>
</tr>
<tr>
<td>Surface Layer Resistivity (Crushed Rock)</td>
<td>$\rho_s$</td>
<td>2500 $\Omega$-m</td>
</tr>
<tr>
<td>Spacing Between Parallel Conductor</td>
<td>$D$</td>
<td>4.97 m</td>
</tr>
<tr>
<td>Depth of Grid Conductor</td>
<td>$h$</td>
<td>1.524 m</td>
</tr>
<tr>
<td>Length of One Ground Rod</td>
<td>$L_r$</td>
<td>3.048</td>
</tr>
<tr>
<td>Parameter</td>
<td>Symbol</td>
<td>Value</td>
</tr>
<tr>
<td>----------------------------</td>
<td>--------</td>
<td>-------</td>
</tr>
<tr>
<td>Split Factor</td>
<td>$S_f$</td>
<td>0.6</td>
</tr>
<tr>
<td>Fault Time Duration</td>
<td>$t_f$</td>
<td>0.5 s</td>
</tr>
<tr>
<td>Decrement Factor</td>
<td>$D_f$</td>
<td>1.026</td>
</tr>
</tbody>
</table>

**Table 4.1 – Given Parameters**

Although these parameters were given and some of them already cover the first few steps of the logic flow diagram provided by IEEE 80, each step will be explained for the purpose of how the numbers came about.

### 4.4 Field Data

The Field Data consist of the area of the ground grid and the soil resistivity. This is the first step taken before any additional design work can be done. The area of the grid will help determine the amount of conductor and the grid resistance in later calculations. A copper plate at a certain size that covers a switchyard is the best option, but due to economic reasons, a grid with a series of horizontal conductors is sufficient enough to provide a path for fault currents. From the given parameters in Table 4.1, the preliminary area selection is 84.6m by 49.6m. Although it is mentioned that the selection is preliminary, it could also be the final selected area if certain criteria is met.

The soil resistivity was taken from a geology report that was provided to an engineer. The average apparent soil resistivity at the first five feet was measured to be 50 Ω-m. According to the report, that measurement was made using the Three Point Method that was mentioned in IEEE Std 80 and IEEE Std 81. As the depth of the soil goes deeper, the soil resistivity was reported to decrease. Since the ground grid was
predetermined to be installed five feet under ground, the measurement of the soil resistivity at the first five feet is taken.

4.5 Conductor Size

Step two of the process requires preliminary information that will help in sizing the grounding conductor. The first information requested was the fault current, $3I_0$. This is the main value that will help determine the size of the conductor. The grounding conductor is sized according to the fault current because the grounding conductor should be able to withstand the fault when it occurs. For this project’s analysis, the fault current was given to be approximately 17,000 Amps.

The next parameter used to determine the size of the conductor is the fault duration allowed for the conductors. For this project, the duration of the fault current, $t_c$, is selected to be 1 second. 1 second was selected because it is considered the worst case scenario for that duration of time. 1 second is a long time in the protection world, since it takes only a few cycles to open a breaker during a fault.

The size of the conductor is calculated below, based on the above mentioned parameters.

$$A_{kcmil} = I \cdot K_f \cdot \sqrt{t_c}$$

$$A_{kcmil} = 17 \cdot 10.45 \sqrt{1}$$

$$A_{kcmil} = 210.5 \text{ kcmil}$$

Although the conductor was calculated to be 210.5 kcmil, the conductor selected was 500 kcmil. The 500 kcmil was based on given guidelines to be sized more than enough to
handle the fault current. Based on the selected conductor, the diameter of the conductor \( d \), is 0.018 m.

### 4.6 Maximum Allowable Touch and Step Voltages

The grounding grid is designed to decrease the high amount of Ground Potential Rise (GPR), but it is also designed to where it meets certain voltages that a person can handle. For the third step in the logic flow diagram, the first thing that was needed to be calculated is the surface layer derating factor, \( C_s \).

\[
C_s = 1 - \frac{0.09 \left( 1 - \frac{\rho_s}{\rho} \right)}{2h + 0.09}
\]

\[
C_s = 1 - \frac{0.09 \left( 1 - \frac{50}{2500} \right)}{2 \times 0.1524 + 0.09}
\]

\[
C_s = 0.78
\]

In the very beginning of this chapter, the surface layer resistivity and the duration of the current through the body were given. The surface layer resistivity, was given in IEEE 80 as 2500 \( \Omega \)-m. The shock duration that the body can handle is set at 0.5 seconds. This is the minimum time the body can be exposed to fault currents. For the given values that were mentioned above, the calculated touch voltage for a person who weighs 70 kg is

\[
V_{\text{Touch} \ 70} = (1000 + 1.5C_s \times \rho_s) \frac{0.157}{\sqrt{t}}
\]
4.7 **Grounding System Initial Design**

Step four deals mainly with the layout of the grounding conductors and the amount of conductor being used for this system. The spacing of the conductors, \( D \), was selected to be 4.97 m. \( L_x \) and \( L_y \), maximum length of the conductor in the x direction and the y direction, were determined to be 84.6 m and 49.6 m, respectively. Based on the information given in this section, the total length of the grounding conductor is 1825 m. The length of the ground rods, \( L_r \), were 3.048 m. A total of 25 ground rods were used, which gives the total length of the ground rods, \( L_R \), to be approximately 76 m. Therefore, the total conductor length, which includes the conductor and the ground rods, were added up to 1901 m.

The depth of the ground grid, \( h \), is determined to be buried 1.525 m below grade. The next step is to take into account the geometry of the ground grid. Given the length of each side of the grounding grid, it is determined that the shape of the grid design will be
similar to a rectangle. The geometric factor can be calculated by first finding \( n_a, n_b, n_c, \) and \( n_d. \) \( n_a \) is calculated to be

\[
n_a = \frac{2L_c}{L_p}
\]

\[
n_a = \frac{2 \times 1825}{268}
\]

\[n_a = 14\]

\(n_b, n_c,\) and \(n_d\) are approximately equal to 1 because of the shape of the grid. For calculation purposes, \( n_b, n_c, \) and \( n_d \) are calculated to be

\[
n_b = \sqrt{\frac{L_p}{4 \sqrt{4204.6}}}
\]

\[
n_b = \frac{268}{4 \sqrt{4204.6}}
\]

\[n_b = 1.03\]

\[
n_c = \left[ \frac{L_x \times L_x}{A} \right]^{0.7 \times A}
\]

\[
n_c = \left[ \frac{84.6 \times 49.6}{4204.6} \right]^{0.7 \times 4204.6}
\]

\[n_c = 1.00\]

\[
n_d = \frac{D_a}{\sqrt{L_x^2 + L_y^2}}
\]
The geometric factor is then calculated to be

\[ n = n_a * n_b * n_c * n_d \]

\[ n = 14 * 1.03 * 1 * 1 \]

\[ n = 14 \]

4.8 Grid Resistance

According to IEEE 80, a good grounding grid resistance for a large switchyard setup usually has a measured grid resistance of less than 1 ohm. A lower grid resistance would help provide for a smaller Ground Potential Rise. Using the given parameters mentioned above, the grid resistance is calculated to be

\[ R_g = \rho \left[ \frac{1}{L_T} + \frac{1}{\sqrt{20*4205}} \left( 1 + \frac{1}{1 + 1.524 * \sqrt{20}/4205} \right) \right] \]

\[ R_g = 0.35 \, \Omega \]

4.9 Grid Current

Determining the amount of current that flows within the designed grid is in step 6 of the logic flow diagram in IEEE 80. This is known as the variable grid current \( I_G \). Not
only is it important to know the amount of grid current, it is also used in determining the GPR calculated in the next section.

The split factor $S_f$, which is the ratio between the rms symmetrical grid current and the total zero-sequence fault current, was given to be 0.6. Given the duration of the fault as 0.5 seconds and assuming that the X/R value is 10, the decrement factor of 1.026 m can be determined from Table 2 in the appendix. The maximum grid current is therefore,

$$I_G = D_f * 3I_0 * S_f$$

$$I_G = 1.026 * 17,000 * 0.6$$

$$I_G = 10,465 \text{ A}$$

4.10 Ground Potential Rise

Finding the ground potential rise is the next major step. This step is different than previous steps because this step requires a comparison between GPR and $V_{\text{touch70}}$. If the GPR is calculated to be bigger than $V_{\text{touch70}}$, then additional evaluation of the grounding system design is necessary to make the grid safe from hazardous potential. If the GPR is smaller than $V_{\text{touch70}}$ then the designer is lead to step twelve of the design process to finish the detail design. $V_{\text{touch70}}$ is used instead of $V_{\text{step70}}$ to compare against GPR because $V_{\text{step70}}$ is much larger than $V_{\text{touch70}}$. GPR is calculated to be

$$GPR = I_G * R_g$$

$$GPR = 10,465 * 0.35$$
Comparing GPR to $V_{touch70}$ gives

$$GPR > V_{touch70} ?$$

3662.75 $>$ 871.5

As the result shows, the GPR is larger than the allowable touch voltage. The current design would need to be evaluated again to meet other conditions. This further design consideration is shown in the next step.

### 4.11 Mesh and Step Voltages

In chapter 3, the equation that shows how to calculate the mesh voltage requires the calculations of variables. These variables within the mesh voltage equation are $K_m$, $K_i$ and $K_h$. Other variables were calculated in the previous sections. From the given parameters for $D$, $h$, and $d$, the corrective weighting factor that accounts for the depth of the grid, $K_h$ is

$$K_h = \sqrt{1 + \frac{h}{h_0}}$$

$$K_h = \sqrt{1 + \frac{1.524}{1}}$$

$$K_h = 1.59$$

The correction factor for grid geometry, $K_i$, is calculated to be

$$K_i = 0.644 + 0.148*n$$

$$K_i = 0.644 + 0.148*14$$
\[ K_i = 2.716 \]

Using \( K_s \) and \( K_{ii} \), the spacing factor for mesh voltage, \( K_m \), can be calculated. \( K_{ii} \), the corrective weighting factor that adjust conductors on the corner mesh, is considered to have a value of 1 because the shape of the grid is rectangular.

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

\[
K_m = \frac{1}{2\pi} \left[ \ln \left( \frac{4.97^2}{16 \cdot 1.524^2 \cdot 0.018} + \frac{(4.97 + 2 \cdot 1.524)^2}{8 \cdot 4.97^2 \cdot 0.018} - \frac{1.524}{4 \cdot 0.018} \right) + \frac{1}{1.589} \ln \left( \frac{8}{\pi(214-1)} \right) \right]
\]

\[ K_m = 0.53 \]

The mesh voltage can now be calculated by using the calculated and given parameters mentioned above.

\[
E_m = \frac{\rho \cdot I_G \cdot K_s \cdot K_i}{L_c + 1.55 + 1.22 \left( \frac{L_x}{\sqrt{L_x^2 + L_y^2}} \right) L_R}
\]

\[
E_m = \frac{50 \cdot 10,465 \cdot 0.53 \cdot 2.716}{1825 + 1.55 + 1.22 \left( \frac{3.048}{\sqrt{84.6^2 + 49.6^2}} \right)} 76.2
\]

\[ E_m = 387.1 \text{ V} \]

The step voltage needs to be calculated next. The step voltage and the mesh voltage will be used for comparison in the next few steps. To calculate the step voltage, \( E_s \), other unknown variables will also need to be calculated. These unknown variables include \( K_s \) and \( L_s \).
Similar to calculating the mesh voltage, variables such as h, D, and n are given.

Using these given values, spacing factor for step voltage is

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

\[ K_s = \frac{1}{\pi} \left[ \frac{1}{2 \times 1.524} + \frac{1}{4.97 + 1.524} + \frac{1}{4.97} \left(1 - 0.5^{14-2}\right) \right] \]

\[ K_s = 0.22 \]

The effective length for step voltage is

\[ L_s = 0.75 \times L_C + 0.85 \times L_R \]

\[ L_s = 0.75 \times 1825 + 0.85 \times 76 \]

\[ L_s = 1433.5 \text{ m} \]

Now that the previously unknown variables have been calculated, it will be used to calculate the step voltage.

\[ E_s = \frac{\rho \times I_G \times K_s \times K_i}{L_s} \]

\[ E_s = \frac{50 \times 10,465 \times 0.22 \times 2.716}{1433.5} \]

\[ E_s = 218.1 \text{ V} \]

### 4.12 Comparison of Mesh Voltage and Allowable Touch Voltage

Step 9 of the logic flow diagram compares the calculated value of the mesh voltage with the calculated value of the touch voltage for a person weighing 70 kg. The
diagram shows that if the allowable touch voltage were greater than the mesh voltage, then the original design would need some modifications to satisfy certain criteria. If the allowable touch voltage were smaller than the mesh voltage, then the next step would be to compare the step voltage with the allowable step voltage. This will be discussed in the next section.

\[ E_m < E_{\text{touch,70}}? \]

\[ 387.1 < 871.5 \]

The original ground design passes the criteria in step 9. As mentioned earlier, if the criterion in step 9 is reach, then a comparison between the step voltage and the allowable step voltage is compared in step 10.

### 4.13 Comparison of Step Voltage and Allowable Step Voltage

Comparing the calculated step voltage and the calculated allowable step voltage happens in Step 11. This is the final step that the design has to meet before the grounding system is considered safe for the switchyard. Similar to section 4.12, where the mesh voltage and the allowable touch voltage is compared, modification of the design is required if the criterion is not met.

\[ E_s < E_{\text{step,70}}? \]

\[ 218.1 < 2819.8 \]

As shown in the comparison, the step voltage is considerably smaller than the allowable step voltage. Therefore, during a fault, a typical human weighing 70 kg will be able to become part of the circuit and will have a safe amount of current running through their body.
Chapter 5

CONCLUSION

A grounding grid design was performed using hand calculations, a spreadsheet calculator and a computer simulation program. The results from the computer simulation program are provided in the Appendix. Using the chosen parameters, the substation model was analyzed to determine whether it meets the safety requirements of the IEEE Standard 80-2000 edition.

The safety analysis indicated that the designed grounding grid meets the safety requirements of the IEEE Standard 80-2000 edition.
APPENDIX

Computer Design Using WinIGS

A.1 WinIGS Program

WinIGS is an analysis/design tool for grounding system design. It enables design of typical power system substation grounding. WinIGS supports the IEEE Std 80 safety criteria as well as the IEC criteria for grounding system safety. Program details can be obtained from web address — www.ap-concepts.com/ —.

A.1.1 Program Features

As provided by advanced grounding concepts, WinIGS has the following summarized features,

- It performs analysis and design of a grounding system or multiple grounding systems.
- It allows the user to model any power system together with its grounding structures.
- It analyzes the performance of the system under steady state, normal, and fault conditions, and evaluates its performance against industry-standard criteria.
- Allows the user may select either the IEEE Std. 80 criteria or the IEC-479-1 criteria, both of which have been integrated into the program.
- Allows for editing of the grounding system geometric data via specialized GUI based editors.
• Device parameters can be accessed by double clicking on the device drawing.

• Analysis results, corresponding to a specific device, can be displayed by double clicking on the device drawing.

• The grounding system geometric data are edited via the ground editor, which displays the grounding system as a scaled drawing, either in top, side, or perspective views.

A.1.2 Screen Prints of Data Entry and Model Set Up

Figure A.1 Single Line Diagram of Ground Model
Figure A.2 Grid Current Source Parameters
### Figure A.3 Resistor Parameters

#### 1 Ohm Resistor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance (Ohms)</td>
<td>1.0</td>
</tr>
<tr>
<td>Reactance (Ohms @ 60 Hz)</td>
<td>0.0</td>
</tr>
<tr>
<td>Circuit Number</td>
<td>1</td>
</tr>
</tbody>
</table>

First Node Name: **SOURCE_A**

Second Node Name: **GRSYS_N**

---

1.000 Ohms
Figure A.4 Source Ground Parameters
Figure A.5 Top View of Grounding System
Figure A.6 Grounding Conductor Parameters
Figure A.7 Grounding Electrode Parameters
Figure A.8 Homogenous Soil Model Parameters
A.1.3 Screen Prints of Results

Figure A.8 Ground Resistance Report
Figure A.9 Reduction Factor Results
Figure A.10 Safety Criteria Results
Figure A.11 Plot of Permissible Current vs. Shock Duration
Figure A.12 Equi-Earth Voltage Plot

Equi-Earth Voltage Plot
V_{perm} = 300 \text{ V}, \ V_{\text{max}}(\ast) = 3.557 \text{ kV}
Figure A.13 Equi-Touch Voltage Plot

Equi-Touch Voltage Plot
Vperm = 871 V, Vmax(+) = 1.909 kV
Figure A.14 Equi-Step Voltage Plot

Equi-Step Voltage Plot

Vperm = 2316 V, Vmax(+) = 192.3 V
Figure A.15 Earth Voltage Profile
Figure A.16 Touch Voltage Profile
Figure A.17 Step Voltage Profile
REFERENCES


