GROUNDING DESIGN FOR PERSONAL SAFETY OF A LARGE SCALE WIND POWER PLANT

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ABSTRACT

Grounding of electrical power systems has and will always be one of the most essential aspects of any electrical system design. Without a proper, well designed and effective efficient grounding network personal safety is at risk, equipment protection cannot be assured, and proper system operation cannot be maintained. Because of these reasons grounding design has become well researched, with long established standards strictly dictating the construction and integration of such ground networks. However with an ever diversifying power grid generation mix, integration of new technologies has become common. The need for these diverse technologies along with their cultural and societal demand has enabled them to outrun the standards and conceptual knowledge required for their safe construction. One such area exists in the grounding design of large scale Wind Power Plants (WPP). While most generation facilities aim to reduce their landmass to the smallest possible footprint wind power plants require adequate spacing in order to optimize wind quality and power generation with construction costs. This necessitates a generation facility or power plant that can reach up to several square miles. At areas of this size and distribution, established grounding design practices become ineffective and inapplicable while current standards become insufficient due to failing assumptions.

This thesis offers an overview of grounding concepts tailored to the unique requirements of Wind Power Plants, a discussion concerning the recommended design methodology for such a network, and real world simulations of these problematic scenarios as a basis of study for WPP grounding. Currently there is very little literature and no standard or guidelines in industry for the specific challenges posed by WPP grounding. Lack of this documentation has led to debate in industry over the topic. It is hoped that this research will provide a basic WPP grounding design methodology and demonstrate the need for the further creation of a standard or guide.

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CHAPTER 1 : BACKGROUND FOR ELECTRICAL GROUNDING DESIGN THEORY FOR PERSONNEL SAFETY

This Chapter introduces the basic concepts of grounding design, theory and its goals as a basis for understanding. Detailed design criteria, and specific methodology are presented in greater depth and entirety in later chapters.

1.1 Grounding Design: Goals and Concept

The main goal of Grounding is to ensure site safety with respect to personnel, equipment, and operation. IEEE Std. 80 "IEEE Guide for Safety in AC Substation Grounding"(2) is the applicable standard for all electrical "AC substations" and it defines the objectives of a grounding system as follows:

- To provide means to carry electric currents into the earth under normal and fault conditions without exceeding any operating and equipment limits or adversely affecting continuity of service.

- To assure that a person in the vicinity of grounded facilities is not exposed to the danger of critical electric shock.

This thesis focus on the second objective, that of personal safety. Personal safety is lost when a dangerous current is conducted in the human body through an unsafe path typically due to the existence of an accidental circuit. In power systems these accidental circuits are commonly referred to as "faults". The term "dangerous current" refers to any current that is of a great enough magnitude and duration to cause harm to personnel. This value can be given by the following equation.(2).

$$\mathbf{I_B = \left(\frac{k_{50kg}}{\sqrt{t_s}}\right) = \frac{0.116}{\sqrt{t_s}}} \qquad \textbf{(1.1)}$$

Where I_B is the tolerable body current in A, k_{50kg} is a constant related to 99% of a statistical population weighing 50 kg, and t_s is current duration in sec. Clearing times are often assumed to be less than 0.5 seconds(2) giving an approximate “dangerous current” of 150mA.

The term “unsafe path” refers to all circuit paths that include personnel as an integral part of the loop. IEEE Std. 80 enumerates the circumstances in which electric shock accidents are possible and these circumstances are included below for reference.

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.

Any existence of a voltage or potential gradient that allows a lethal amount of current to flow through a human body is considered unsafe and must be avoided. The potential gradient that a site sees upon current injection to the ground can be simply explained with Ohm’s law.

$$\mathbf{GPR = I_G * Z_G \quad or \quad V = I * Z} \tag{1.2}$$

Each of these terms are analyzed in this chapter to show how they contributes to personal safety, what each term is composed of and dependent on and how this impacts grounding design as a whole. The goal is to give an elementary understanding of grounding design theory for personal safety prior to discussing personal safety for wind power plant grounding.

1.2 Ground Fault Current (I_G)

In order to assure personal safety due to faults it becomes vital to know what is occurring with respect to the fault current. Potential gradients of the site is directly dependent on the applicable amount of fault current thus safety ishighly dependent on this as well. Figure 1.1 shows a typical fault on a power system.

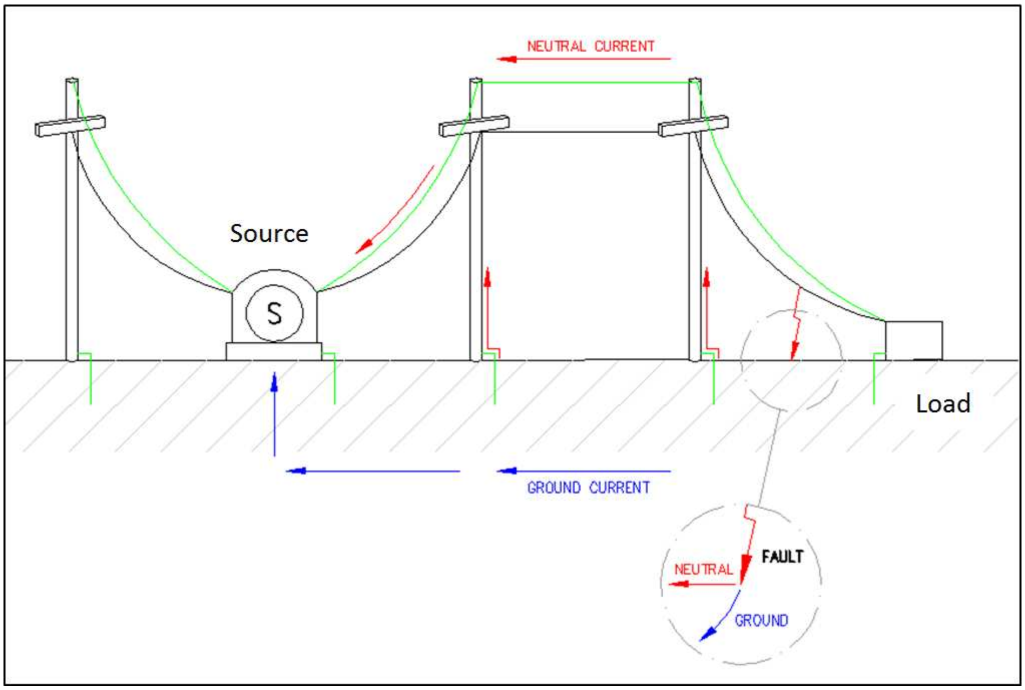


Figure 1.1 Available Paths for Power System Fault Currents

In this figure a single-phase (or line) –to-ground fault has occurred near the load. Upon entering the ground, the fault current (I_F) essentially splits. One portion flows up through any ground path available and return to the source through the neutral conductor. The rest travels back to the source through the ground (I_G). The amount of current that flows into the ground is described by the fault current division factor or split factor (S_f) and is defined in IEEE Std. 80. The ground return current, the current traveling back to the source through the ground, (I_G) then can be more accurately written as:

$$\boldsymbol{Ground\ Fault\ Current\ (I_G) = I_F * S_F} \tag{1.3}$$

Where:

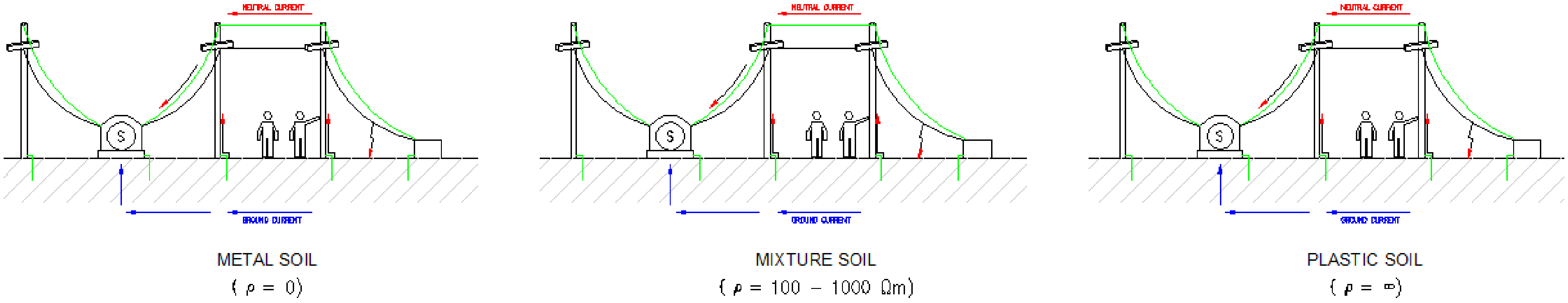
I_F = Total Fault Current

S_F = Fault Current Division Factor

It is a common misconception that all current flows only through the path of least resistance; however in truth current takes all paths depending on their resistance. Because of this, grounding design must incorporate all possible paths to ensure that the fault current or more importantly all “dangerous” portions of the fault current take the “safest” path back to the source. Ideally grounding design aims to keep personnel out of possible current paths while limiting the amount of the current in any path that includes personnel. This brings into question what conditions would lead to the safest operation.

1.3 Soil Interaction with Power System Grounding

In a power system, facilities are most often built directly onto the earth and because of this personnel will usually be in contact with the earth or soil. The soil then becomes a vital part in most if not all accidental circuits and the resistance of this soil greatly determines the safety of the individuals on that soil. Figure 1.2 shows the three possible soil scenarios that could exist; highly resistive (essentially insulating) soil (plastic), highly conductive soil (metallic), and a semi-conductive mixture of soil.



METAL SOIL
($\rho = 0$)

MIXTURE SOIL
($\rho = 100 - 1000\ \Omega m$)

PLASTIC SOIL
($\rho = \infty$)

Figure 1.2 Various Types of Electrical Soil Characteristic

Plastic soil (infinite soil resistivity) will not conduct any current and therefore a ground fault current would be zero. Thus it is very safe. Metallic soil (zero soil resistivity) will conduct very well. Therefore the entire fault current will travel through the soil, avoiding personnel; thus this is also a very safe condition. The mixed soil, however, is semi-conductive therefore a person may be seen as a more attractive path back to the source; thus this condition is the most dangerous of the three. Unfortunately this semi-conductive soil condition is what actually exists at every electrical site.

1.4 Soil as a Conductor with Finite Resistivity

In Grounding design the earth or soil must be seen as a conductor. As with any conductor, resistance increases with length but decreases as cross sectional area increases.

$$\boldsymbol{R = \frac{\rho L}{A}} \tag{1.4}$$

The larger the region of soil, lower is its resistance. When a fault current is split between a short wire and a small section of soil the majority of the current will travel in the wire due to the fact that the wire's resistance is so much lower than the soil; however if the current is split between a long wire and a great expanse of soil the current could split either way depending on the soil characteristics of the large expanse. At large distances the impedance of the soil will drop due to the large cross sectional area available to the current while the wires resistance will only increase with length. In this manner the resistance of the soil and that of the wire could be comparable. This could result in a larger amount of current being injected into the soil or other paths more readily available to it.

1.5 Electrical Soil Characteristics and Modeling

Soil electrical characteristics can vary greatly with respect to moisture content, chemistry (salinity), temperature, soil structure, granular size, and countless other factors making the prediction of where the fault current will travel nearly impossible without good soil data and an accurate soil model. Additionally soil is deposited in layers and these layers vary in both electrical and thermal properties. For calculation purposes soil is modeled as a number of layers having different resistivities and thicknesses. Collectively the group of layers and their respective resistivities compose the overall soil model or “electrical soil structure”. Soil structure greatly impacts the way the fault current will behave and thus directly impacts the safety of a site. This soil structure for instance determines if a fault current is more likely to travel on the surface of the soil or in the deep layers or at what optimal depth ground conductors should be placed to more effectively channel current safely back to the source. Depending on how conductive the soil is, a site may be safe or unsafe. IEEE Std. 80 provides reliable, simple calculations in determining site safety criteria or safe thresholds based upon the site soil characteristics, and are discussed in greater depth later.

1.6 Ground Conductors: A Physical Sense

Establishing personnel safety in grounding design is most commonly achieved by a number of tools, one of which is offering a low resistance return-path. The intention is that this low impedance path becomes the “easiest” path for the dangerous current to “safely” travel to its final destination, the lower potential side of the source. Thinking of the soil as a conductor, the better the connection between the site and the soil is, the easier current will flow. In order to make an insulator more conductive one would need to add conductive material to it. This can be illustrated with a wooden fence post. Dry, the wood will not easily conduct; however if it is soaked in water it will conduct much more readily. In the same way as adding moisture to the post, adding copper to the soil will generally cause the ground to conduct more readily. Just as important as the addition of conductive material is the interface of that conductive material with the soil both with respect to geometry as well as the physical contact achieved. All these factors, when applied correctly can generally be used to make the ground conduct more readily, or in other words decrease the ground impedance of the site. This conductive material is typically added to the soil in the form of horizontal copper grids and vertical copper ground rods. These ground rods work to increase the surface contact with the deeper soil and ideally use the soil structure to contact the most optimal (low resistivity) layers of soil. In Power Systems Analysis and in basic Electrical Circuit Theory the grounding connection described above is denoted as a point and is typically represented by the ground symbol shown in Fig. 1.3

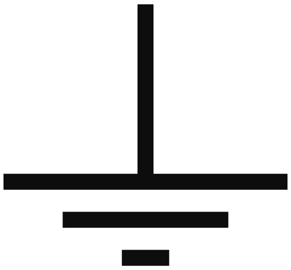


Figure 1.3 Circuit Schematics Ground Symbol

However for large scale systems this symbol does not physically exist as a point but rather as a network of horizontal and vertical conductors buried within the soil. This network is commonly referred to as a ground grid and usually consists of a buried copper grid with strategically placed copper rods driven to optimal depths. Thus a power system's "ground" is actually a ground grid incorporating an entire network of conductors at various depths and geometries all connected together and buried in the soil. Figures 1.4 - 1.6 show typical grounding grids at various stages of completion. Here it can be seen that grounding conductors are placed throughout the station, connected to every conductive structure and buried.

1.7 Ground Impedance (Z_g)

The electrical soil structure as well as the size, geometry and composition of the ground conductors ultimately comes together to result in an equivalent ground grid impedance. This impedance denotes the impedance that a ground fault current sees when attempting to flow into the soil.

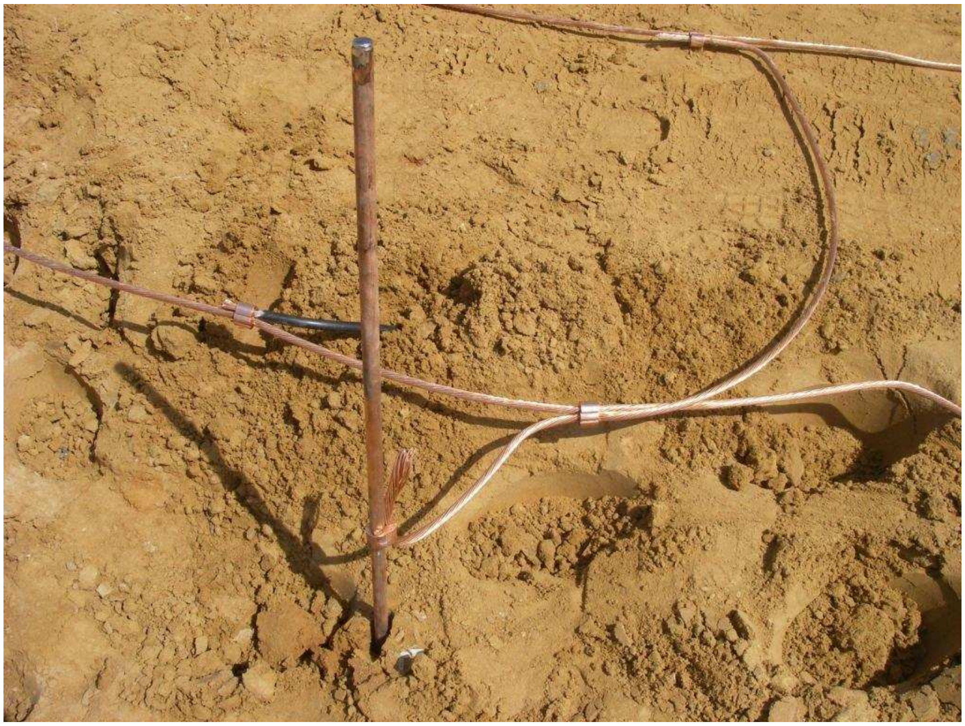


Figure 1.4 Typical Underground Grounding Grids

Figure 1.5 Typical Ground Grid Installation

Figure 1.6 Typical Finished Grade Grounding Connection

As mentioned this impedance is a complex value dependent on several variables. Its calculation can be simple or extremely difficult depending on the assumptions. It is critical to know which assumptions can be made and under which conditions they hold. Several common assumptions are discussed later in order to highlight the new challenges wind farms pose. For now it should only be noted that despite the fact that the ground impedance is a critical factor in establishing personnel safety the calculation of this factor is by no means straight forward. Additionally it is worth noting that IEEE Std. 80 uses the term “resistance” when referring to this term assuming a fully resistive value with no reactance. This is due to the fact that local station grounding grids are small enough that the reactive component can be neglected; however as the size of the ground grid is increased (like in a wind farm) the ratio of reactance to resistance increases. While the reactive component is not substantial for localized ground grids it cannot be neglected for larger installations (such as wind power plants). In truth all ground grids (even small localized ones) will have at least a small reactive component. Because of this relationship the term “impedance” has been used in this thesis as an all-inclusive term to incorporate the possibility of a reactive component. While it is out of the scope of this thesis it should be noted that this reactive component becomes much more important when dealing with the phenomenon of lightning as reactance is frequency dependent.

1.8 Ground Potential Rise (GPR)

Ohms law states that any current traveling through a resistance will cause a voltage rise. This law holds true for ground fault currents traveling through the soil. Furthermore IEEE Std. 80 establishes that the existence of high potential gradients (voltages) is the primary cause for electric shock. The portion of the fault current traveling through the ground (I_G) will pass through the ground impedance (Z_G) on its way back to the source. As it passes through the resistive soil there will be a voltage gradient across the soil that it has traveled through. This voltage gradient is realized as a potential difference across the ground impedance which is termed as the ground potential rise (GPR). Simply explained GPR is a voltage rise at a localized area. The point where the current enters the soil will have the highest concentration of current and thus by Ohm’s law the highest voltage with respect to remote earth at zero potential. As this current is dispersed through the massive amounts of paths available to it the corresponding voltages become smaller and smaller. What occurs is a voltage spike that gradually decreases until a zero potential (zero volts) is reached. Figure 1.4 shows this via a 3D graph of a complex ground grid under an injected fault. Voltage is on the vertical axis and the horizontal plane represents the footprint.

This graph shows that the soil itself is being elevated to a higher voltage (by the fault current injected via the ground grid) than its normal zero reference point. How high and over what extent is due to the magnitude of the fault going into the ground as well as the ground grid impedance defined by the soil characteristics, geometry and structure.

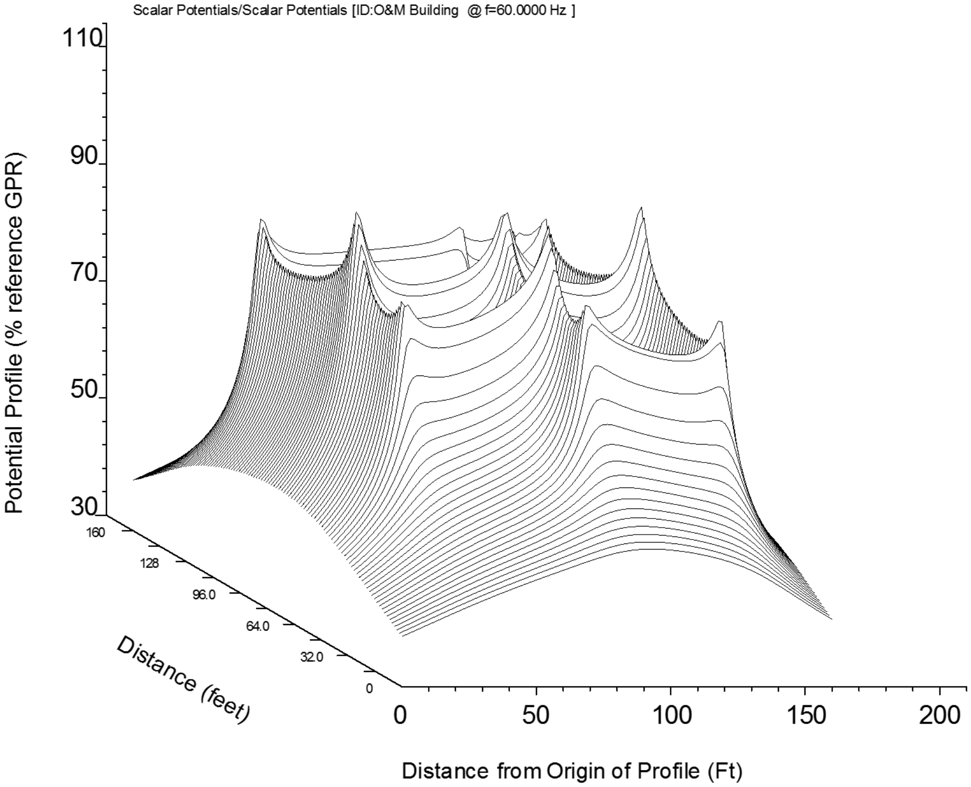


Figure 1.7 3D Ground Potential Rise

The GPR will directly affect the voltages personnel are subjected to. Because of this GPR is directly related to personal safety and therefore is a vital parameter to quantify.

1.9 Basic Grounding Theory: Summary

Thus Ohm's law introduced in Equ. 1.2 of this thesis may be rewritten in its entirety as:

$$\boldsymbol{GPR} = (\boldsymbol{I_F})(\boldsymbol{S_F}) * (\boldsymbol{Z_G}) \qquad \textbf{(1.5)}$$

Where I_F, is the total available fault current (single-line-to-ground fault current) is usually known but S_F and Z_G require complex calculations in order to determine with any accuracy. Furthermore these calculations are unique to every site as the factors involved in their calculation vary greatly with every site and a truly infinite number of possibilities exist. Having established a basic understanding of the goals of grounding design (i.e. safety of personnel and equipment operations), its methods and its implications (calculation of GPR, S_F, Z_G, and I_F), the next logical question is “How can a site be qualified as safe?”.

CHAPTER 2: SAFETY CRITERIA FOR GROUNDING SYSTEMS

2.1 Personnel Safety: Safety Criteria

Critical voltage thresholds can be calculated for different scenarios and these thresholds are described in IEEE Std. 80 as safety criteria. These safety criteria become the measure of allowable potential gradients across the site. If a site potential gradient exceeds these criteria harmful electric shock can occur. Numerous studies have been performed to evaluate the level of current that is considered lethal to human beings. These studies are listed and referenced in IEEE Std. 80 and it is their findings that have determined the critical current limit that IEEE Std. 80 designs to.

The three most common hazardous scenarios are that of “Step”, “Touch”, and “Transferred” or “Stray” potentials. In this section Step and Touch potential are discussed in detail as they are the most common. Additionally Transferred potential are discussed in much greater detail later in this thesis.

2.2 Safety Criteria Assumptions

The IEEE Std. 80 safety criteria for both Touch and Step potentials assume several factors. These assumptions are of note and are addressed prior to discussing the safety criteria itself. The first assumption made is that of body mass. IEEE Std. 80 has equations for both 70kg and 50kg personnel. For this thesis and in all good grounding design the 50kg assumption is be used. This is mostly to ensure safety for children and small adults and in general a more conservative design. Even sites that are completely closed to the public could be open to smaller than average adults.

The second assumption is that of human body resistance. In studies it has been determined that human body resistance can range anywhere from 500Ω to 3,000Ω. This resistance changes with such factors as: moisture, health (cuts or punctures in the skin), and clothing. IEEE Std. 80 ignores the resistance of gloves and contact surfaces to specify a standard human body resistance of 1,000Ω and has been the acceptable standard.

Lastly human tolerances to electrical current have been studied and safe limits have been observed. Based on the data IEEE Std. 80 has established formulas to evaluate the “safe” voltage thresholds allowable for both touch and step potentials. These basic formulas are discussed conceptually in the next two sections. All variables for those equations are defined immediately after.

2.3 Step Potential

Step potential is defined as: “the difference in surface potential experienced by a person bridging a distance of 1m with the feet without contacting any grounded object.” This describes the possible voltage gradient that could exist between the feet of a person in taking a normal stride. The following diagram (Fig. 2.1) has been used to illustrate this concept.

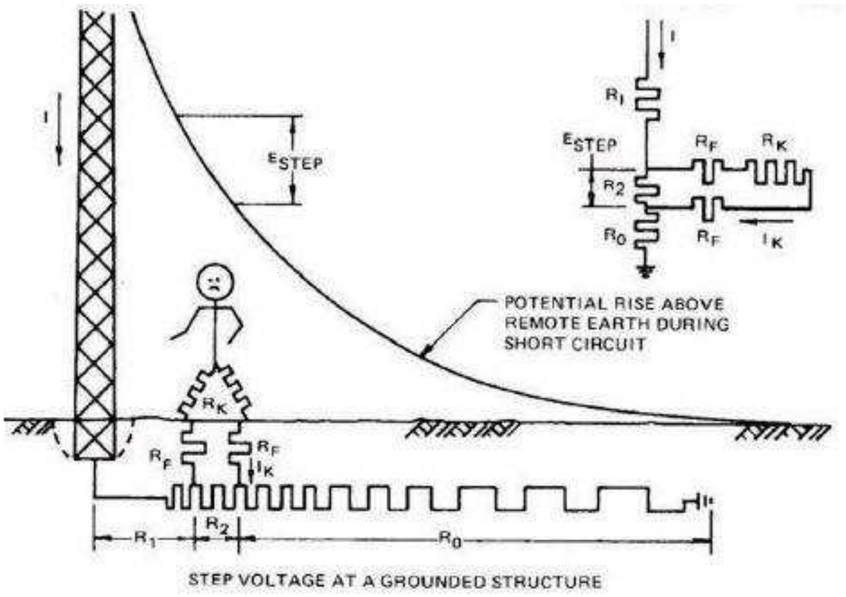


Figure 2.1 Step Potential(8)

Here a person is caught mid-stride during a fault condition. Depending on the local GPR and its decay rate, this person could possibly bridge a large potential ground gradient with their stride or “Step”. The safety criterion for Step potential is the threshold voltage at which a harmful portion of the ground current flows through the person’s legs to bridge the step distance. Simply put the ground current sees a less resistive path across the step distance and split to take it. The safety criterion for step potential for a 50 kg person is mathematically defined in IEEE Std. 80 with the following equation (Eq. 2.1) and is discussed at length later.

$$\boldsymbol{E_{step50} = (1{,}000 + 6C_s * \rho_s)\left(\frac{0.116}{\sqrt{t_s}}\right)} \tag{2.1}$$

Here the current flows up one leg and down the other (body resistance). The foot resistance can be clearly seen in the figure to be in series. This arrangement incorporates double the foot resistance of the circuit, and is responsible for the coefficient of the $6C_s$ term.

Step potential is typically considered less dangerous than Touch potential. This is due to the fact that the current does not travel through the heart but only through the legs. In addition to this because of the higher foot resistance safety criteria for step is typically much higher than that of touch. This being said, it should be noted that depending on the shock, Step potential shocks could lead to collapse in an unsafe area where continued shock could occur now entirely across the heart.

2.4 Touch Potential

Touch potential is defined as: “The potential difference between the ground potential rise (GPR) and the surface potential at the point where the person is standing while at the same time having a hand in contact with a grounded structure.” This describes the possible voltage gradient that could exist across a person in contact with a grounded site structure and the ground. The following diagram (Fig 2.2) has been used to illustrate this concept.

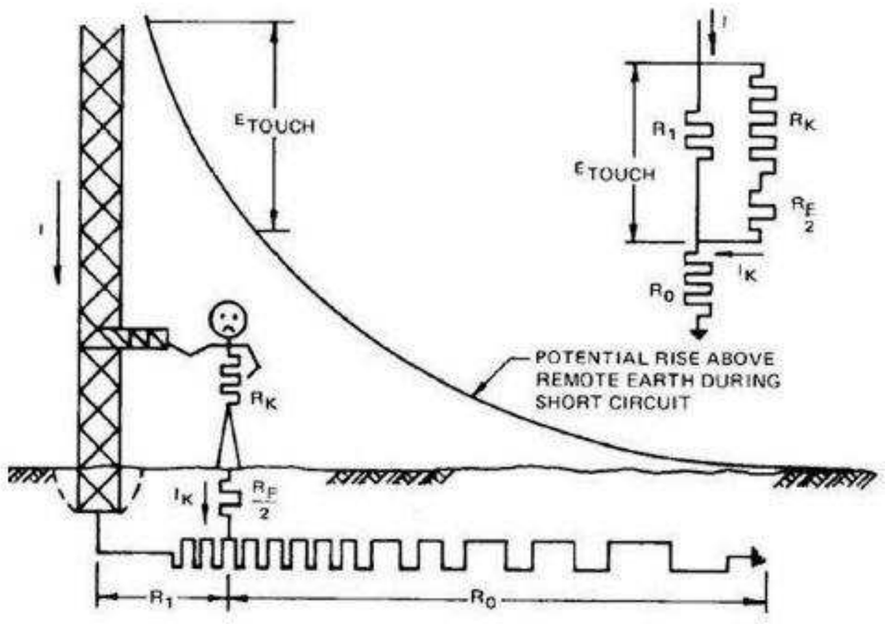


Figure 2.2 Touch Potential$^{(8)}$

Here a person is in contact with a site structure during a fault. Depending on the local GPR a dangerous potential gradient could exist between the structure and the point where the person is standing. This could induce a dangerous current to flow through the person. The safety criterion for Touch potential for a 50 kg person is mathematically defined in IEEE Std. 80 with the following equation (Eq. 2.2) and is discussed at length later.

$$\boldsymbol{E_{touch50} = (1{,}000 + 1.5C_s * \rho_s)\left(\frac{0.116}{\sqrt{t_s}}\right)} \tag{2.2}$$

Here the current flows down through the person’s body and legs. The foot resistance can be clearly seen in the figure to be in parallel. This arrangement shall effectively half the foot resistance, causing the Thevenin equivalent impedance of the ground circuit to differ and is responsible for the constant portion of the 6C$_s$ term becoming 1.5C$_s$.$^{(2)}$ In addition to a lower safety threshold touch potentials are often seen as more dangerous as the current passes through the heart rather than only the legs. This means that touch potential is generally harder to protect against and more dangerous when it does occur than Step potential.

2.5 Safety Criteria Ramifications

The equations for safety criteria are included again below and are further explained to understand what factors are the most prevalent in determining the safety criteria of a site. The IEEE Std. 80 equations with regard to a 50 kg person are as follows:

$$\boldsymbol{E_{step50} = (1{,}000 + 6C_s * \rho_s)\left(\frac{0.116}{\sqrt{t_s}}\right)} \tag{2.3}$$

$$\boldsymbol{E_{touch50} = (1{,}000 + 1.5C_s * \rho_s)\left(\frac{0.116}{\sqrt{t_s}}\right)} \tag{2.4}$$

Where:

$$1{,}000 = Human\ body\ resistance \rightarrow constant$$

$$6 = Related\ to\ Z_{th}\ of\ a\ step\ circuit\ loop \rightarrow constant$$

$$1.5 = Related\ to\ Z_{th}\ of\ a\ touch\ circuit\ loop \rightarrow constant$$

$$0.116 = Energy\ limit\ based\ on\ body\ mass \rightarrow constant\ for\ given\ mass$$

$$\rho_s = Soil\ resistivity\ of\ the\ surface\ layer \rightarrow dependent\ upon\ the\ soil$$

$$t_s = Duration\ of\ the\ fault\ current\ in\ seconds \rightarrow set\ based\ on\ protective\ relays$$

$$C_s = Surface\ layer\ derating\ factor = 1 - \left(\frac{0.09\left(1 - \frac{\rho}{\rho_s}\right)}{2h_s + 0.09}\right) \rightarrow dependent\ upon\ the\ soil$$

Where:

$$h_s = Surface\ layer\ thickness$$

$$\rho = Resistivity\ of\ the\ sublayer$$

In the above definitions it can be seen that the safety criteria of a site is primarily dependent upon the soil characteristics of that site. This means that regardless of the design the only way to ensure safety 100% is to know the local soil structure and characteristics. Without this there is no safe threshold to compare any potential gradient to and thus no way to verify a site as “safe.”

CHAPTER 3: WIND POWER PLANTS

In this chapter a brief overview of WPP operation and common practice with respect to WPP construction (specifically grounding) is discussed. This overview enables a detailed discussion of the new grounding challenges WPPs have introduced.

3.1 Wind Power Plant: Definition

Currently there is no standard for the grounding of a wind power plant. Noticing this shortcoming, IEEE has established a Task Force (Task Force on Wind and Solar Plant Grounding for Personal Safety)(13) responsible for developing a standard or guide specifically for wind power plant grounding. This IEEE task force has defined a Wind Power Plant as follows:

> "Definition: A wind power plant (WPP) is a group of electrically interconnected wind turbine generators having one or more points of interconnection to the utility electric system."

This definition simply means that each WPP is composed of several individual wind turbine generator stations. These generator stations "collect" together the total cumulative energy (through the "Collector System") and then transmit to the Power Grid. Common grounding practice, at this point, is to treat WPPs as a collection of AC stations, using IEEE Std. 80 as a guide for their "Safe" grounding. This approach, while commonly used in industry, neglects several important factors. Among those factors are: failing assumptions commonly made for AC station grounding, as well as new challenges inherent in wind power plant construction.

3.2 Wind Power Plants: Onshore Vs. Offshore

In recent years the construction of offshore windfarms has increased in popularity. Typically offshore installations enjoy better wind quality, higher wind speeds and longer sustained wind this coupled with the use of much larger turbines (5-7MW/turbine offshore as compared to 2- 4MW/turbine onshore). Due to this offshore wind is gaining in popularity especially outside the US, inside the US offshore wind farms, however, are not largely pursued due in part to public perception. Obviously the grounding of these two systems varies greatly thus this thesis focuses only on onshore windfarms. However that being said the basic definition and (electrical) concepts for a wind power plant introduced in this section (excluding construction details) can easily be extended to offshore installations.

3.3 Wind Power Plants: Typical Operation

The IEEE Task Force definition ultimately necessitates that a WPP is designed with three basic end functions in mind: generate energy, collect energy, and transmit energy. Each of these end functions contribute directly or indirectly to the necessary grounding of the overall WPP and thus they are each be discussed in greater detail.

3.3.1 Generation:

Wind Turbine Generator (WTG) sizes have grown much larger over the years, today 2MW- 4.2MW machines are common for onshore installations with off-shore installations approaching 5-7MW. These machines produce power at a typical voltage of 690V (for 60 Hz Systems) depending on the turbine manufacturer and country of installment (frequency). To generate this power most efficiently and cost effectively WTGs are placed in remote areas and spaced far apart from one another (typically 2-3 rotor diameters to avoid wake effects; however this also depends on the prevailing wind direction) where high wind qualities may be obtained. This results in WTGs usually being very spread out across large land areas, in remote locations, far away from major load centers.

3.3.2 Collection:

Due to this sparse distribution of generator stations, the energy produced by each WTG must be “collected” together before being transmitted to the load centers. This collection is realized by electrically connecting all the wind turbines together. Often this is done via several circuits that will take the energy from a group of wind turbines to a local substation for further transmission. Again because of the distance between each WTG and the substation, this collections process is usually done at medium voltage. (typically at 34.5 kV) in the US.

3.3.3 Transmission:

With WPPs in remote areas all the collected energy must be transmitted to the large load centers such as cities, industries, and homes. Transmission of this energy is done from a centralized, local substation that will step up the medium collection voltage to high voltage for transmission into the power grid. These transmission voltages are most commonly 230 kV or 345 kV, depending on the total capacity of the WPP and the availability of the local grid connections.

3.4 Wind Turbine Generators: Individual Stations

To complete the entire process described above each WTG will require a step up transformer to reach MV collection voltage. This transformer will either be located in the nacelle at the top of the wind turbine or on a pad at the base of the tower (varies by WTG manufacturers). Regardless of the location, the basic operation is the same and can be represented with the following single line (Fig. 3.1)

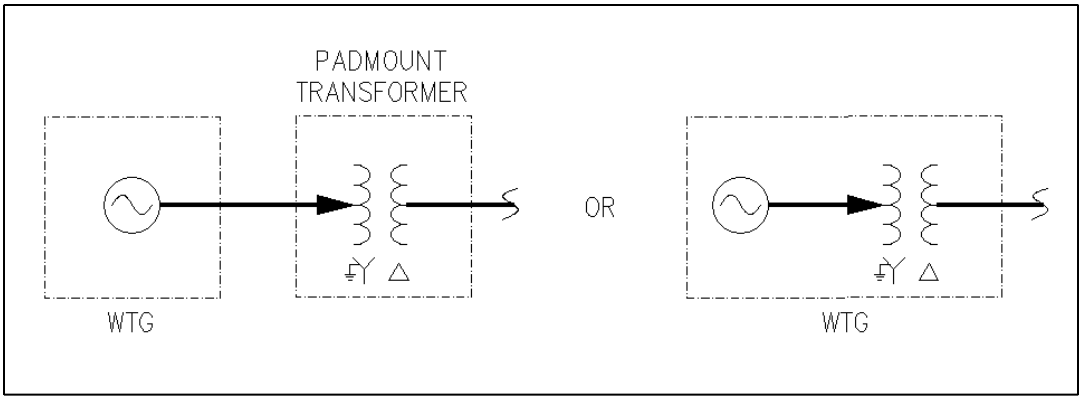


Figure 3.1 Simplified WTG Single Line Representation

In addition, a main power transformer will be required at the substation to step the MV collector voltages to HV transmission voltages. Collectively this can be shown in the following single line, Figure 3.2

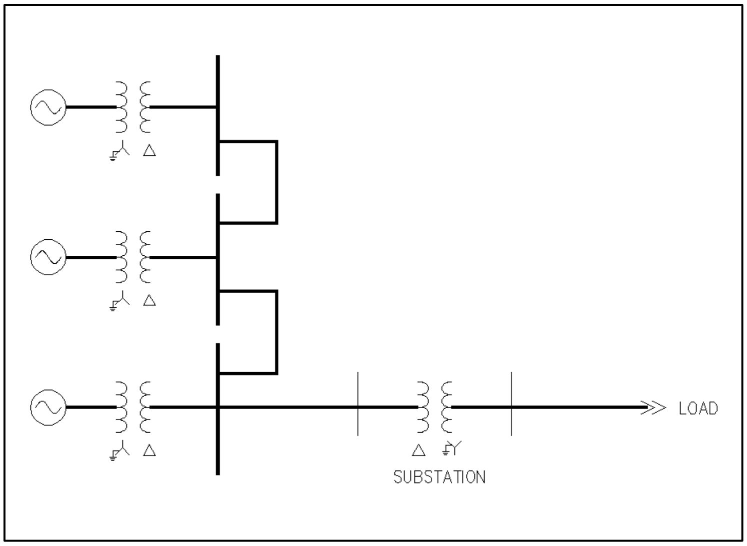


Figure 3.2 Simplified Single Line of an Interconnected WPP

From the above single line diagram it can be easily seen that every WTG will behave as an independent MV station. Additionally every WTG will be a possible fault location with fault currents attempting to return to either the WTG or to the substation.

From a grounding perspective this necessitates that every wind turbine generator (WTG) be seen as its own station or site. This view of each WTG as an individual generating station is already accepted in industry and consequently it is the reason that IEEE Std. 80 is currently used for WPP grounding. However, because every site can be effectively seen as a generating station, each site must then be tested for safety with respect to the local safety criteria and standards laid out in IEEE Std. 80 which as of yet is not widely accepted by industry. This is largely due to the absence of a governing standard for wind farm grounding coupled with extra testing costs and added schedule time.[1]

3.5 Wind Power Plant: Interconnected Stations

Despite the fact that each WTG can be seen as a separate station it should also be apparent from the single line diagrams of figures 3.1 and 3.2 that all WTGs are electrically connected. This electrical connection is obviously realized in the collection system conductors, however it is also obviously less realized through the soil. Due to these connections both foreseen and unforeseen, a fault on one WTG will cause a necessary reaction on all others. This necessary reaction may or may not be safe. Thus WPP grounding cannot merely be concerned with ensuring safety at each individual site but must also extend to ensure the safety of the entire interconnected generation system. This condition is discussed in much greater detail later and is the main focus of this thesis. For now it is sufficient to merely state that this interconnected condition coupled with the

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[1] Please note that though there was an IEEE standard created for the grounding of generating stations (IEEE Std. 665) this standard has since been withdrawn in favor of the application of IEEE Std. 80 to both AC substations and AC generating stations.

previously mentioned distribution of WPPs has created many challenges for grounding design of those same WPPs.

3.6 Wind Power Plant: Construction

Each wind turbine is seen as an individual generating station and all are connected back to one central location with the entire system composing the wind power plant. In industry, WTGs are most commonly collected through the use of MV underground cable. As individual sites, each wind turbine has an individual local grounding network. The type of local grounding network used varies between turbine manufacturers, with some requiring entire local ground grid networks and others requiring only the turbine rebar (structural steel within the foundation). These manufacturer requirements are largely upheld with the warranty rather than any applicable standard. The picture below (Fig. 3.3) shows the structural steel of a WTG before the foundation concrete is poured- this particular site required blasting.

Figure 3.3 WTG Foundation Structural Steel Installation

After the turbines have been placed and constructed, trenches are dug between select turbines to form circuits of generating stations. With trenches already being dug a ground conductor is laid in the same trench as the MV collector cable. The ground conductor is then attached to the individual ground network at the base of every turbine. This connection is established regardless of the type of the local ground network, connecting to either an external ground grid or directly to the turbine rebar. In this manner the entire site is connected via a single ground conductor network. The pictures (Figs. 3.4 and 3.5) below show a typical trench installation with copper ground wire, MV cables, and fiber optic cable.

Figure 3.4 WPP Collection Trench Typical Arrangement

Figure 3.5 WPP Collection Trench Installation

The interconnections described above are done until every wind turbine has been connected into a circuit. The number of circuits in a WPP and their location depends on the size, distribution, soil, turbine type, cost, etc. and is beyond the scope of this thesis. However, it should be noted that these construction factors will affect the overall layout of the circuits. As is seen later, this layout can have profound impacts upon grounding design for personnel safety.

3.7 WPP Grounding Design: Challenges

Due to the characteristics of WPPs discussed above several challenges arise with respect to a WPP's safe grounding design. These specific challenges as well as their implications are further elaborated in this section.

3.7.1 Land Area:

WPP overall efficiency is heavily dependent on the wind quality available. The best wind quality typically occurs in flat unobstructed areas. Any structure that can disrupt the wind will adversely affect the wind quality of the area. Because of this, WPPs are usually built in remote areas far away from buildings and other large load centers. Additionally the WTGs of a WPP are similarly spread out as to not affect one another. (2-3D spacing, where D represents the WTG rotor diameter) This spacing is optimized to achieve the maximum power output for each WTG.

While traditional generation facilities have aimed at decreasing their overall footprint Wind Power Plants must balance footprint with wind quality and cost. These traditional facilities aim to decrease right of ways and land ownership, making the most power with the least utilized resources. A typical substation or generation plant as mentioned in IEEE 80 may span an area of 200 ft x 200 ft while even a small WPP can cover an area of several square miles. Such traditional facilities are small and in nearly every case the entire generation facility is seen as one station.

Because of the large land area associated with WPPs it becomes impossible to create a single accurate soil model spanning the entire power plant. As mentioned in Chapter 1 soil varies greatly with respect to depth, resistivity, layer structure, etc. as well as with horizontal distance. This wide variance means that a single WPP could contain a large number of very distinct soil structures. Recall from Chapter 1, that the safety criteria defined in IEEE Std. 80 is predominantly dependent on the soil characteristics, thus a site cannot be assured as safe without first obtaining an accurate soil model of the site.

A large scale wind power plant rated at 250MW can easily have 100 or more turbines, 100 or more junction boxes, several meteorological towers (met masts), an O&M Building, and a substation. Since each of these sites can be interacted with by personnel all must be assured of safety. This necessitates soil models to establish accurate safety criteria for each site (often over 200). This process is both expensive as well as time consuming. In addition to individual testing to establish reliable local safety criteria an overall or average soil model is also required in order to determine the split factor a fault current may possibly have when traveling across the entire site.

3.7.2 Public Access:

With wind power plants covering such large areas it becomes highly impractical to secure an entire site from the public. Effectively fencing and monitoring a secure perimeter of that magnitude would be expensive and difficult, thus it is not done. Due to this the added design problem of public access to the WPP arises.

In the case of a traditional generation stations and substations a fence can easily encompass the entire site boundary. Furthermore the land used for these traditional sites is entirely used as it has been condensed to only the essential footprint required. However, in the case of wind power plants the huge majority of the land area is unused. Because of this, land for WPP is most often leased instead of purchased. Leasing the rights to the land is more cost effective than purchasing it, as well as being easier to negotiate, since the landowners will retain many rights. In fact it is very typical that the land leased for a WPP is still farmed, cultivated, and lived on by the land owners. In this typical scenario livestock is free to roam throughout the turbines, children are free to play amongst them, irrigation systems and farm implements will remain present, and agricultural work still takes place between and around them. The picture (Fig. 3.6) below shows one small leg of a collector circuit spanning miles of open access farmland. This particular site was owned by a single landowner but many times this is not the case.

Figure 3.6 Open Areas of Typical Installations

From a safety standpoint, this means that untrained civilian personnel are living and working amongst a group of large electrically connected generator stations. In addition to this there is an added factor of uncertainty in that WPP grounding designers will not know what to "safely" prepare for; whether it is a 6 ft. "step" span of valuable livestock a small 30 kg child, a large tractor parked near a turbine, or a farmer ploughing the soil on top of buried MV cable.

3.7.3 Large Interconnected Systems:

As mentioned previously a WPP is a completely interconnected electrical system extending over several square miles. This means that any change at one location will have an immediate effect on every other location. For the case of traditional generation sites all fault location of a particular bus are considered to have the same effect because the entire site is seen as a single point. For WPPs a fault at one turbine has a unique effect on every other point across the site. For a traditional power plant assuring the safety of the entire site means assuring safety for one fault location. For a WPP assuring safety for the entire site means ensuring safety for every possible fault location across that entire site.

3.7.4 Large Varying Distances from Fault to Source:

In traditional generation facilities the entire site is built above an interconnected ground grid. This ground grid is small enough and fine enough that the following two assumptions are often made:

1. The site ground grid is equipotential in the event of a fault
2. Fault currents are assumed to travel in the low impedance grid rather than the relatively high impedance ground

Note: there are of course exception cases where these assumptions are not made

In the case of WPPs, these two assumptions break down and are no longer valid. This breakdown occurs due to the great distances which WPPs cover. Both will be detailed further in the following section.

3.7.5 Equipotential Assumption:

The equipotential assumption assumes that across any energized conductor the voltage drop across that conductor is negligible i.e. that the conductor is a quasi-perfect conductor with negligible series resistance. As distances or, more importantly as length of a conductor increases conductor resistance also increases. For WPPs the ground conductors span great distances. Even though the site is in fact interconnected the great distances mean that voltage drops across the ground conductors occur. Because of this the assumption that the entire site is simultaneously at the same potential at every point is no longer valid especially for a wind power plant. Figure 3.7 and 3.8 illustrate this fact by plotting the GPR of the ground conductors by color for a 1 Amp fault injected at the WPP substation (presented in bird's eye view as well as 3D respectively). Figure 3.9 gives the relevant color scale for this 1 Amp fault injection.

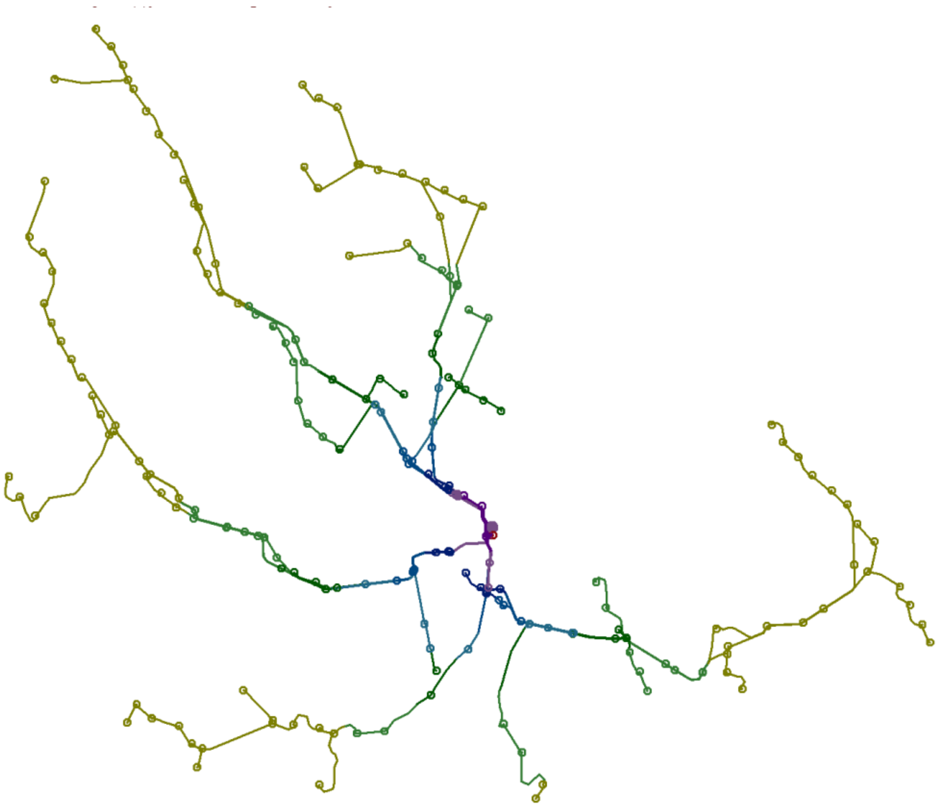


Figure 3.7 Birds Eye View of Ground Conductor GPR for an Entire WPP

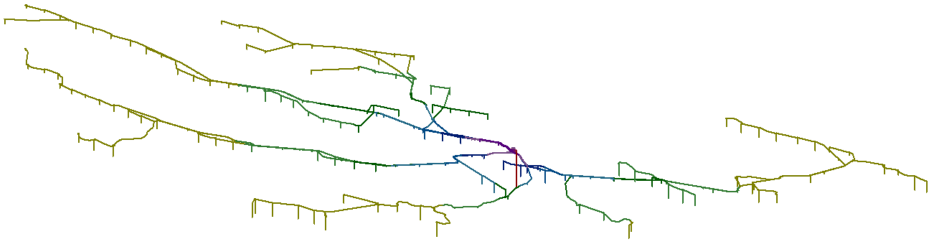


Figure 3.8 3D View of Ground Conductor GPR for an Entire WPP

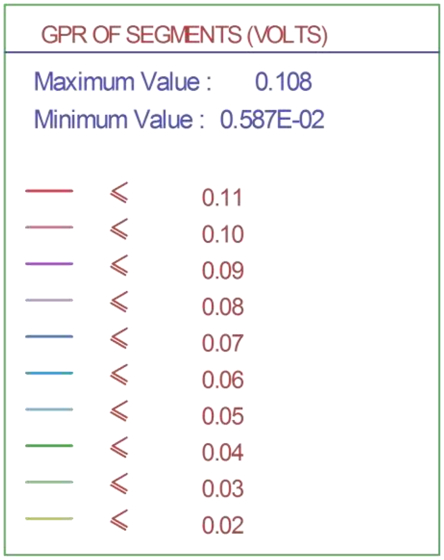


Figure 3.9 GPR Color Scale

3.7.6 Assumption of Negligible Conduction:

The resistivity of soil in comparison to metallic ground conductors is very high. Recall that the resistance of a path to the flow of current was defined in Chapter 1.

$$R = \left(\frac{\rho L}{A}\right)$$

Here it can be seen that the resistance of the path depends on the distance that path traverses as well as the cross sectional area of that available path. For traditional generation sites a fault within the facility attempts to return to the source, most often the generator step up (GSU) transformer, which is installed on the same ground grid as the generators. The fault current then sees a low resistivity, short path against a high resistivity, small cross section of soil. Because of this very little current flows into the soil.

For a WPP the fault still attempts to return to the source however the source (GSU) is now extremely far from the fault. Now the fault current has a low resistivity yet very long conductor path against a high resistivity, yet massive cross section of soil. It is not clear that the soil will offer a higher resistance than the ground conductor. In fact the opposite is often true. This means that ground fault currents can “jump” through the soil to other structures or circuits on their way back to the source. The assumption that fault currents are safely conducted through the intended low impedance paths provided is then not necessarily true as those currents could take a short cut through the a lower impedance path provided by the soil, possibly endangering anything in between.

3.8 Summary

Wind Power Plants must be evaluated with respect to personnel safety as both individual generating stations as well as larger interconnected sites. Wind Power Plants cover large areas of publicly accessible lands in which fault current paths are unknown and/or hard to predict. Grounding design for a WPP is fundamentally different than that of a traditional generation or AC substation in many aspects. This difference is due to the nature of WPPs and their practical construction. Because of this WPP grounding design requires additional and special measures in order to ensure personal safety.

CHAPTER 4: METHODOLOGY FOR “SAFE” WPP GROUNDING DESIGN

The basic methodology for ensuring personal safety of a WPP presented in this thesis is somewhat similar to the one currently being proposed by the IEEE Task Force on Wind and Solar Plant Grounding for Personal Safety(3) and this is still under review. However it is a methodology currently used by leaders in the renewable energy industry. In addition to this, alternatives to this method (similarly being used in industry) are also presented and compared. This comparison targets only the ramification of personnel safety as all other topics fall outside of this thesis’s scope.

4.1 Brief Method Overview

The major steps of the proposed method are illustrated in the flow chart of Figure 4.2 (pg.40). Each major step (and all subsequent minor steps) is discussed in detail throughout the following chapter.

4.2 Soil Models and Resistivity

Before any analysis is done, an accurate soil resistivity model must be constructed for each grounding point across the WPP. These grounding points include (but are not necessarily limited to) all wind turbine generators, junction boxes, meteorological masts, Operations& Maintenance buildings, and substations. This step may be completed via several different methods to varying degrees of complexity and completion. However it is the first step (unanimously agreed by all stakeholders) in any grounding study regardless of commercial preference.

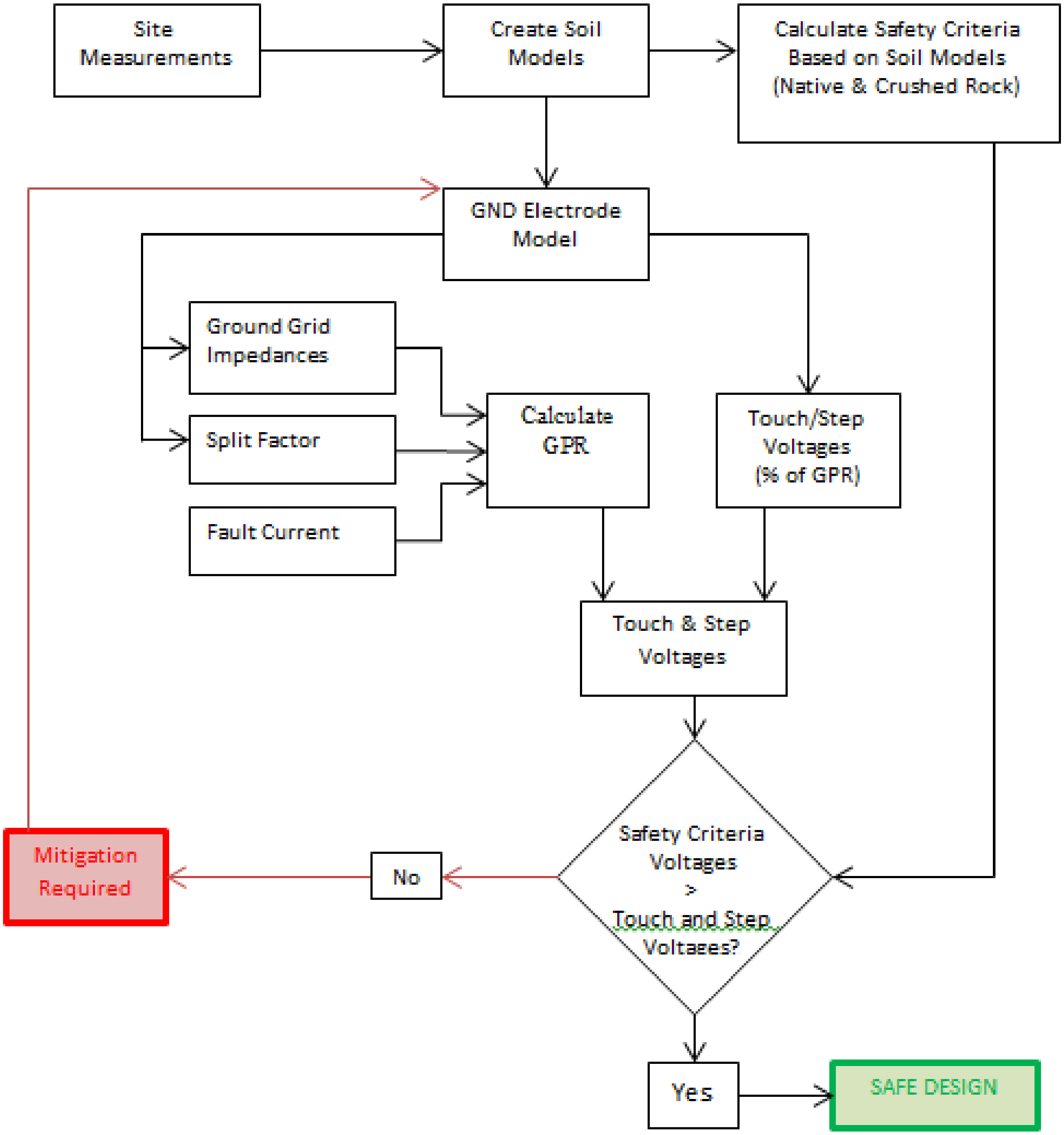


Figure 4.1 Flow Chart of Basic Grounding Method for a WPP

4.2.1 Soil Modeling: Purpose

Soil models are typically composed of multiple layers. As mentioned in Chapter 1; a uniform (or homogeneous) soil is all but impossible to find in a real world environment. A grounding point's safety criterion along with the ground impedance is primarily dependent upon the associated soil structure. Summarizing, for any given WPP this means:

1. The soil characteristics can vary wildly and unpredictably with a very large number of possibilities.

2. In order to calculate the safety criteria and ensure the grounding is safe, its soil structure must be known to define what voltage levels are in fact safe at that grounding point.

3. The ground impedance (and therefore the available GPR) is directly related to the soil characteristics.

From the numerous soil models created and key assumptions (as discussed in Chapter 1) safety criteria are calculated for every location tested.

4.2.2 Soil Modeling: Method

Soil electrical resistivity data is most commonly measured using the Wenner or Slumberger-Palmer four pin methods (1) (4). These two methods are very similar varying only in the respective probe spacing distances. Each test method has its own pros and cons and comparisons of the two methods have been widely studied and published (4) (6). Regardless of the type of four-pin method used, the basic concept is the same: by injecting a known current and measuring the associated voltage drop an apparent resistance vs land area (defined by the electrode spacing) is obtained. Figure 4.2 shows a log-log graph of this apparent soil resistance for multiple locations. Lines have been included to indicate industrial rules of thumb for quickly interpreting the raw data.

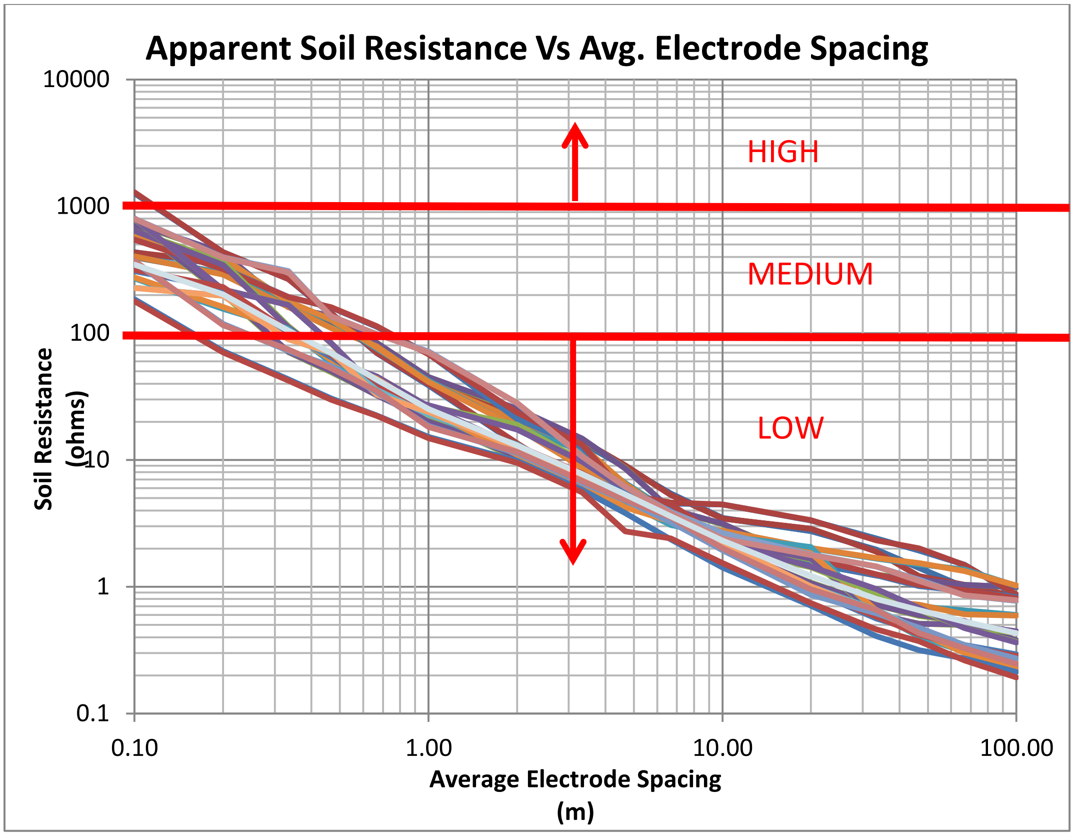


Figure 4.2 Apparent Soil Resistance Vs Average Electrode Spacing of an Array of Locations

Recall from Chapter 2 that, as the average electrode spacing is increased the measured apparent resistance decreases as the area of the measured soil is increasing far more rapidly than the length between the current probes $\left(R = \left(\frac{\rho L}{A}\right)\right)$. The rate at which this decrease occurs gives insight into the type of soil that has been included. A fast decrease in apparent resistance indicates that those soil layers are of low electrical resistivity. A slow decrease or “flattening-out” indicates that the soil layers in that area are of high electrical resistivity. Figure 4.3 shows one such graph to illustrate these trends.

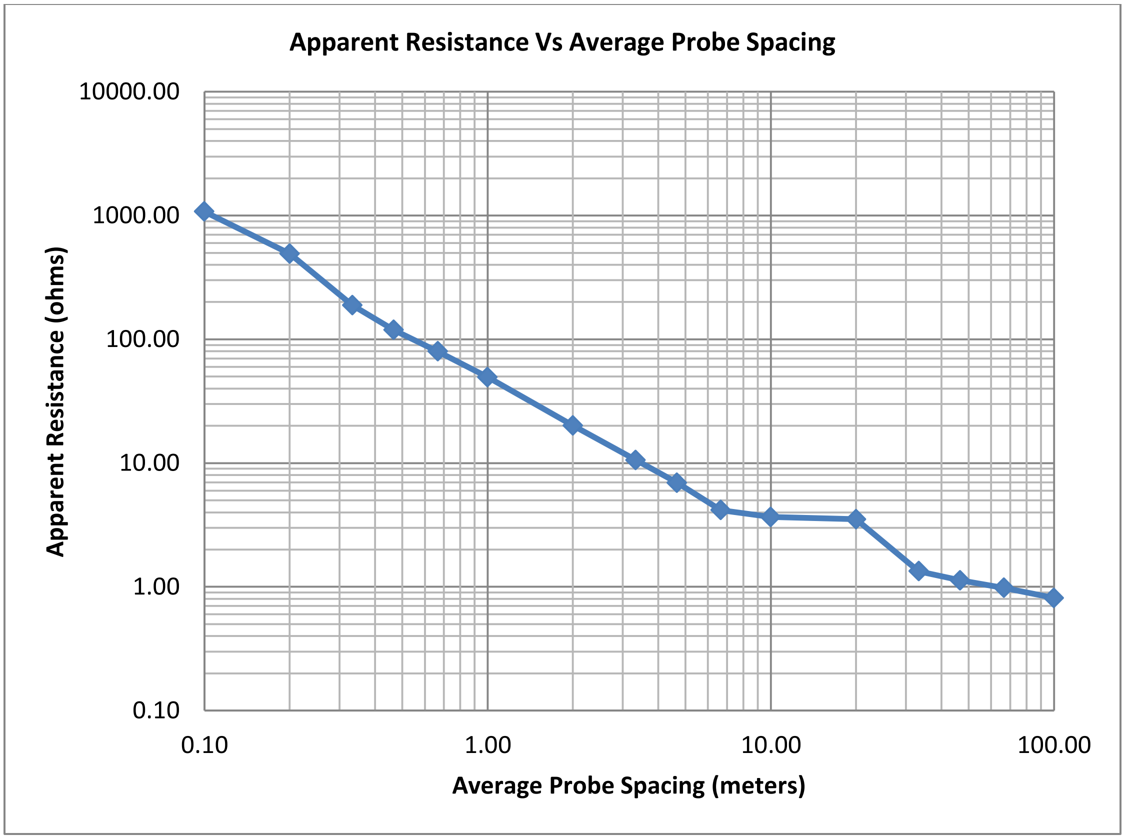
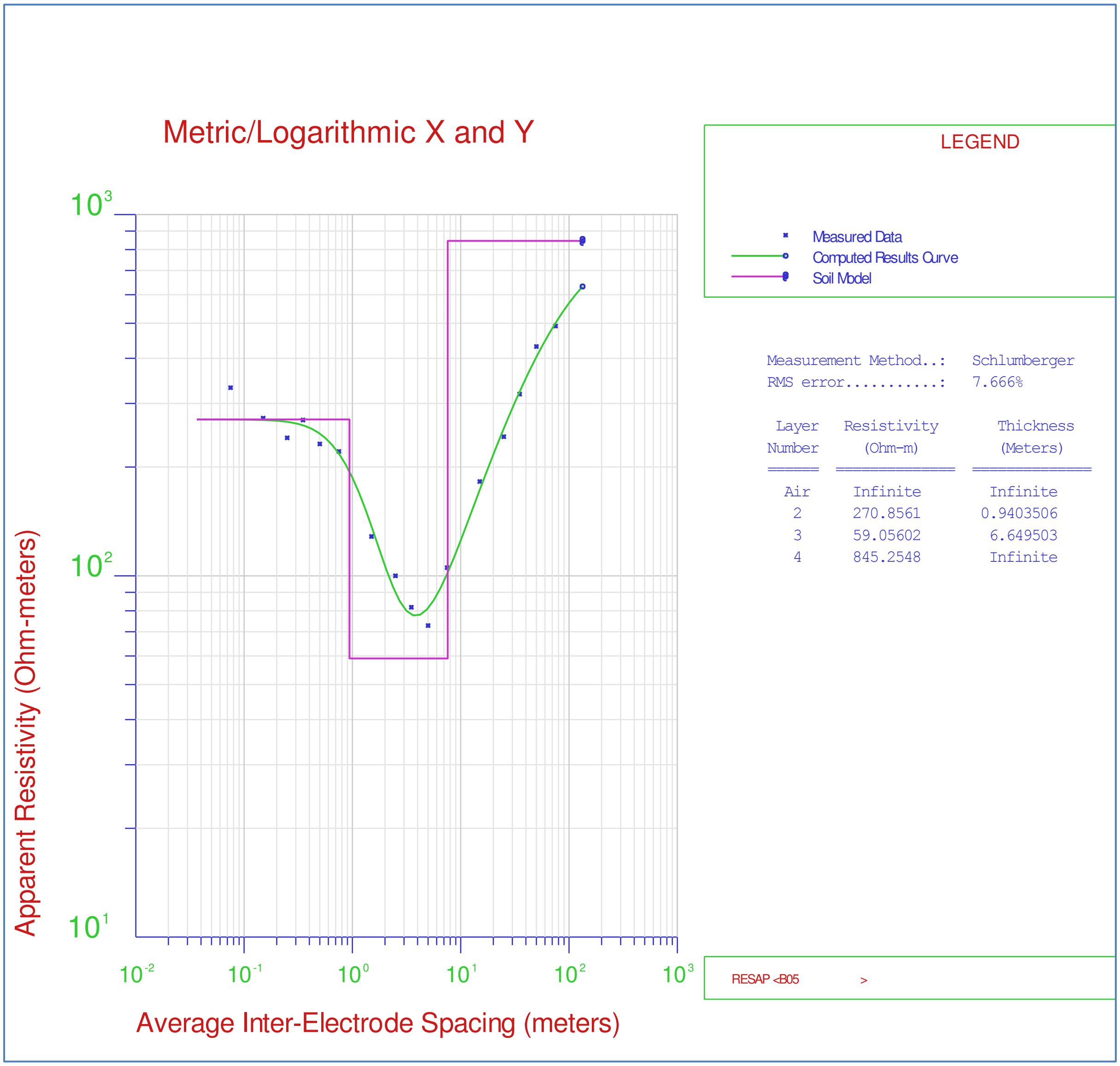


Figure 4.3 Apparent Resistance Vs Average Probe Spacing of a Single Location

This data can further be taken and converted into a soil model of layered resistivities with various thicknesses.(1)(6) The details of these measurement techniques and how they are converted into a soil structure model are well established and

beyond the scope of this thesis; however for conceptual clarity it should be stated that probe spacing is mathematically related to the depth of the test. For further understanding detail information on these measurement methods, as well as others, can be found via the references provided at the end of this Thesis. By conducting the test at several probe spacing, an overall soil structure model may be created down to a specified depth. One such model is provided below in Figure 4.4.



Measurement Method..: Schlumberger
RMS error...........: 7.666%

Layer Number	Resistivity (Ohm-m)	Thickness (Meters)
Air	Infinite	Infinite
2	270.8561	0.9403506
3	59.05602	6.649503
4	845.2548	Infinite

Figure 4.4 Soil Structure Model

The X-axis of Figure 4.4 displays the average electrode spacing in meters versus the Apparent Resistivity in Ohm meters shown on the Y-axis. Both the axes are shown here in a logarithmic scale. The average electrode spacing is related to soil depth, while the apparent resistivity is related to the soil electrical resistance. Each blue point represents a field measured data point. The purple line represents the soil structure model that has been implemented or attempted as a solution. The green line represents the curve fit function that resulted in the purple soil structure solution. To the right is a results print out that shows the different layers that compose the purple solution structure, along with their respective thicknesses and resistivities. In addition an error percentage is provided that represents the error between the field data and the green curve fit. Typically this error percentage is targeted to be 10% or less in industry, yet due to outliers this percentage could reach values as high as 20%. It ultimately falls to the duty of the designer to interpret and target a realistic soil model as well as to account for any additional risk that may arise from poor testing. It should also be noted that there may exist several unique soil structure models that will result in similar error percentages/ fits for the same soil data.

As mentioned in Chapter 1, the above soil structure is meant to model the changes in resistivity with depth at the tested location. This can best be physically visualized by rotating the graph by 90° as shown in Figure 4.5 (page 43). Here it can be seen that the soil is composed of horizontal layers. The first layer is approx. 0.9 m thick and has a resistivity of 270 ohm-m. The next layer is appx. 6.6 m and has a resistivity of 59 ohm-m. Both these layer lie atop an infinitely thick layer with a resistivity of 845 ohm-m. While the data printout or the curve-fit algorithm may change depending on the calculation tool the basic concept of the soil structure model is always the same.

4.2.3 Soil Modeling: Industry Practices and Preferences

The Slumberger-Palmer test method mentioned above can be an expensive and time consuming. Conducting this measurement for over 200 grounding points represents a large cost (order of magnitude, \$100,000 or more) to industrial contractors (\$50,000-\$100,000 and typically 2-4 weeks for easily accessible projects and up to \$300,000 and 4-6 weeks for challenging locations).

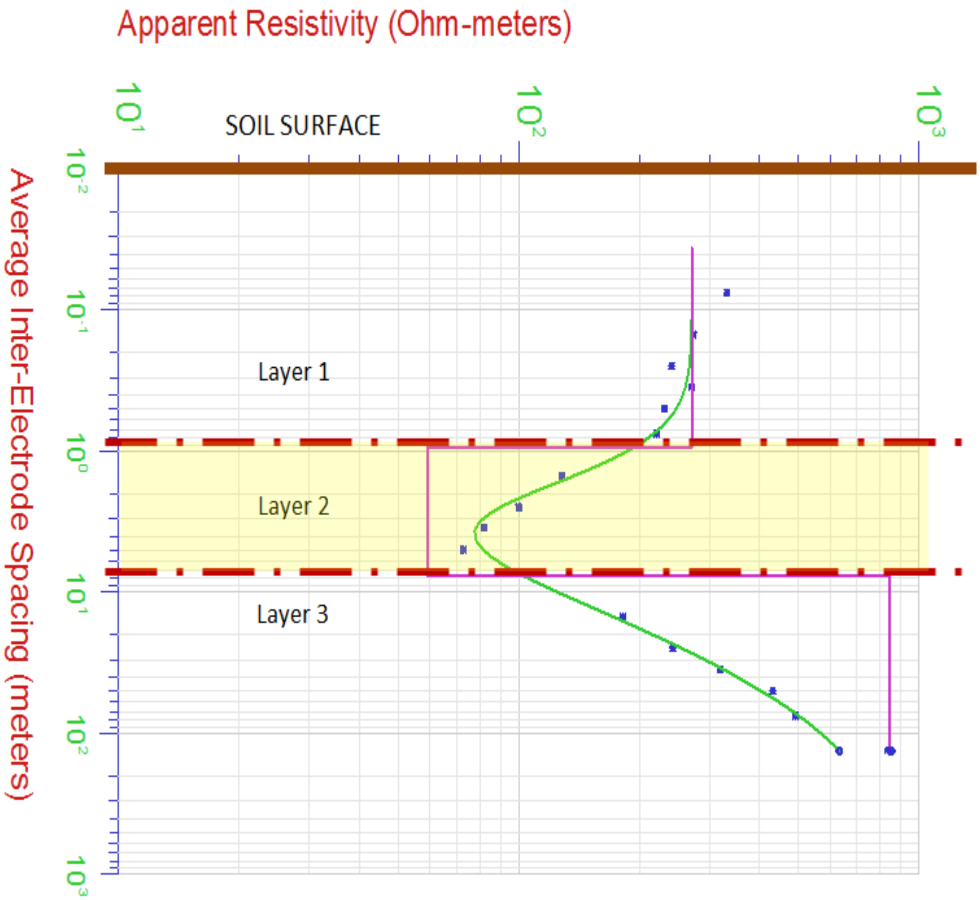


Figure 4.5 Soil Structure Model

Due to the lack of any standard for "wind" applications there are several schools of thought currently being proposed and practiced by industry.

1. Measure every Grounding point (WTG, JB, O&M, MetMast, Grounding Transformer, Substation) to ensure safety and attempt to avoid or optimize any possible mitigation costs.

2. Measure a reduced amount of grounding points (The number of reduced grounding points tested is currently dependent on the amount of risk exposure a "designer" is willing to accept) and use a median or average value for design to reduce soil testing

costs, hoping that a minimum number of sites will require additional grounding needs (additional costs).

3. Measure a reduced amount of Grounding points and use the worst case discovered for design of the entire WPP to reduce soil testing costs and attempt to avoid any future mitigation costs. It should be noted that the “worst case” location is not a straight forward determination and can only be identified once the entire grounding system has been studied. (i.e. worst case with respect to impedance, or safety criteria, or available fault current, etc.)

Because this research is concerned with grounding design for personnel safety, it is proposed that every site be measured (Option 1). This is the only way to truly ensure through design that the entire WPP is safe. In fact it can be extended further that measuring every site is the ONLY predictable way to positively ensure safe conditions across the entire wind farm. Though this is beyond the scope of this thesis, it is believed that in some cases that this option may in fact be the most cost effective option as well. Figure 4.6 below shows a definitive change in the soil from soft dirt to hard rock within roughly a 15 ft. horizontal distance with no identifying factors present on the top-soil. This particular site varied wildly with respect to soil variation despite appearing to be the same terrain from the surface.

4.3 Calculation of Safety Criteria

Once an accurate soil model has been established for each grounding point of the WPP, safety criteria may be calculated as specified by IEEE Std. 80 for every location tested. Recall from Chapter 1 that the safety criterion of a site is primarily dependent on the soil structure of that site.

Figure 4.6 Real World Soil Variations

4.3.1 Safety Criteria: Purpose

Safety Criteria will later be used as a critical threshold with which to compare actual voltages and thus evaluate safety for every grounding point. As an example: a touch-voltage safety criteria of 210 V would mean that any touch voltages existing in the local area greater than 210 V may cause a lethal electric shock. Local area is typically defined in industry to be any area within a 200 ft. radius of the test point. This distance is largely used due to the micro-siting stage of WPP construction. Typically this step occurs late in the project and will involve moving the grounding points to accommodate for unforeseen issues. Usually these moves are less than 200ft. Contractors do not intend to fund a retest for every micro movement of a grounding point and so they will take on the risk that the soil resistivity within this limited radius is constant. It should be noted however that currently this assumed distance is completely dependent on risk exposure.

4.3.2 Safety Criteria: Calculation Method

Safety Criteria calculation is well documented and explained in IEEE Std. 80. Given a uniform soil model, the standard provides simple and conservative equations for calculating the safe voltage thresholds for both Touch and Step scenarios given by the following equations.

$$E_{touch} = I_B(R_B + 1.5\rho) \quad \textbf{(4.1)}$$

$$E_{step} = I_B(R_B + 6.0\rho) \quad \textbf{(4.2)}$$

For soils with a thin (typically less than 18”) surface layer of different resistivity a de-rating factor must be applied to account for where the majority of ground current will flow. IEEE Std. 80 provides two main methods of calculation; exact analytical equations and approximate empirical formulas. The empirical formulas have already been provided in Chapter 2. These formulas assumed an approximation of the surface layer de-rating factor (C_s). This term is related to the “reflection coefficient” (k) that occurs between two layers of different material resistivities ($\rho_s\ and\ \rho\ respectively$), and the thickness of the thin surface layer (h_s). Figure 4.7 (page 47) shows the split in the current due to the change in impedance between the respective layers as well as labeling the important variables. Upon hitting the boundary some of the current will be reflected. The magnitude of this reflection will be based upon the respective resistivities at the boundary. If ρ_s is smaller than ρ then a larger amount of the current will be reflected or vice versa if it is larger. This will result in one of the layers carrying more of the current than the other.

For the case of a thin surface layer IEEE offers an equation that has been proven to be within 5% of the analytical equation. IEEE Std. 80 also provides pre-calculated values of the analytical C_s equation as a function of surface material thickness (h_s) and the reflection coefficient (k) of the two materials. Figure 4.8 (page 47) shows the graph of these pre-calculated exact values for quick calculation of C_s.

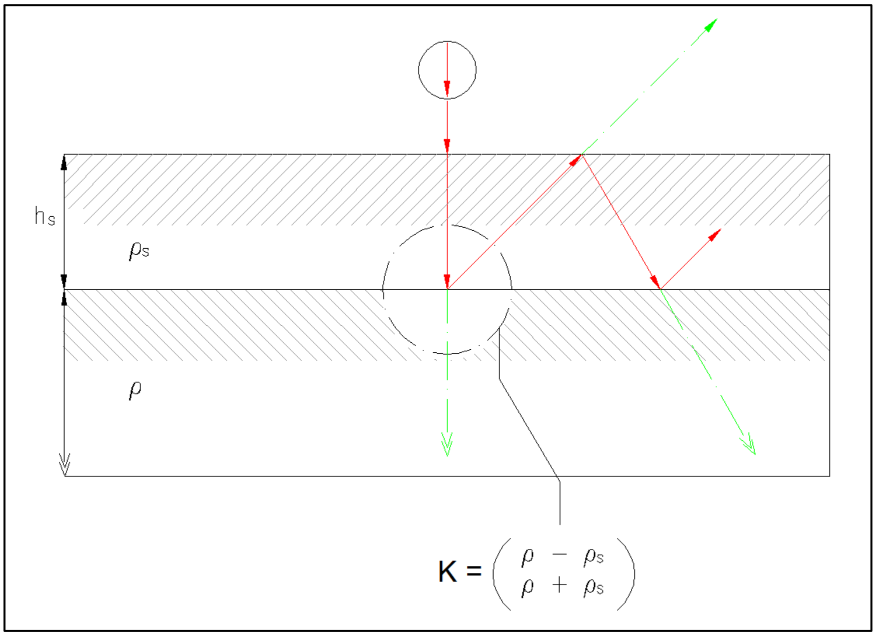


Figure 4.7 Surface Layer Effects on Ground Current

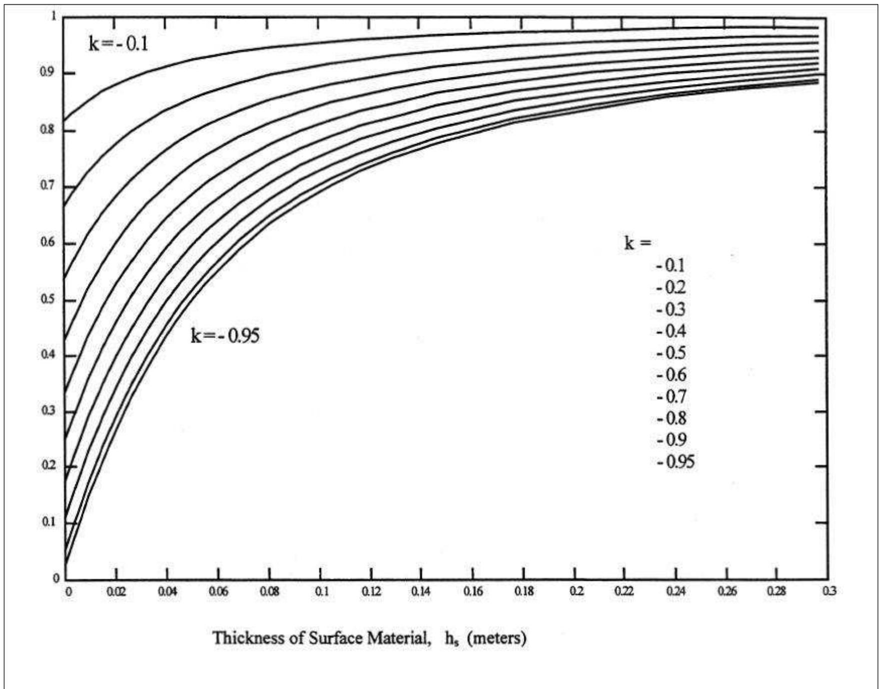


Figure 11—C_s versus h_s

Figure 4.8 Pre-Calculated De-Rating Factor Values(2)

In addition to this IEEE also gives the semi-empirical equation for C_s. In summary IEEE Std. 80 provides several methods for calculating the “safe” voltage thresholds of a grounding point with respect to Touch and Step hazards. The level of conservatism or applicability may vary with the method and assumptions chosen however each method can give a viable “safe” threshold for Touch and Step scenarios.

4.3.3 Industry Practices and Preferences:

As previously mentioned various assumptions may be made in the calculation of safety criteria. These assumptions include the size of human considered (50 kg or 70 kg), the resistance of the human body (1,000Ω in most cases) and the clearing time of the fault (t_s). While these assumptions can massively impact the outcome of the safety criteria, as long as the assumptions are clearly stated the safety criteria calculations can be easily recreated. This means that often the only true variance in industry for safety criteria is in the “safe” radius of its assumption (i.e. the radius for which one assumes the soil model used in its calculation is valid). Again this is typically 200-300 ft.; however, as discussed this distance is more used to avoid expensive re-testing than it is an accurate representation of the soil consistency. Currently the distance one can assume from a soil test is in no way regulated and falls under an assumed risk of the designer/contractor.

4.4 Calculation of GPR

The next step is to calculate the Ground Potential Rise (GPR). Touch and Step voltages are directly related to the GPR and are often calculated as a percentage of the GPR, thus to calculate the Touch and Step voltages present at a site the GPR must first be known. In order to calculate GPR three basic values are required: ground grid impedance (Z_G), fault current (I_F), and fault current split factor (S_F). The relationship of these values was given in equation 1.1. (Included below for convenience)

$$GPR = (I_F)(S_F) * (Z_G) \tag{4.3}$$

4.4.1 Fault Current (I_F)

The fault current is often known at the Point of Interconnection (POI) i.e., the Substation and is calculated separately at the medium voltage bus for each grounding point. For the POI this calculation is usually done by the utility at the cost of the contractor. For the remainder of the WPP this calculation is done by the developer through the use of any power flow software or hand calculations after accurately modeling the power system in question. Figure 4.9 identifies these fault locations on a simplified one line diagrams for easy understanding and visualization.

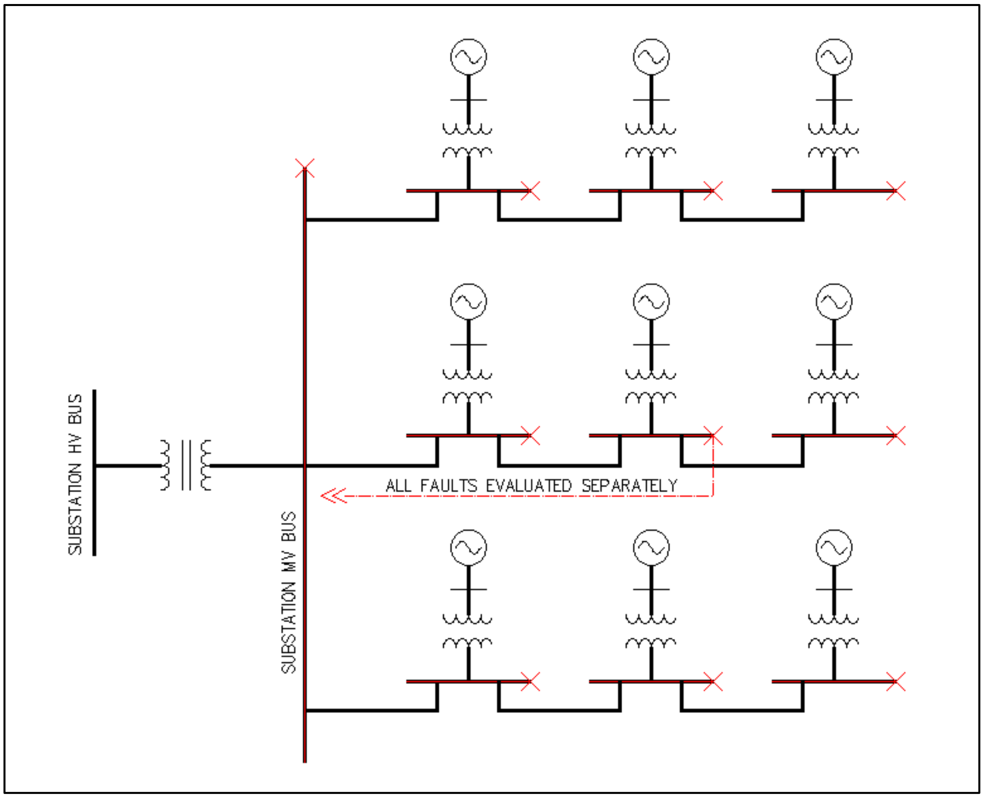


Figure 4.9 Single Line to Ground Fault Locations to be Evaluated

The red x’s in Figure 4.9 represent fault locations that will each need to be evaluated separately (i.e. for this system 10 faults would need to be evaluated. Because each turbine will have a local ground grid connected to the generator step-up unit (GSU) only the MV fault will need to be considered for GPR at the turbine. Any fault on the LV side will travel back to the GSU nearly exclusively via the ground grid, with very little if any contributing to the GPR by flowing into the ground. The typical LV voltage at turbines is 690 V while the typical MV voltage is currently nearly always 34.5kV (Currently work is being done to increase this voltage however). Typical values for the HV transmission voltage vary based on the size and strength of the grid and the cost of construction. Common numbers to see include 115 kV, 230 kV, and 345 kV.

4.4.2 Fault Current Split Factor (S_F):

As mentioned in Chapter 1, upon being injected the fault current will split into two main paths: the portion of the fault that travels through the intended return paths (the bare ground conductor, and concentric neutrals) and the portion that travels through the soil. The ratio of that soil current (i.e. the amount of the fault current that will contribute to Ground, Touch, and Step potentials) to the total fault current is defined as the Split Factor (S_F). This split factor is ultimately calculated by paralleling the neutral return paths with that of the soil return path and conducting a current division calculation. Figure 4.10 illustrates this simplified concept.

Here each line represents a return current path. These paths are composed of line parameters defined by the material characteristics, and installation geometry. In addition to this all lines are surrounding be the appropriate soil structure. A fault can then be placed at one end and the various divisions of current can be calculated.

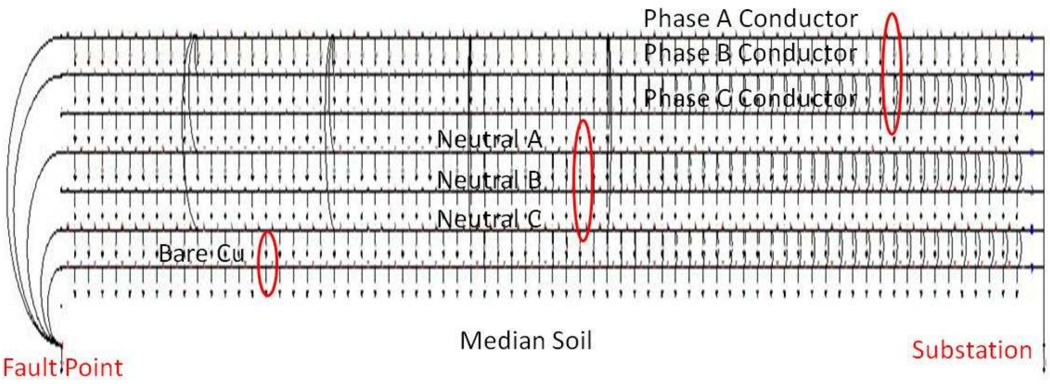


Figure 4.10 Split Factor Current Divider Model

Calculation of this split factor can be done in several ways to differing degrees of complexity. IEEE Std. 80 provides perhaps the most simplified version in the form of pre-calculated tables for various configuration scenarios. Figure 4.11(page 51) is one such chart taken from IEEE Std. 80. Here one would count the transmission lines and the feeders at a station then pick the appropriate curve. After a curve is selected then one would find the grid resistance of the station and move up the line until it intersected the selected curve. Then moving horizontally towards the Y-axis a % of total fault current or split factor can be acquired. As mentioned there are several different scenarios included in IEEE Std.80.

These scenarios, while useful, are limited in scope and very conservative. Alternatively the most advanced methods of calculation exist in the form of software solutions that solve the current division model through the use of fundamental electromagnetic theory (as opposed to simple circuit theory). This is done in order to incorporate the effects of all conductor paths as well as the surrounding soil, and even other installations in the area.

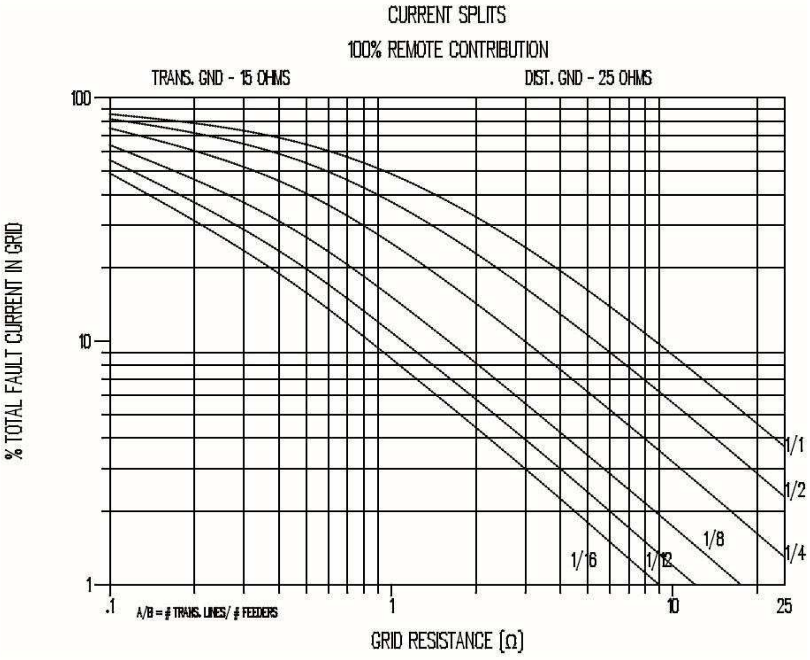


Figure 4.11 IEEE Std. 80 Curve to Approximate Split Factor (S_F)(2)

4.4.3 Ground Impedance (Z_G) Calculation Method

As mentioned in Chapter 1 ground grid impedance is dependent on several complex factors. These complex factors vary greatly from grounding point to grounding point and there are a large number of combinations available. For this purpose ground impedance is most accurately and efficiently calculated through the use of complex algorithms and software. While hand calculations do exist for simplified ground grid geometries (like in a regular substation or switching station), the highly irregular shapes of WPP ground grids and the land area involved make the hand calculations impractical and perhaps not very accurate.

For the purpose of this thesis calculation methods of the ground impedance are outside the scope, However, for further detailed calculations and theory please consult the provided reference(7). This reference should give a basis of understanding of ground electrode impedance and the calculation methods for simplified geometries. This being said it is worth noting that ground impedance is generally most directly tied to the amount of ground conductors used and the resistivity of the respective soil layer they are buried in.

4.4.4 Ground Impedance (Z_G): Stand Alone and Network

Intuitively the ground impedance of a given grounding site is dependent upon how much of the ground electrode is considered and the area it covers. As mentioned in Chapter 2 a WPP's ground system is a completely interconnected system. This creates two possible types of ground impedances for every grounding point:

1. Stand Alone: Includes only the local ground electrode evaluated independently, and disconnected from the rest of the system.
2. Network: Incorporates the entire ground electrode system, including trench ground conductors as well as the grids of all other grounding points.

Figure 4.12 illustrates the physical differences of these two impedance types

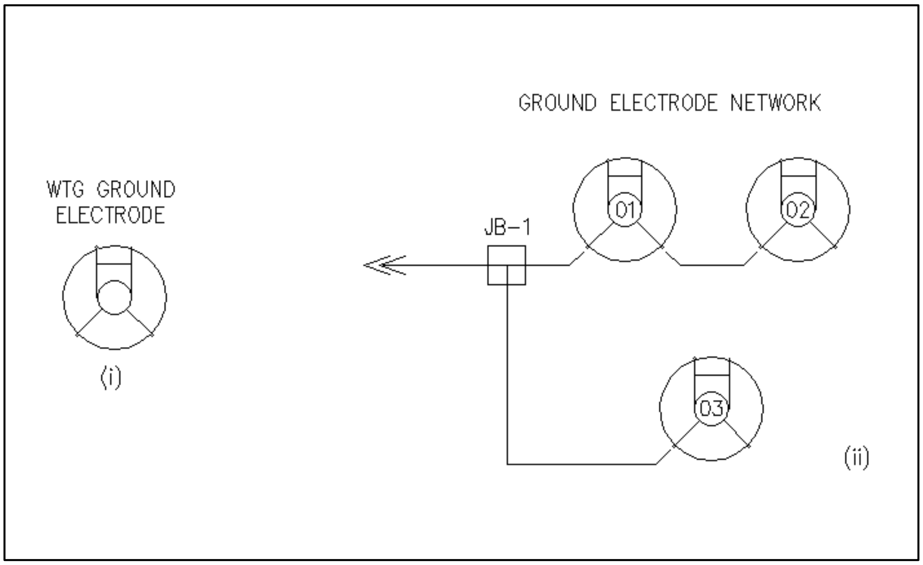


Figure 4.12 Local Vs Network Impedance

4.4.4.1 Stand Alone Impedance:

The image on the left (i) of Figure 4.12 represents the stand alone ground electrode of a WTG. As a Stand-Alone Impedance this electrode would be evaluated independently and completely disconnected from any other system.

4.4.4.2 Network Impedance:

The image on the right (ii) of Figure 4.12 represents the network ground electrode of a WPP. As a Network Impedance this electrode would be evaluated as one single electrode extending across the entire WPP. Typically this electrode will span many square miles. At large distances the equipotential assumption of the ground grid is no longer a valid assumption. This failing assumption along with the irregular shapes of WPP systems means that Network Ground Impedance is heavily dependent on the fault location and from where the impedance has been measured with respect to that fault location. Because of this network ground impedance can further be broken into three types: “Self-Impedance”, “Mutual”, and “Transferred” Impedance.

4.4.5 Ground Impedance (Z_G): Self Impedance, Mutual and Transferred Impedance

Using the same network electrode system from Figure 4.12, Figure 4.13 shows the electrical relationship between the Network Impedances: Self, Mutual, and Transferred respectively. This will now be discussed at length.

4.4.5.1 Self-Impedance:

Injecting a ground current (I_G) of $1\angle 0^{\circ} p.u.$ at T02 through the ground impedance Z_{G2} will result in a voltage rise (V_{02}). Z_{G2}, then is the self-impedance of the network measured at T02 for a fault injected at T02. Mathematically, .

$$\textit{Self Impedance} = Z_{Gi} = \frac{V_i}{I_{Gi}} \qquad (4.4)$$

Where the index i represents the (node) designated value at the fault location.

Because the sites are interconnected the current I_G will also cause a voltage rise in the surrounding area (earth/ground). This will cause a voltage rise profile across the entire WPP that will vary from the max voltage at the fault location (T02) down to the minimum of zero potential at some infinitely remote location. This voltage rise of the ground is commonly known as the ground potential rise (GPR) and is shown by the light gray line as the GPR scaled to some actual fault magnitude.

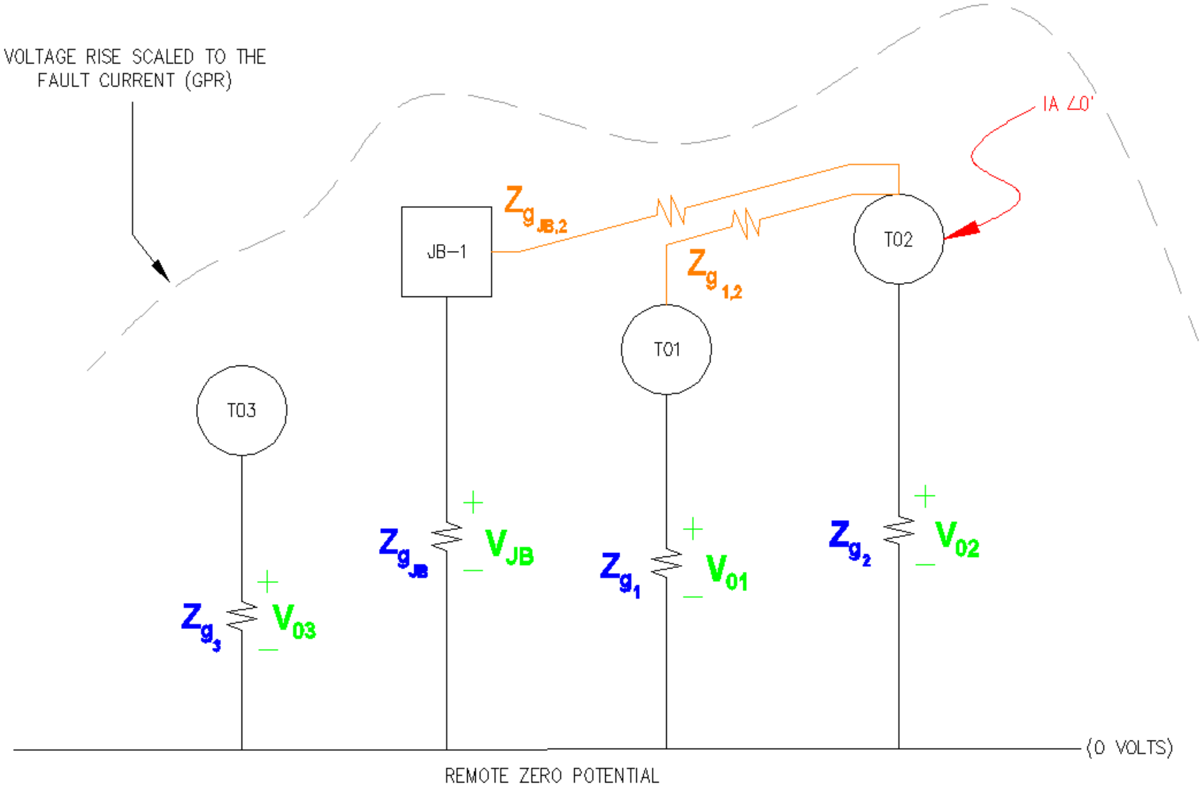


Figure 4.13 Impedances Across a WPP and the Resulting Voltage Rises

4.4.5.2 Mutual Impedances:

In Figure 4.13 the “orange” colored impedances represent the impedance due to the physical connections between grounding points which will be defined as the Mutual Impedance.

$$\boldsymbol{Mutual\ Impedance = Z_{ij} = \left(\frac{|V_i - V_j|}{I_{gj}}\right)} \qquad \textbf{(4.5)}$$

Where the index i remains the same (value at faulted location) and the index j represents the (node) designated value at a grounding point other that the fault location. Here the designation of ij represents the impedance between the faulted location (*i*) and the remote ground point being evaluated (*j*)

Intuitively high impedance between ground points suggests a weak connection while low impedance suggests a strong one. For example, in Fig. 4.13 the orange impedance between T03 and T02 will be large, resulting in a much lower voltage at T03 when a fault occurs at T02. Because of this we say that T03 has a weak connection to T02. In the event of a fault at T02, the likelihood of a safety issue at T03 is much less than that of JB-1, whose mutual impedance with T02 is much lower.

4.4.5.3 Transferred Impedance:

While the Mutual Impedance is helpful for understanding, the impedance of note is the impedance labeled in “Blue” in Fig. 4.13 which we will call Transferred Impedance.(3)

$$\boldsymbol{Transferred\ Impedance} = \boldsymbol{Z_{gij}} = \frac{\boldsymbol{V_j}}{\boldsymbol{I_{gi}}} \qquad \textbf{(4.6)}$$

This impedance is not a measured impedance per-say, but rather a calculated impedance based on the resulting GPR (a result of the mutual impedance) and the injected current. This impedance represents the impedance between the grounding point and the remote zero potential, more commonly referred to as the Ground Potential Rise (GPR). Transferred Impedance then becomes a factor by which the GPR at a ground point can be determined for any ground fault occurring at some remote location in the network. More importantly, because Touch and Step voltages are always some portion of the GPR, Transferred Impedance becomes a necessary factor to ensuring safety for the entire WPP.

4.4.5.4 Network Impedance Matrix:

By calculating the Transferred Impedance at all grounding points for a fault at every one of those points a WPP-wide impedance table can be created. This table will now be defined as the Network Impedance Matrix. Fig. 4.14 and Table 4.1 respectfully give a simplified WPP network and the associated Network Impedance Matrix. Here the diagonal terms represent the Network Self Impedances. All non-diagonal terms represent the Transferred Impedances seen at the measured site location for the specified faulted location. (e.g. $Z_{T02,T01}$ would represent the transferred impedance at T02 for a fault injected at T01.)

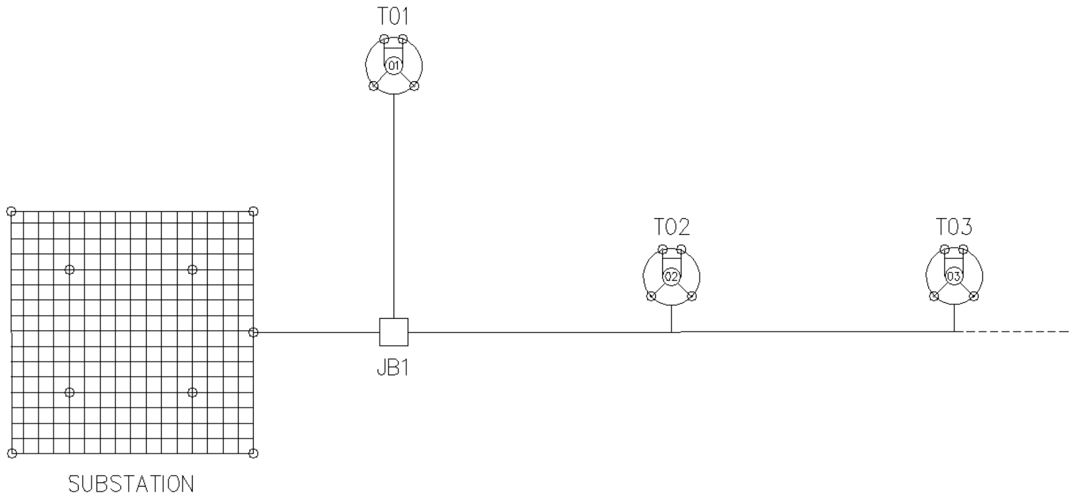


Figure 4.14 Wind Power Plant Layout

Table 4.1 Impedance Matrix (3)

		Fault Current Injection Point				
		Sub	JB1	T01	T02	T03
Measured Site Location	Sub	$Z_{SUB,SUB}$	$Z_{JB1,SUB}$	$Z_{T01,SUB}$	$Z_{T02,SUB}$	$Z_{T03,SUB}$
	JB1	$Z_{SUB,JB1}$	$Z_{JB1,JB1}$	$Z_{T01,JB1}$	$Z_{T02,JB1}$	$Z_{T03,JB1}$
	T01	$Z_{SUB,T01}$	$Z_{JB1,T01}$	$Z_{T01,T01}$	$Z_{T02,T01}$	$Z_{T03,T01}$
	T02	$Z_{SUB,T02}$	$Z_{JB1,T02}$	$Z_{T01,T02}$	$Z_{T02,T02}$	$Z_{T03,T02}$
	T03	$Z_{SUB,T03}$	$Z_{JB1,T03}$	$Z_{T01,T03}$	$Z_{T02,T03}$	$Z_{T03,T03}$

4.4.6 Network GPR Matrix:

This network impedance matrix multiplied by the ground fault current matrix, will result in a Network GPR Matrix of the same size with elements of the form.

$$\boldsymbol{GPR_{i,j} = Z_{i,j}\left(I_{Fj}S_{Fj}\right)} \tag{4.7}$$

An example GPR matrix for the WPP of figure 4.10 is shown below in Table 4.2 (page 60). Here the diagonal terms represent the GPR of the point of fault injection while the off-diagonal terms represent the subsequent GPR at the specified location. The same notation as that of the impedance matrix is duplicated here.

Table 4.2 GPR Matrix (3)

		Fault Current Injection Point				
		Sub	JB1	T01	T02	T03
Measured Site Location	Sub	$GPR_{SUB,SUB}$	$GPR_{JB1,SUB}$	$GPR_{T01,SUB}$	$GPR_{T02,SUB}$	$GPR_{T03,SUB}$
	JB1	$GPR_{SUB,JB1}$	$GPR_{JB1,JB1}$	$GPR_{T01,JB1}$	$GPR_{T02,JB1}$	$GPR_{T03,JB1}$
	T01	$GPR_{SUB,T01}$	$GPR_{JB1,T01}$	$GPR_{T01,T01}$	$GPR_{T02,T01}$	$GPR_{T03,T01}$
	T02	$GPR_{SUB,T02}$	$GPR_{JB1,T02}$	$GPR_{T01,T02}$	$GPR_{T02,T02}$	$GPR_{T03,T02}$
	T03	$GPR_{SUB,T03}$	$GPR_{JB1,T03}$	$GPR_{T01,T03}$	$GPR_{T02,T03}$	$GPR_{T03,T03}$

4.4.7 Industry Practices and Preferences

Often local self-impedance is tested in industry for every wind turbine-generator location. This is largely due to the fact that turbine manufacturers often require the “stand-alone” impedance test as a prerequisite to guarantee the turbine warranty. Network ground impedance is not currently tested or calculated by industrial contractors for several reasons, among them are the following:

1. Typically ground impedance is measured using the “fall of potential method.” This method is well documented and is given in great detail in IEEE Std. 81(1) as well as numerous other industrial publications (9). Measuring the impedance of such a large network with this method however is highly impractical. Largely due to the fact that a valid fall of potential test requires that the network can be assumed as a point source and with the large sizes of these installations it is nearly impossible to get far enough away for a valid fall of potential test(1)(5)(9).

2. The large concerns with regard to safety are that of Touch and Step potentials. Often times a fault current will be injected at a specific grounding point and the relative Touch and Step voltages are measured. In this way industries can test to see if the grounding points are safe without having to spend valuable time and effort in design. If a grounding point is determined as unsafe then mitigation is done at that grounding point only. Because of this, the overall network impedance measurement is not always considered essential in industry.

3. It is rightly assumed that if the stand-alone impedance is acceptable (typically less than 10 Ω stand alone as dictated by the manufacturer or some other ohmic value specified by the client: e.g. 2 Ω to 4 Ω for some manufacturers.), then the addition of more copper (via a grounding network) will only work to improve the ground self-

impedance as the conductivity of the soil is only being increased by adding conductive materials to it.

4. The maximum GPR will always occur at the fault injection point. (Recalling that Touch and Step voltages are always a percentage of the available GPR, it is largely assumed in industry practicethat if the “max GPR” for a fault is safe then every other site must be safe as well.

While the above reasons are intuitive or even theoretically sound in some cases they do not address the safety issues that may arise at other points in the system. As mentioned in Chapter 3 the challenges of WPP grounding exist largely due to the spread out and interconnected nature of a WPP system; therefore to ignore the interconnected effects on that system is an inaccurate view and not accepted by the “safety first” engineering community. Ultimately the only way to ensure safety is to ensure that every point of the system is safe during every fault condition.

Figure 4.15 will be used to help illustrate the possible effects of this interconnected nature of WPPs and why it is possible (although not apparent) that a safe fault at one grounding point (T01) could result in an unsafe condition at another (T02). To explain this situation better, consider the example that T01 lies on very resistive soil while T02 lies on very conductive soil. T01 will most likely have a high GPR due to the fact that its soil is highly resistive (e.g. high self-impedance); however T01 will also likely have very high safety criteria (also due to the high soil resistance). This means that even though high touch voltages may occur at T01 (e.g. 500-800V) the safety criteria will still be higher (e.g.900-1000V) and the grounding point will be safe. Recall however from Figure 4.9, that a fault at T01 will cause a subsequent GPR at T02 through the transferred impedance between the two grounding points.

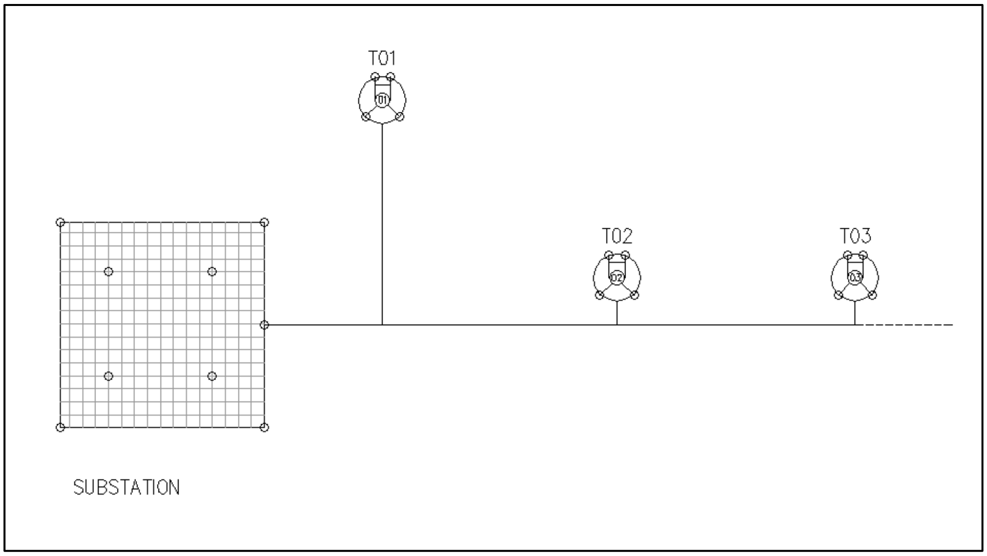


Figure 4.15 Simplified Interconnected WPP

This GPR will in fact be lower than that of T01 possibly even resulting in lower Touch and Step voltages at T02 (e.g.200-400V). However, the safety criteria of T02 will also be lower due to that point's low soil resistivity (e.g. 300-500V). If the T02 voltages due to a fault at T01 are larger than the T02 safety criteria then T02 may be an unsafe location for a fault at T01. This is also described below in terms of the logic.

$$SOIL\rho_{T01} > SOIL\rho_{T02} \rightarrow \boldsymbol{generally\ implies} \rightarrow V_{Safe,T01} > V_{Safe,T02}$$

$$I_F\ @\ T01 \rightarrow GPR_{T01}$$

$$GPR_{T01} \rightarrow GPR\ @\ T02 = GPR_{T02,T01} < GPR_{T01}$$

$$GPR_{T02,T01} \rightarrow V_{Touch_{T02,T01}} \& V_{Step_{T02,T01}}$$

$$\underline{\boldsymbol{if}\ \ldots}$$

$$(V_{Touch_{T02,T01}} > V_{SafeTouch,T02}\ \boldsymbol{or}\ V_{Step_{T02,T01}} > V_{SafeStep,T02})$$

$$\rightarrow \boldsymbol{T02 = Unsafe\ Location\ for\ a\ Fault\ at\ T01}$$

Because of this possibility, the transferred ground impedances must be calculated for every possible combination of fault location in order to ensure that there are no unsafe conditions that are created due to the interconnection of the network. Only an elaborate or advanced software can accomplish this task for a large system.

4.4.8 Current Industry Practices and Preferences

While Calculating the GPR, evaluating the safety criteria, and calculating the actual Touch and Step voltages are all based on well-established formulas interpreting what the "worst case" scenario is not. Due to the current lack of any WPP Grounding standard the interpretation of the worst case scenario and how to evaluate it has fallen to the WPP contractor. This interpretation is often delivered to a client that may not have an understanding of WPP grounding themselves or that has a different competing interpretation of the worst case scenario. One typical approach in industry is to calculate a "worst case" GPR for the data available. This worst case GPR could then be assumed over the entire site (causing an overbuilt system) or it could be evaluated only to the location it occurs (neglecting the possible transferred safety issues). Additionally in many cases this GPR "max" will be calculated by only varying the fault current (using the same average soil, and the same ground grid impedance for every site). As mentioned previously, the shortcoming of both these methods lie in that they do not take into account the transferred GPR from one turbine-generator location to another.

4.5 Comparison to Safety Criteria

Once the GPR is known, expected Touch and Step voltages can be calculated. These Touch and Step voltages can then be compared to the appropriate, site specific safety criteria, and a site can be determined as safe. This is described below:

$$(touch/step)Voltage_{GPR_{i,j}} < (touch/step)Voltage_{Safe,i}$$

and

$$(touch/step)Voltage_{GPR_{i,i}} < (touch/step)Voltage_{Safe,i}$$

or unsafe:

$$(touch/step)Voltage_{GPR_{i,j}} > (touch/step)Voltage_{Safe,i}$$

and

$$(touch/step)Voltage_{GPR_{i,i}} > (touch/step)Voltage_{Safe,i}$$

In the event that a site is deemed unsafe there are several mitigation techniques that may be implemented. Detailed discussions of these mitigation techniques are beyond the scope of this thesis however a limited and brief list commonly practiced is provided below for a conceptual understanding of the cost impacts proper grounding design can have upon a project.

1. **Adding Crushed Rock**: Crushed rock typically has a resistivity value of 2,000-5,000 ohm meters. Because of this adding a thin layer of crushed rock can increase the top layer soil resistivity and therefore increase the safety criteria (allowable Touch and Step voltages). This is typically a first line of defense as it requires no additional calculations (assuming that safety criteria calculations were done for both native and crushed rock surfaced in the prior steps). A typical site is shown below in Fig. 4.16. (page 64)

2. **Lowering the ground impedance**: Lowering the ground impedance will reduce the GPR and thus will reduce the actual Touch and Step voltages present on a site. This can be done by adding additional copper ground conductors/rods to the ground grid, by surrounding the ground conductors with low resistivity filler material, or even by distributing chemical mixtures into the ground. This solution necessitates a complete recalculation of all the steps detailed in this chapter. See figure 4.17 (page 65).

Figure 4.16 Typical Crushed Rock Used to Increase Surface Resistance

3. **Moving a Site**: Increasing or decreasing the distance between sites can have a massive effect on all the electromagnetic phenomena involved in the GPR. This solution is often a last resort tactic, and will involve a complete recalculation of all the steps detailed in this chapter. This is seldom an option due to the cost associated with additional permitting or poor wind quality.

4.6 Summary: Emphasis on Transferred Potentials and Testing

Due to their interconnected nature, Wind Power Plants require a more thorough approach to grounding than most any conventional site to date. It can be shown that any single GPR on an interconnected network can cause transferred potentials from one site to another in the event of a fault. Because of this it is crucial when designing the ground grid of a WPP that all calculations be performed for every local site as well as for the interconnected site in order to guarantee safety during any fault.

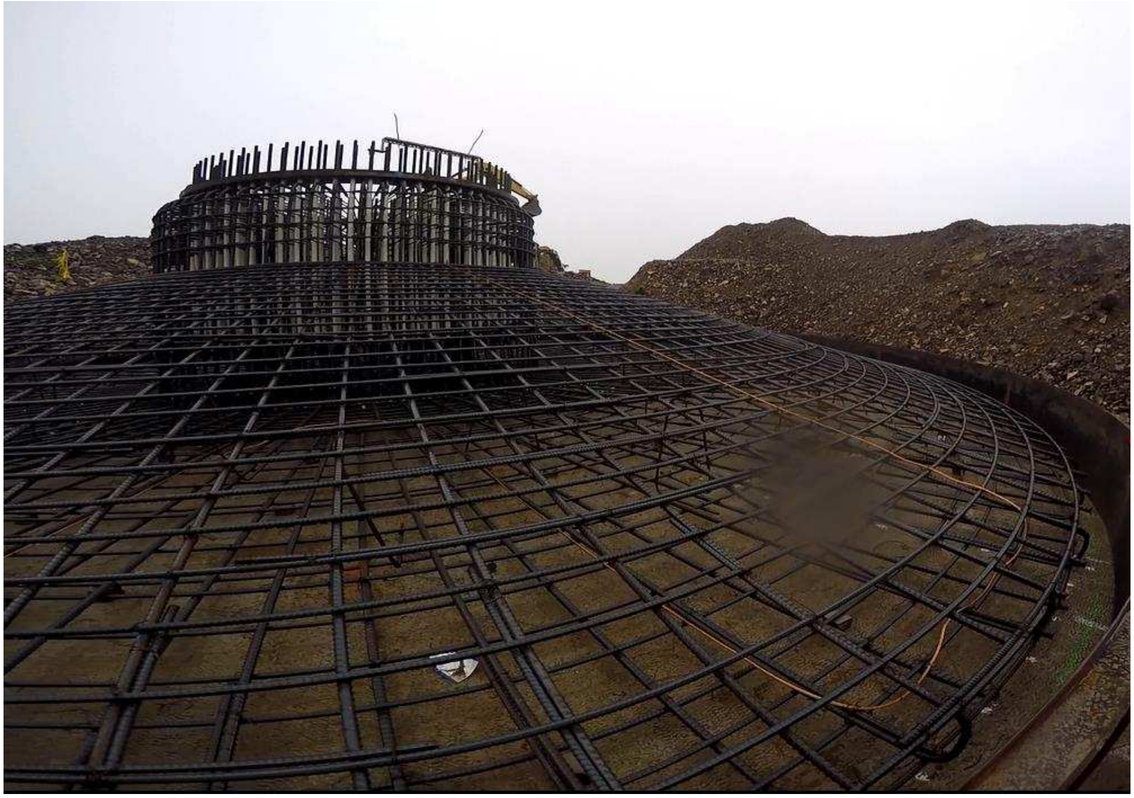


Figure 4.17 Wind Turbine Ground Grid

Currently in industry there is debate among Renewable Energy communities. Minimal site testing coupled with quicker and cheaper design has made local WTG grounding the focus of WPP grounding design for many in industry, however this approach does not take into account the interconnected nature of the WPP and as such cannot guarantee safety at each site for every fault. Failing to account for transferred GPRs of the interconnected WPP can either result in over-built more expensive systems or the possibility of higher safety risks to those owning, operating, or living near WPPs.

CHAPTER 5: CASE STUDY

In this chapter a real-world case study including the key points and results is presented following the methodology presented in Chapter 4. The interconnected site has 116 Wind Turbine Generators (WTGs), 83 Junction Boxes (JBs), 2 Permanent Met Masts (METs), 1 Substation (SUB), and 1 Operation and Maintenance Complex (O&M). In total 203 grounding points are considered across the WPP spanning approximately 60 square miles.

One particular site (designated as WTG B08) amongst the 203 grounding points is the main focus of this study. This chapter also expands to include the sites most affected by fault occurrences at WTG B08 and illustrates the complications that must be accounted for in real grounding of an interconnected system. Reduced samples of the full data can be found in the attached appendices at the end of this thesis.

5.1 Grounding Design Software: 3D Electromagnetic Wave Mapping

As mentioned earlier grounding design for personal safety has been studied extensively for traditional sites. IEEE Std. 80 provides conservative hand calculations for the safe design of substations; however the extension of these simplified techniques is tedious for the calculations required in ensuring personal safety for WPPs. While the concepts covered and the basic results of these calculations are sufficient to ensure safety it is the required expansion of their application that has made it more difficult. Where once a single hand calculation could be done for simple geometries of traditional sites, numerous calculations are now required for the irregular and complex geometries of a WPP. The time required and complexity of these calculations has made their hand-implementation difficult and impractical.

WPP grounding design is best done through the use of specially designed software. Furthermore because WPP grounding design incorporates such large areas of conductive and semi-conductive materials that directly and noticeably affect safety, the best type of software for this purpose is that of “3D

Electro-Magnetic Wave Mapping." This type of software utilizes calculations using the Electro-Magnetic Wave theory rather than simple circuit theory. Because of this the applications of such software extend far beyond simple power flow capabilities. In fact 3D Electro-Magnetic Mapping (EMM) software has been effectively used for everything from basic power system analysis to biological cell research and is a well-established and accepted method of calculation.

The CDEGS© program module provided by SES Technologies is one of the premier EMMs available. Additional grounding software packages include but are not limited to WinIGS, SKM, CYMGRID, etc. This software CDEGS© is extensively used for grounding design. All methods discussed in this chapter (as well as nearly every method used in industry, incorporate CDEGS or some other equivalent form of grounding design software.)

CDEGS can be used for multiple different applications as it is essentially and Electromagnetic Wave calculator. While simplified mathematical models and calculations have been presented in this thesis for conceptual presentation and understanding, all case studies were performed using the CDEGS software package. As there are several grounding softwares available and because this thesis is concerned with conceptual WPP grounding rather than software analysis, CDEGS operations and modules (proprietary) will not be discussed; however program results will be presented and discussed at great lengths.

5.2 Soil Data Collection:

Before any work is undertaken Geotechnical exploration is conducted extensively across the entire site and beyond. This exploration encompassed multiple facets of the soil characteristics for multi discipline use (civil, mechanical, electrical, wind resource, etc.); however for grounding design, the relevant data collected is the electrical resistivity measurements. These measurements are conducted with the Schlumberger-Palmer version of the four probe method discussed earlier in Chapter 3(4). A visual representation of all the data is provided in Fig. 5.1 and 5.2 (page broken up into part 1 and part 2 respectively due to the amount of tests taken.

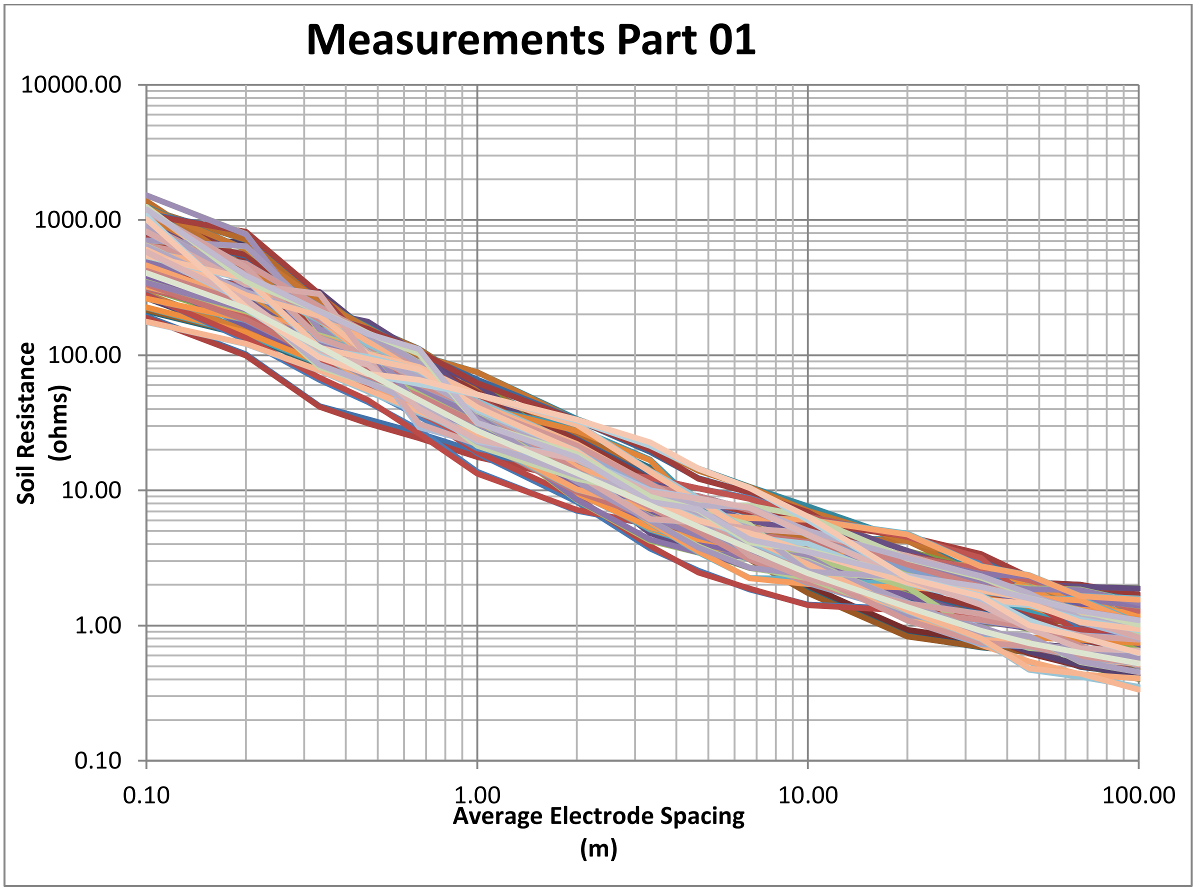


Figure 5.1 Average Electrode Spacing Vs Apparent Resistance Part 01

These plots show the apparent resistance vs. the electrode spacing as discussed in Chapter 4. This data can be seen to be roughly consistent among all 203 sites with a fairly narrow “bandwidth” variation. It can also be seen that the majority of soil resistance measurements lie between 100 Ω and 1,000 Ω with a few cases breaching the 1,000 Ω value.

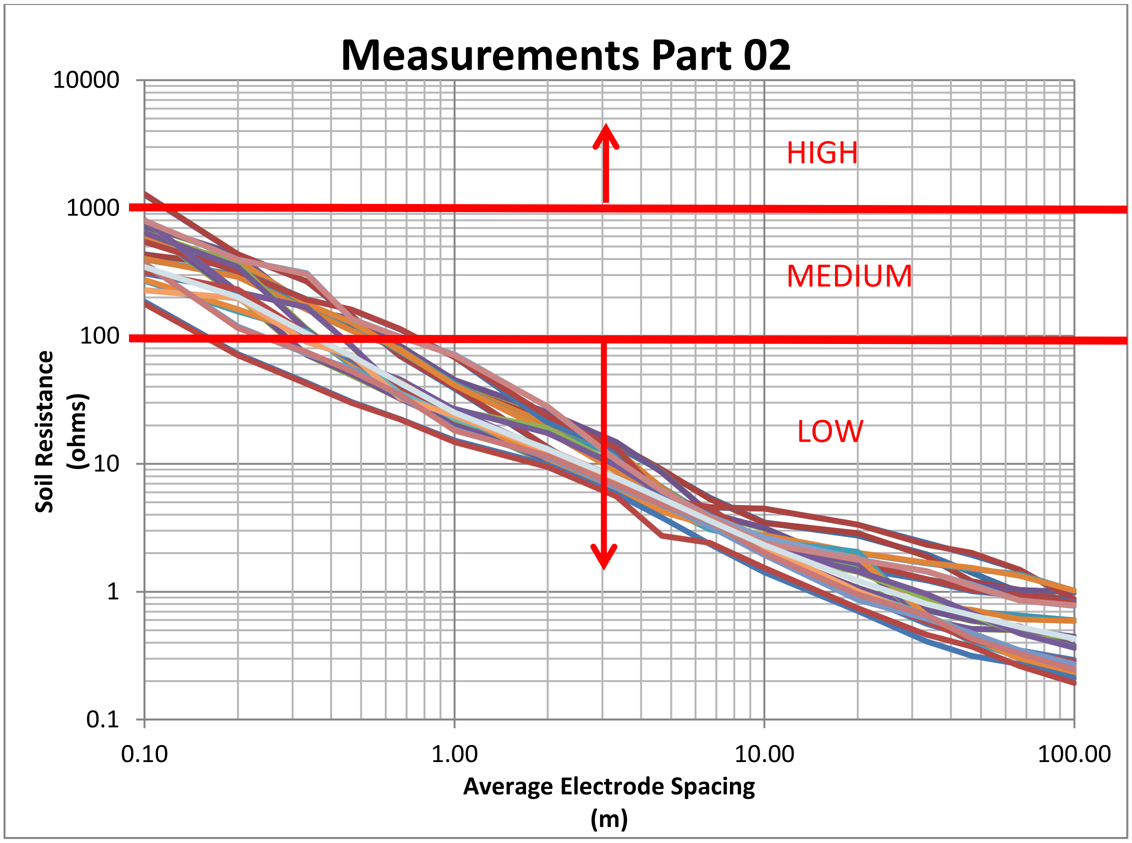


Figure 5.2 Average Electrode Spacing Vs Apparent Resistance Part 02

A general engineering rule of thumb with regards to interpreting resistance values as low, med, and high was provided in figure 4.2 of Chapter 4. These classifications are purely based on experience and are given here to only to provide a general understanding from a quick inspection of the data. It should be noted that these categories have no influence on later calculations only as preliminary general indicators of what grounding designs may be required based on the initial data. From the above graphs it could be guessed that the soil is a roughly consistent medium resistance soil.

This is not always the case and, it should be noted that sites with much larger variances regularly exist. Below is one such site for reference.

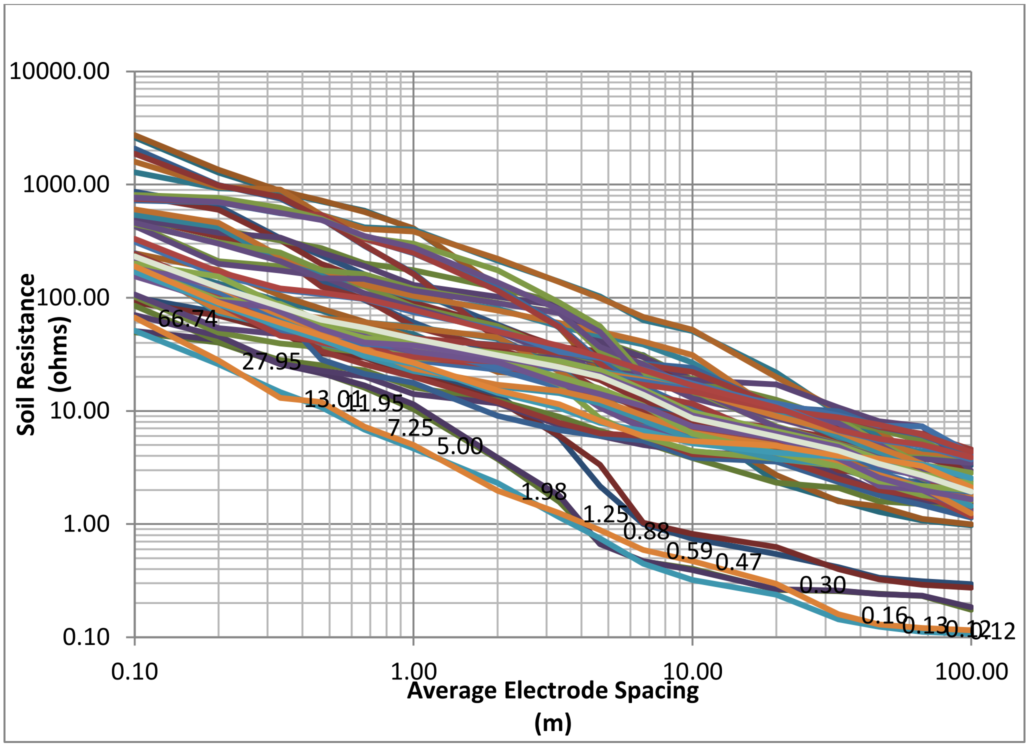


Figure 5.3 Average Electrode Spacing Vs Apparent Resistance (High Variance)

The soil electrical resistivity data is checked for errors and approved for further use in the soil structure modeling process. This is done by identifying outliers (points far outside the general trend) as well as trend reversal (Apparent resistances that increased despite an increase in probe spacing/effectively measured area). Below Figure 5.4 (page 74) shows the soil measurement data for the WTG B08.

5.3 Soil Modeling:

ERT Data is then input into the CDEGS soil calculation module, RESAP (12). This module utilized a computer algorithm to construct a soil structure. The exact workings of the algorithm are proprietary and that probe spacing is mathematically related to the effectively measured depth. For more detailed explanation on how apparent resistance values can be converted into layered resistivities consult references 1-6.

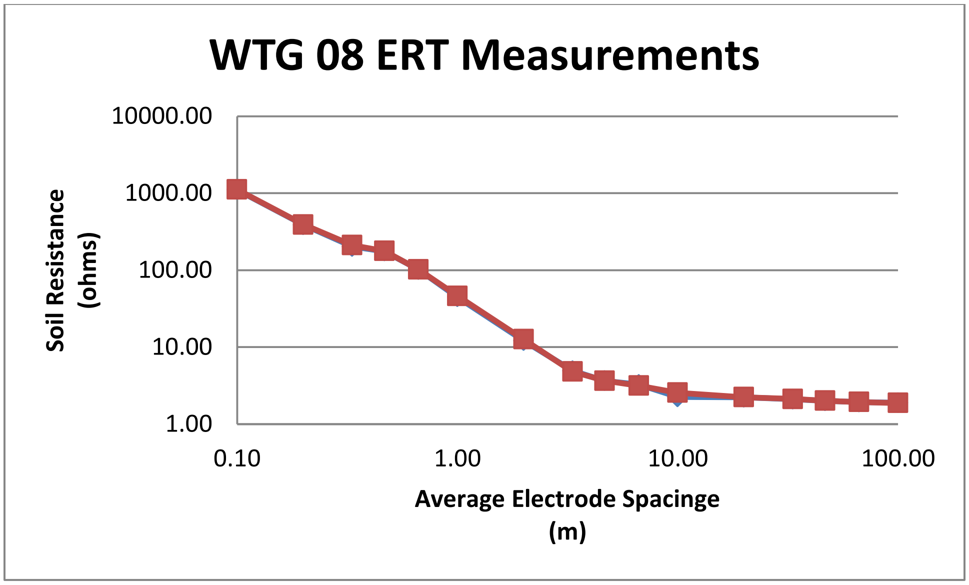


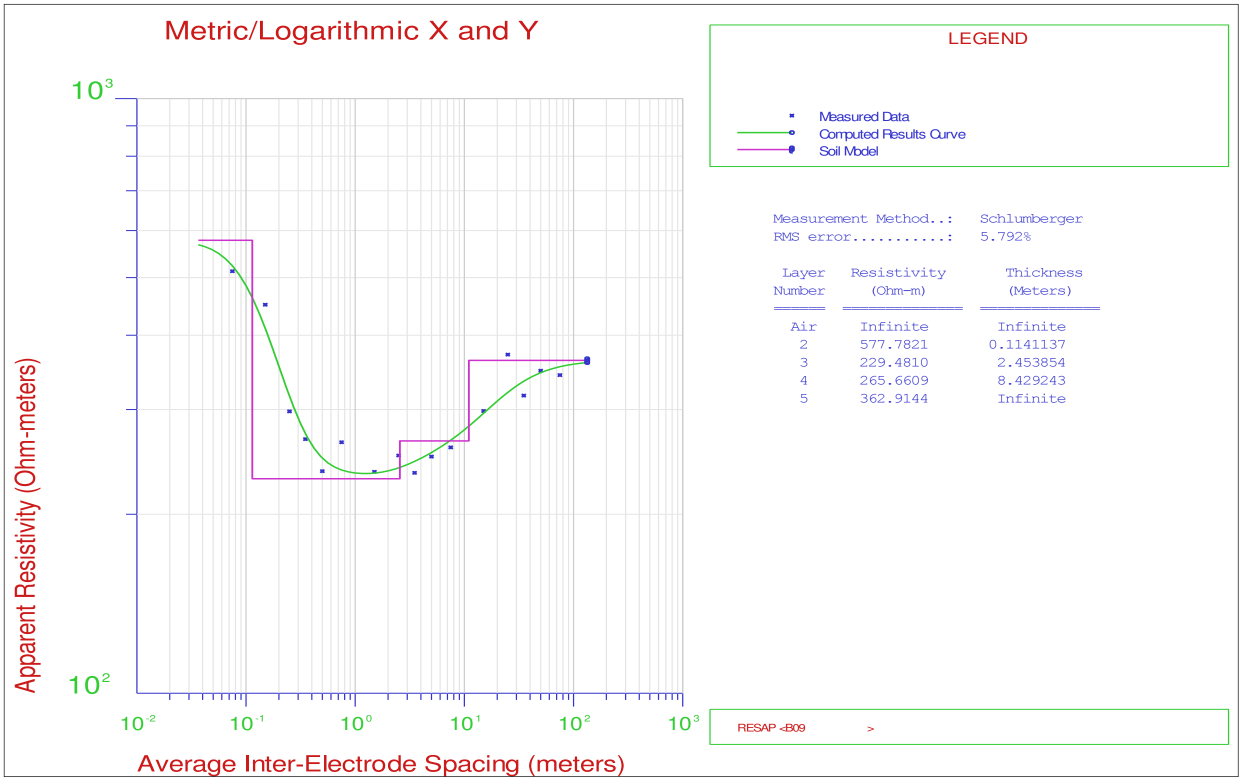
Figure 5.4 Average Electrode Spacing Vs Apparent Resistance (WTG BO8 Data)

In this way a soil structure model is created for each of the 203 grounding points. Calculated soil structure models are essentially curve fit to the data and a percent error is calculated. As a rule of thumb in soil modeling, an error of less than 10% is typically seen by industry as an acceptable model. For this reason the curve fit model was tweaked and edited until the computed soil structure model was within 10% error of the real world ERT data.

Below the ERT data as well as the soil structure model for WTG B08 are provided. (Table 5.1 and 5.5 respectively) Here it can be seen that a four layer soil model is used to represent WTG B08 with a percent error of 5.8%. This soil structure model suggests that WTG B08 sits on a top layer of medium resistant soil above a low resistivity layer finally followed by two increasing resistive layers.

Table 5.1 Ground Resistivity Measurements

Average Spacing	**WTG B08**	
	Test 1	Test 2
(m)	(ohm)	(ohm)
0.1	1107.00	1118.00
0.2	387.90	391.30
0.33	202.20	210.50
0.47	175.80	177.30
0.67	101.30	101.90
1.0	44.82	46.28
2.0	12.09	12.63
3.33	4.93	4.81
4.67	3.65	3.66
6.67	3.26	3.16
10.00	2.25	2.55
20.00	2.23	2.24
33.33	2.11	2.12
46.67	2.00	2.01
66.67	1.93	1.94
100.00	1.89	1.88



Measurement Method..: Schlumberger
RMS error...........: 5.792%

Layer Number	Resistivity (Ohm-m)	Thickness (Meters)
Air	Infinite	Infinite
2	577.7821	0.1141137
3	229.4810	2.453854
4	265.6609	8.429243
5	362.9144	Infinite

Figure 5.5 Soil Model Profile

Recall that a full interpretation of the graph in Figure 5.5 is provided in Chapter 4.

5.4 Safety Criteria:

Once an accurate (less than 10% error) soil model is produced, safety criteria are calculated. Recall from Chapter 1 that safety criteria is heavily dependent upon a sites soil structure. Safety Criteria for this case study is done in the CDEGS MALZ module (12). This module is set to calculate safety criteria as per the IEEE Std. 80 method; assuming a 50kg person, neglecting additional foot resistance, assuming a 1,000 Ω body resistance as specified in IEEE Std. 80, and using the lethal current thresholds also specified by IEEE Std. 80.

Safety Criteria is calculated for 6 different scenarios at each of the 203 grounding points. These six cases included 3 different fault clearing times for both native ground and ground covered by a thin surface material (crushed yard rock of resistivity 3,000 ohm.m). The results for WTG B08 can be seen in Table 5.2 below.

Table 5.2 Software Calculated Safety Criteria

WTG B08	**Touch 0.2 Sec**	**Step 0.2 Sec**	**Touch 0.5 Sec**	**Step 0.5 Sec**	**Touch 1.0 Sec**	**Step 1.0 Sec**
No Crushed Rock	338 V	661 V	229 V	447 V	166 V	324 V
Layer of Crushed Rock	1104 V	3724 V	747 V	2519 V	541 V	1826 V

Additionally the safety criterion is calculated by hand for easy comparison to the CDEGS 0.5 sec values by using the equations previously provided in Chapter 1, in conjunction with the empirical equation provided in IEEE Std. 80 for the Surface Layer Derating Factor. (Within 5% of the analytical value).

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

This comparison can be found in Table 5.3.

Table 5.3 Safety Criteria Software Vs Hand Calculation Comparison

Safety Criteria @ $t_s = 0.5$	CDEGS Value	Hand Calculations
V-Step (Native)	447 V	454 V
V-Touch (Native)	229 V	236 V
V-Step (Crushed Rock)	2519 V	2507 V
V-Touch (Crushed Rock)	747 V	750 V

As mentioned in Chapter 4, safety criteria is used as a safe threshold with which to evaluate the calculated or measured values of Touch and Step voltages at the test location.

5.5 Ground Grid Modeling:

After the safety criteria for Touch and Step are calculated, the ground grid for every site is modeled in the CDEGS MALZ module. Ground grid design for the various types of sites differed based on their unique shape and requirements. Due to this a separate ground grid model is created for every grounding installation considered. (i.e. WTG, JB, SUB, O&M, MET). The ground grid model created for each installation is shown below in Figures 5.6-5.10

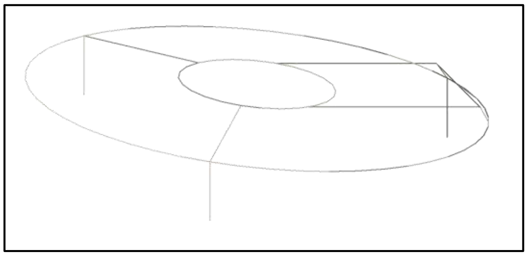


Figure 5.6 WTG Ground Grid

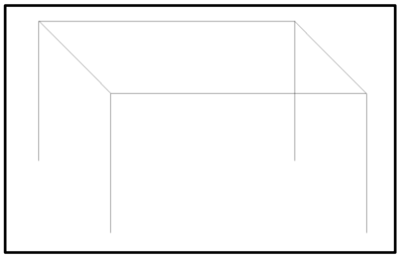


Figure 5.7 Junction Box Ground Grid

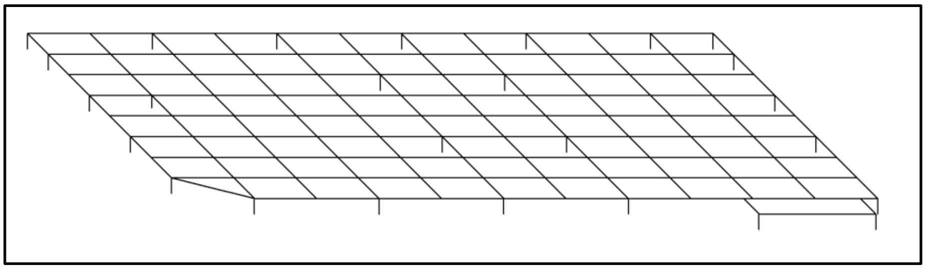


Figure 5.8 Sub Station Ground Grid

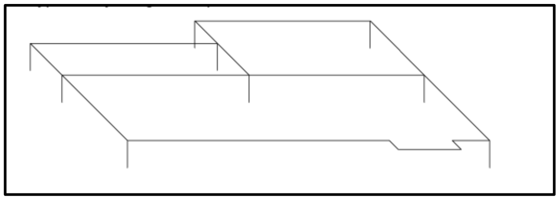


Figure 5.9 O&M Ground Grid

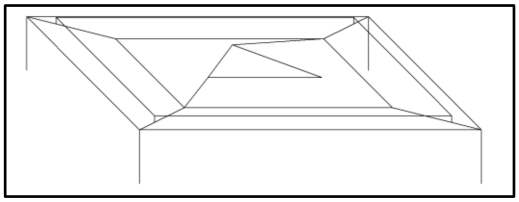


Figure 5.10 MET Mast Ground Grid

All grounding points are modeled in CDEGS using their unique soil structure model created in RESAP and the applicable ground grid geometry listed above buried at their constructed soil depth. In this way the local stand-alone impedance calculation is performed on each of the 203 grounding points.

5.6 Local Site Calculations:

Stand-alone impedance calculations are conducted for every grounding point. These stand-alone calculations are performed in order to acquire the designed stand-alone impedance and the expected Touch and Step voltages that would be present at the stand alone grounding point in the event of a fault.

5.6.1 Impedance:

Stand-alone impedance calculations are performed via the CDEGS MALZ module. MALZ takes into account the various soil resistivity layers along with the surface area interfacing between ground conductors and that soil. The result of these calculations is a stand-alone ground grid impedance of the grounding point in question. After the WTG grounding points are constructed a “fall of potential” or “slope” test(5)(9) is performed to verify that the stand-alone impedances are in compliance with their calculated values. The stand-alone ground resistance for WTG B08 both measured and tested is included below.

Table 5.4 Design Value Compared to Actual Measured Value (WTG B08)

Ground Point	Designed Impedance	Field Measured Impedance
WTG 08	4.569 ohms	0.221 ohms

It should be noted that the discrepancy between the values can be accounted for by three main factors:

- The grounding grid model for this project is a conservative model: not accounting for the structural steel rebar. This rebar can have a substantial effect.
- The soil data is taken in summer (mid-July) in drier soil while the grounding grid is measured in the late winter/ early spring with much higher levels of precipitation thus the soil likely contained much more moisture and would consequently have been far more conductive.
- The soil model created contains a 10% + or - error.

That being said this site happened to be conservatively design and tested at an optimum time; however seeing the opposite is a regular occurrence, and it is common to see measured impedance values slightly higher or lower than the designed value. For an example of this an abbreviated comparison Table is given below for a WPP. For this simulation a portion of the turbine rebar is used, and the impedance measurements are taken at a dryer time of year.

Table 5.5 Impedance Design Value Vs Field Measured Impedance

WPP		
Turbine	Designed Impedance (ohms)	Field Measured Impedance (ohms)
T101	2.13	3.74
T102	4.35	4.13
T103	1.66	4.35
T104	4.66	2.96
T105	5.09	3.21
T106	4.57	2.73
T107	2.81	2.62
T108	3.05	2.93
T109	3.72	2.02

5.6.2 Touch & Step Voltages:

Touch and Step values are calculated for every location. These values are calculated using the CDEGS software in accordance with IEEE Std. 80 section 16.8 as percentages of the GPR. IEEE Std. 80 does give hand calculation methods in section 16.5.1 and 16.5.2 however these hand calculations are only approximations valid for uniform soils as cited by IEEE Std. 80

> “The calculation of the mesh and step voltages for the grid as designed can be done by the approximate analysis techniques described in 16.5 for uniform soil ,

> or by the more accurate computer analysis techniques as demonstrated in 16.8 Further discussion of the calculations are reserved for those sections"

Section 16.8 describes the basic operations used for calculating the Touch and Step voltages. These steps include:

- Modeling the individual components of the grounding system
- Forming a set of equations for the interaction of those components. (in this case Electro Magnetic Theory via Maxwell's equations)
- Solving these equations based on the injected current.
- Computing the potential at any desired surface point.

In this way the Step and Touch voltages are calculated on a per unit basis or percentage of the total GPR.

By calculating the Touch and Step voltages as percentages of GPR, Touch and Step voltages can later be computed for any GPR the grounding point may experience; whether it be local or transferred. The Touch and Step plots for WTG 08, are shown below in Fig 5.11 (page 83) and 5.12 (page 83), respectively.

Touch voltage is only considered around touchable surfaces while Step voltage is considered at every location. In this way it can be seen that the applicable Touch voltage percentage that will occur at WTG B08 is 10.04% of the GPR (the ring around the touchable tower) while the applicable Step voltage is 5.51% of the GPR (a global maximum).

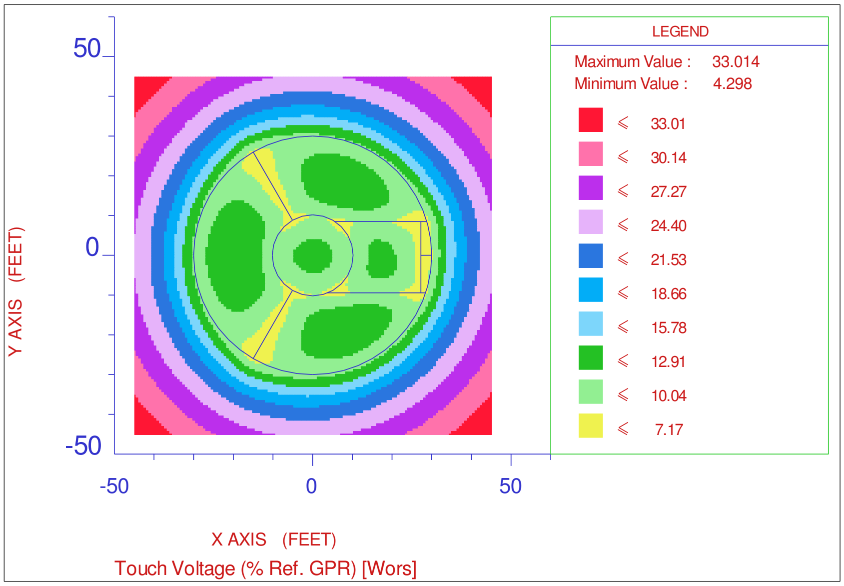


Figure 5.11 Touch Voltage Plot

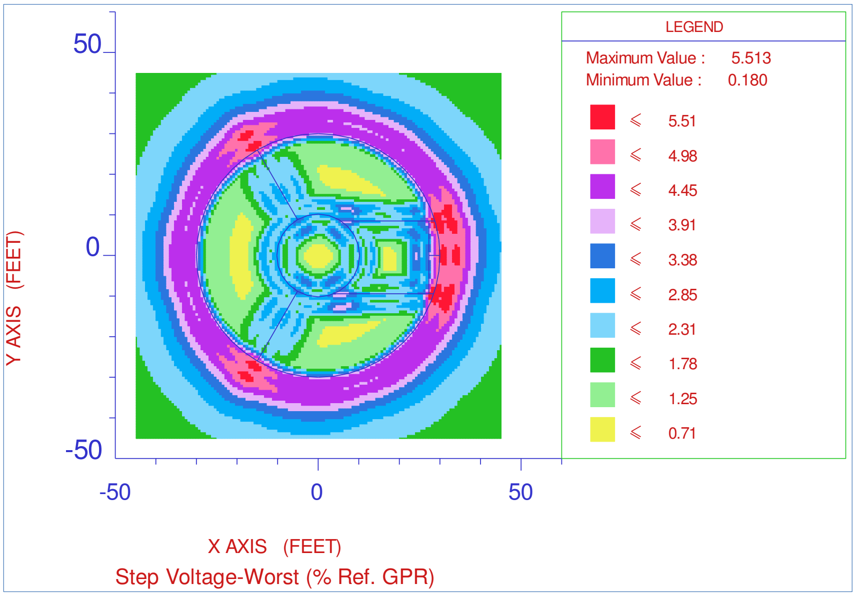


Figure 5.12 Step Voltage Plot

5.7 Interconnecting the Models:

The entire site is then modeled as an interconnected WPP. Modeling this interconnection presents a problem with respect to the soil structure used. The overall model of the entire WPP is shown below with every grounding point having its own unique soil structure.

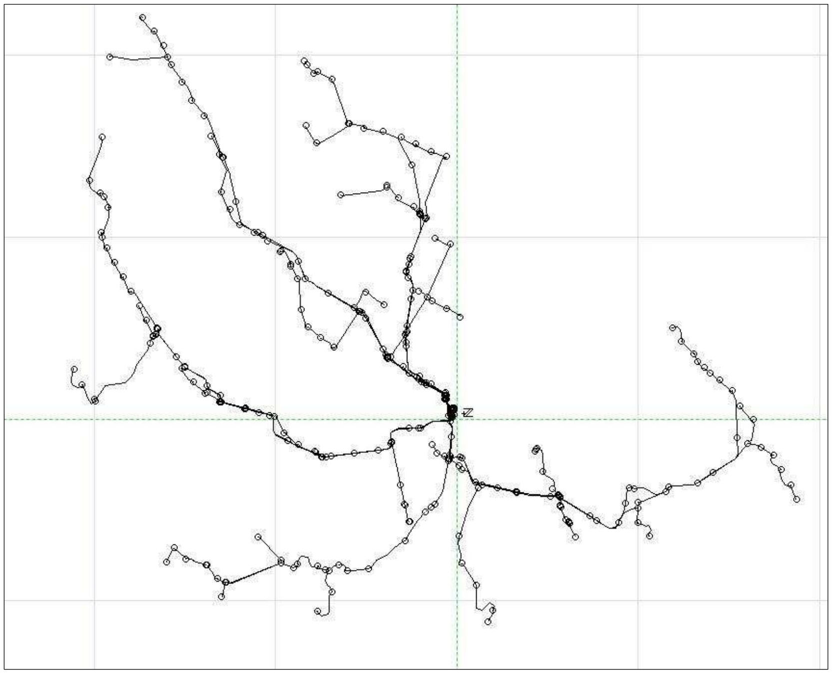


Figure 5.13 Interconnected Model of Entire WPP Case Study

CDEGS, however, allows for only one soil model to be used in a simulation. Because every site has a separate soil model, selecting one soil structure to use across the entire site is not accurate. As mentioned in Chapter 4 one of the biggest challenges in grounding design for a WPP exists in the transference of GPR from one site to another through the interconnected nature of the WPP. If a standard soil is chosen then the phenomenon of dangerous transferred GPRs will not be visible as the max GPR will occur at the faulted grounding point and the safety criteria of all grounding points will be same. In this scenario if the faulted point is safe it could be proven that all other grounding points are also safe for that same fault.

To circumvent this, the unique soils of every test site are normalized to a median soil. This process is detailed in the following sections.

5.7.1 Normalizing the Soil:

In order to construct an overall model two things are done. A median soil structure is computed from the available measured data; and each ground point is represented by a ground rod that when placed in the median soil would result in the equivalent ground impedance to that of its local soil. These operations are further detailed below

5.7.1.1 Median Soil:

A median soil model is created by evaluating the global median of all the available ERT data points and calculating a soil structure model based on these "median" soil measurements. This median data can be better visualized in figure 5.14(page 86) Here the red line approximates the median soil data that was used to compute the median soil structure.

5.7.1.2 Equivalent Rods:

Equivalent ground rods are determined for the median soil by varying the lengths of those ground rods in the median soil model until the resulting impedances are equivalent to the local stand-alone impedances at each ground point.

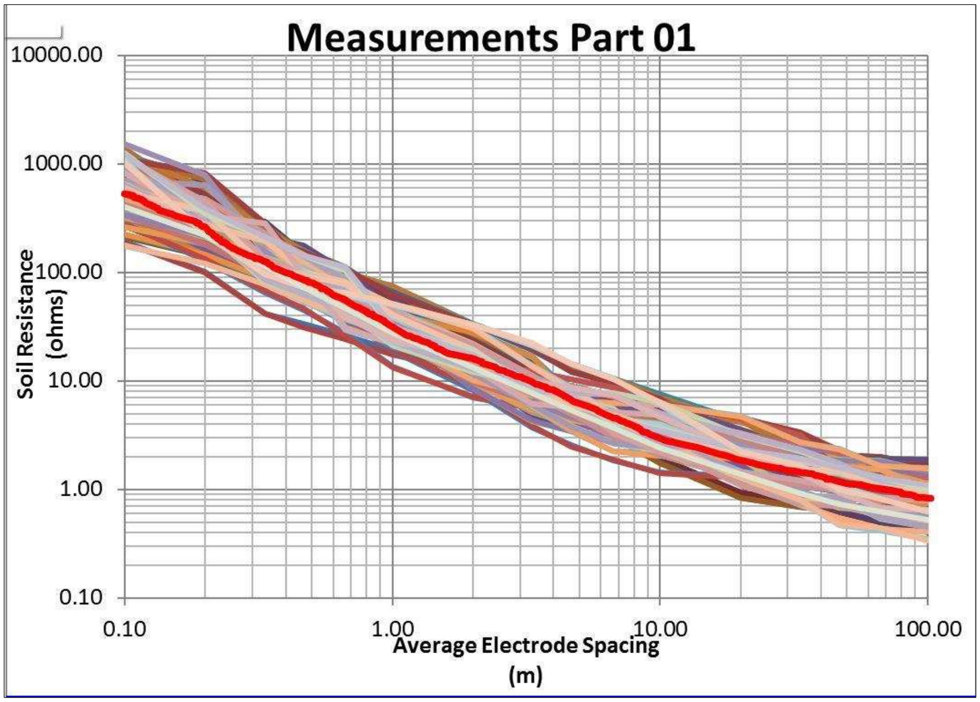


Figure 5.14 Average Electrode Spacing Vs Apparent Resistance (Median Soil Plotted in Red)

By doing this each ground point can be represented by a rod of a specific length that when placed in the median soil will have a stand-alone impedance equal to that of the original stand-alone ground grid in its native soil structure. The equivalent rod length calculated for WTG B08 is given below in Table 5.6.

Table 5.6 Equivalent Ground Rod Calculation

Turbine	Stand Alone Impedance (in Local Soil) (ohms)	Length of Equivalent Rod (in Median Soil) (m)
WTG B08	4.569	57.38

5.7.1.3 Modeling:

With all the rods interconnected together via a trench ground conductor and the concentric neutrals (as discussed in Chapter 2) the entire WPP should then be accurately modeled even though only the median soil is used for this model. The overall site model is shown below in Figure 5.15 incorporating all equivalent rods in place of each measured site. WTG B08 has been marked for reference to the overall site geometry.

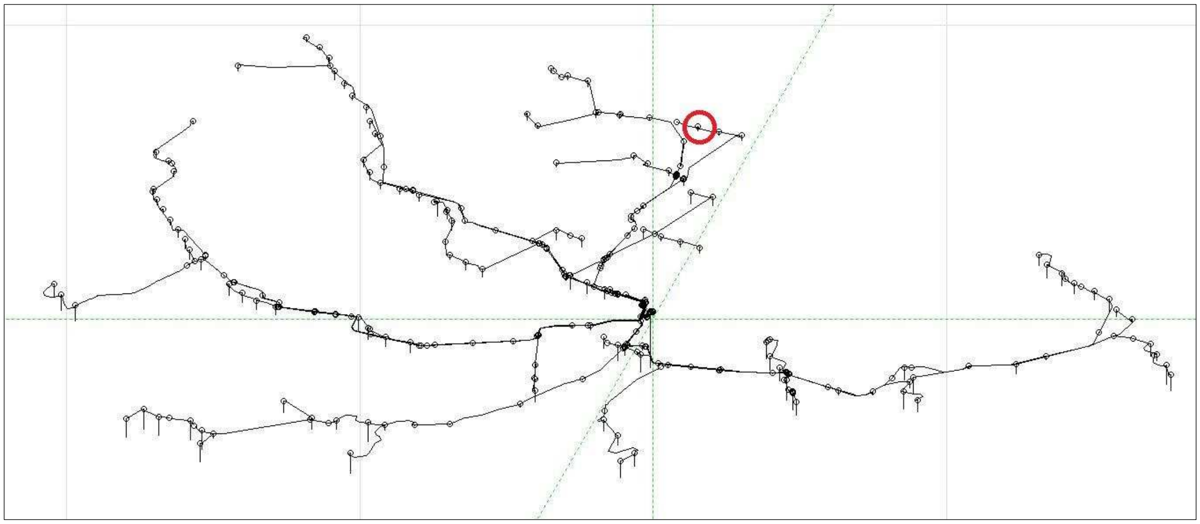


Figure 5.15 Normalized Interconnected WPP Model

5.8 Impedance Calculations:

Once the overall model is built it is evaluated for a fault at every one of the 203 grounding points. This evaluation is done by injecting a fault at a single location and from it calculating the network impedance as seen from the faulted point as well as the transferred impedance that is seen at the remaining 202 grounding points. The result is the 203x203 impedance matrix discussed in Chapter 4 with the Network self-impedances populating the diagonal terms and transferred impedances populating the off-diagonal terms. This impedance matrix is the basis of the GPR calculations to come.

5.9 Split Factor:

In order to calculate GPR, the impedance matrix had to be multiplied by the appropriate ground current (I_G). As mentioned in Chapter 4 this current is calculated by multiplying the available fault current by the appropriate split factor.

The available fault current is known for each grounding point through Power Flow studies, however due to the variances in the soil, the split factor of each grounding point is different. This split factor is calculated using the ROW module in CDEGS. ROW models a current divider through the available return paths immersed in a given soil structure. For this case-study the median soil model is used as the relevant soil structure and the paths considered were as follows:

- 3x Phase conductors (A, B, and C) [insulated]
- 3x Corresponding Concentric Neutrals (A, B, and C)[insulated but grounded to the local ground grid at every grounding point]
- 1xTrench Ground Conductor [Bare and solidly grounded to each ground point]
- Median Soil surrounding all conductors.

203 ROW simulations are created, one for each grounding point. These ROW models only considered one circuit at a time. This means that the current is divided between the direct connections existing between the fault sites (e.g., WTG) and the source (i.e. substation). Because of this simplification the return paths that exist via electromagnetic induction from one circuit to another are neglected. This simplified assumption provides a conservative approach as the addition of other paths would decrease the actual current traveling through the soil.

An illustration of the ROW model for WTG B08 is provided below in figure 5.16 along with the calculated split factor value for a value injected at that location in Table 5.6. For labeling clarity and a detailed description of this model please recall Figure 4.11 from Chapter 4.

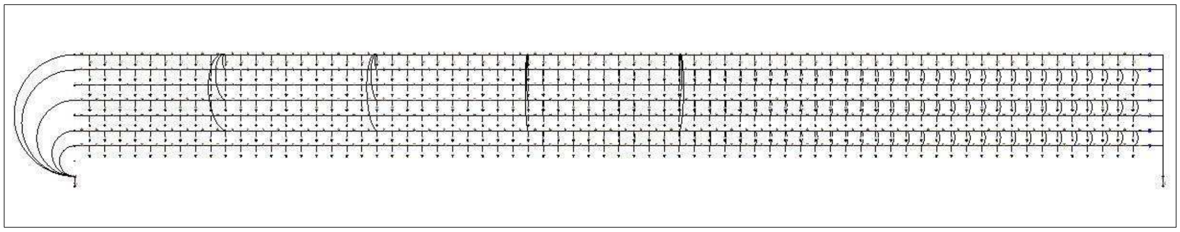


Figure 5.16 ROW Model (WTG B08)

Table 5.7 WTG B08 Split Factor Results

Location	Fault Current (SLG) (A)	Split Factor (%)	Ground Current (A)
WTG B08	7197	11.9 %	856

5.10 GPR: Matrix

Once the Impedance Matrix and the ground current are known, these two terms are multiplied together to acquire the GPR matrix. As mentioned in Chapter 4 this matrix is composed of the local GPRs (diagonal terms) as well as the transferred GPRs (off diagonal terms).

5.11 Site Touch and Step Voltage Values:

Recalling the Touch and Step plots from Section 5.6.2, the percentages from these plots is then used as a quick way to calculate the Touch and Step voltages present at each ground point. This is done by multiplying the available GPR for every fault scenario by the appropriate Touch and Step voltage percentage. This means that every ground point (in this case WTG B08) would have 203 possible GPRs applicable to it, depending on where the fault occurred in the WPP (1 self-induced GPR and 202 transferred GPRs). Each of these GPR values multiplied by the Touch and Step percentages unique to WTG B08 gives a different Touch and Step voltage. In this way 203 fault scenarios and 203 Touch and Step voltage possibilities exist.

5.12 Comparison to Safety Criteria:

After the Touch and Step voltages were calculated for every fault scenario, they are compared to the safety criteria calculated in Section 4.4. This is done by dividing the Touch & Step voltage calculated to the permissible safety criteria.

$$\left(\frac{V_{Touch}}{V_{Touch\,Safe}}\right) < 100\% \rightarrow Safe\ Condition$$

$$\left(\frac{V_{Step}}{V_{Step\,Safe}}\right) < 100\% \rightarrow Safe\ Condition$$

By comparing every Touch and Step voltage to the safety criterions a Touch and Step voltage percentage of safety matrices are obtained. These matrices allow for the final determination of safety for the WPP.

5.13 Final Verdict of Safe Design:

Any values exceeding 90% of the safety criteria were deemed unsafe. The value of 90% was chosen to match the accuracy of the soil modeling error percentage (Chapter 4). Analyzing the percentage of safety matrices (Touch and Step respectively) will show that every location has been proven to be safe for all possible faults. This confirms that the WPP has been designed so as to ensure personal safety with respect to Touch and Step hazards. The max touch and step voltage percentages for WTG B08 are provided below and show that WTG B08 is indeed safe for a fault at any location as well as which fault will result in the worst case at WTG B08.

Table 5.8 Safety Percentages (WTG B08)

Grounding Point	Max Touch % of Safety Criteria	Max Step % of Safety Criteria	Fault Location
WTG B08	15.3 %	4.3 %	WTG B08

Additionally it can be seen which site will be the most dangerous when a fault occurs at WTG B08. The maximum voltage percentages across site for a fault at WTG B08 are given in the table below.

Table 5.9 Critical Safety Points

Fault Location	Max Fault Specific Touch % of Safety Criteria	Grounding Point of Touch Occurrence	Max Fault Specific Step % of Safety Criteria	Grounding Point of Step Occurrence
WTG B08	15.3 %	WTG B08	6.9 %	WTG B09

A thorough evaluation can now at this stage be quickly done by analyzing the percentage of safety matrices. These results are further discussed in Chapter 6 as the method of design can be used to even better show the interconnected nature of WPP and why they are fundamentally different than typical generation facilities or substations.

CHAPTER 6: CONCLUSIONS AND IMPLICATIONS

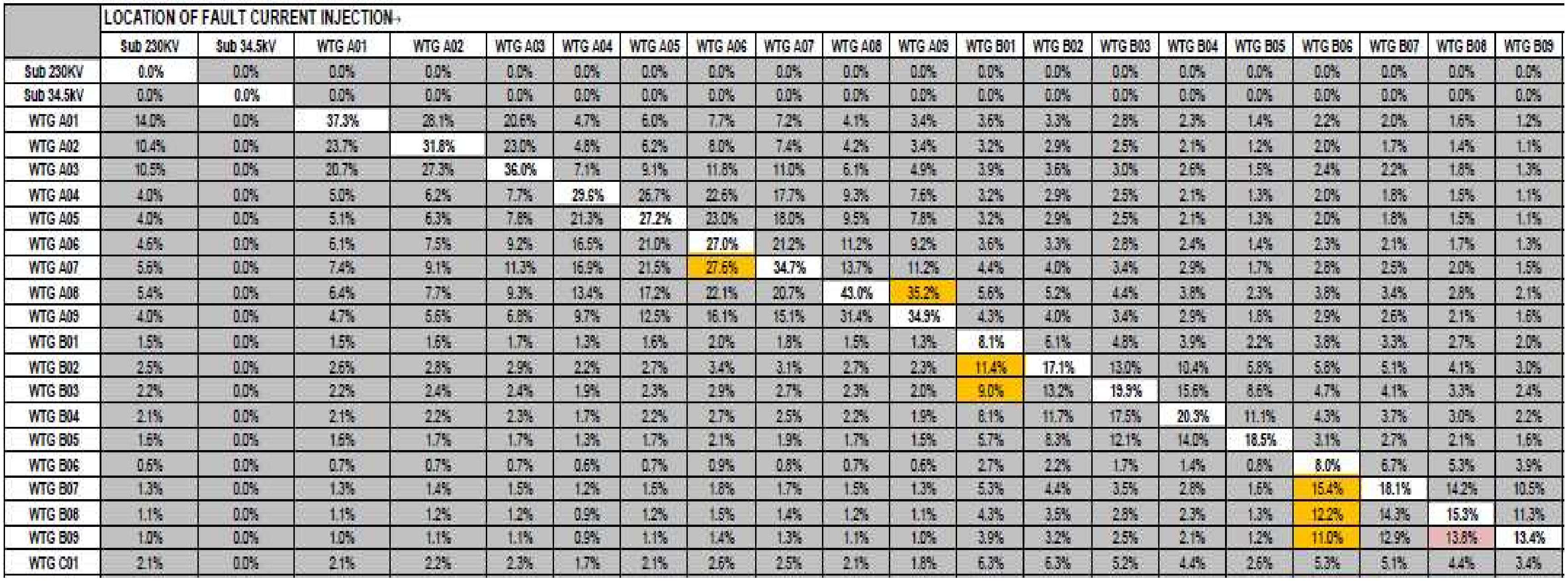
This chapter gives an overview of the findings of this research as well as a discussion of their implications on the need for further research and on the grounding of WPPs for personal safety. .

6.1 Unique Fault Scenarios and their Implications:

As mentioned in Chapter 5 the % Safety Criteria Matrix provides an at-a-glance analysis tool for determining site safety. From inspection these matrices it can be seen whether the design methodology used has resulted in every grounding point being confirmed as safe; however these matrices also give greater insight into the interconnected nature of WPPs.

Greater analysis of the % Safety Matrices reveals that the most dangerous grounding point does not necessarily have to be the faulted point. This is important chiefly because it infers that there could exist sites in which neglecting the possibility of transferred potentials via an extensive interconnected system could result in failing to identify unsafe conditions. Figure 6.1(page 93) provides an excerpt from the touch % of safety criteria matrix.

Here orange cells indicate fault scenarios in which the grounding point with the highest risk is other than that of the fault location. For example Figure 6.1 suggests that in the event of a fault at WTG B06 it is actually riskier to be standing at WTGs B07, B08, or B09 (all of which exhibit a thinner margin with the acceptable safety criteria).



	LOCATION OF FAULT CURRENT INJECTION→																			
	Sub 230KV	Sub 34.5kV	WTG A01	WTG A02	WTG A03	WTG A04	WTG A05	WTG A06	WTG A07	WTG A08	WTG A09	WTG B01	WTG B02	WTG B03	WTG B04	WTG B05	WTG B06	WTG B07	WTG B08	WTG B09
Sub 230KV	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Sub 34.5kV	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
WTG A01	14.0%	0.0%	37.3%	28.1%	20.6%	4.7%	6.0%	7.7%	7.2%	4.1%	3.4%	3.6%	3.3%	2.8%	2.3%	1.4%	2.2%	2.0%	1.6%	1.2%
WTG A02	10.4%	0.0%	23.7%	31.8%	23.0%	4.8%	6.2%	8.0%	7.4%	4.2%	3.4%	3.2%	2.9%	2.5%	2.1%	1.2%	2.0%	1.7%	1.4%	1.1%
WTG A03	10.5%	0.0%	20.7%	27.3%	36.0%	7.1%	9.1%	11.8%	11.0%	6.1%	4.9%	3.9%	3.6%	3.0%	2.6%	1.5%	2.4%	2.2%	1.8%	1.3%
WTG A04	4.0%	0.0%	5.0%	6.2%	7.7%	29.6%	26.7%	22.6%	17.7%	9.3%	7.6%	3.2%	2.9%	2.5%	2.1%	1.3%	2.0%	1.8%	1.5%	1.1%
WTG A05	4.0%	0.0%	5.1%	6.3%	7.8%	21.3%	27.2%	23.0%	18.0%	9.5%	7.8%	3.2%	2.9%	2.5%	2.1%	1.3%	2.0%	1.8%	1.5%	1.1%
WTG A06	4.6%	0.0%	6.1%	7.5%	9.2%	16.5%	21.0%	27.0%	21.2%	11.2%	9.2%	3.6%	3.3%	2.8%	2.4%	1.4%	2.3%	2.1%	1.7%	1.3%
WTG A07	5.6%	0.0%	7.4%	9.1%	11.3%	16.9%	21.5%	27.6%	34.7%	13.7%	11.2%	4.4%	4.0%	3.4%	2.9%	1.7%	2.8%	2.5%	2.0%	1.5%
WTG A08	5.4%	0.0%	6.4%	7.7%	9.3%	13.4%	17.2%	22.1%	20.7%	43.0%	35.2%	5.6%	5.2%	4.4%	3.8%	2.3%	3.8%	3.4%	2.8%	2.1%
WTG A09	4.0%	0.0%	4.7%	5.6%	6.8%	9.7%	12.5%	16.1%	15.1%	31.4%	34.9%	4.3%	4.0%	3.4%	2.9%	1.8%	2.9%	2.6%	2.1%	1.6%
WTG B01	1.5%	0.0%	1.5%	1.6%	1.7%	1.3%	1.6%	2.0%	1.8%	1.5%	1.3%	8.1%	6.1%	4.8%	3.9%	2.2%	3.8%	3.3%	2.7%	2.0%
WTG B02	2.5%	0.0%	2.6%	2.8%	2.9%	2.2%	2.7%	3.4%	3.1%	2.7%	2.3%	11.4%	17.1%	13.0%	10.4%	5.8%	5.8%	5.1%	4.1%	3.0%
WTG B03	2.2%	0.0%	2.2%	2.4%	2.4%	1.9%	2.3%	2.9%	2.7%	2.3%	2.0%	9.0%	13.2%	19.9%	15.6%	8.6%	4.7%	4.1%	3.3%	2.4%
WTG B04	2.1%	0.0%	2.1%	2.2%	2.3%	1.7%	2.2%	2.7%	2.5%	2.2%	1.9%	8.1%	11.7%	17.5%	20.3%	11.1%	4.3%	3.7%	3.0%	2.2%
WTG B05	1.6%	0.0%	1.6%	1.7%	1.7%	1.3%	1.7%	2.1%	1.9%	1.7%	1.5%	5.7%	8.3%	12.1%	14.0%	18.5%	3.1%	2.7%	2.1%	1.6%
WTG B06	0.6%	0.0%	0.7%	0.7%	0.7%	0.6%	0.7%	0.9%	0.8%	0.7%	0.6%	2.7%	2.2%	1.7%	1.4%	0.8%	8.0%	6.7%	5.3%	3.9%
WTG B07	1.3%	0.0%	1.3%	1.4%	1.5%	1.2%	1.5%	1.8%	1.7%	1.5%	1.3%	5.3%	4.4%	3.5%	2.8%	1.6%	15.4%	18.1%	14.2%	10.5%
WTG B08	1.1%	0.0%	1.1%	1.2%	1.2%	0.9%	1.2%	1.5%	1.4%	1.2%	1.1%	4.3%	3.5%	2.8%	2.3%	1.3%	12.2%	14.3%	15.3%	11.3%
WTG B09	1.0%	0.0%	1.0%	1.1%	1.1%	0.9%	1.1%	1.4%	1.3%	1.1%	1.0%	3.9%	3.2%	2.5%	2.1%	1.2%	11.0%	12.9%	13.8%	13.4%
WTG C01	2.1%	0.0%	2.1%	2.2%	2.3%	1.7%	2.1%	2.6%	2.5%	2.1%	1.8%	6.3%	6.3%	5.2%	4.4%	2.6%	5.3%	5.1%	4.4%	3.4%

Figure 6.1 Touch Voltage as Percentage of Safety Criteri

Red cells indicate grounding points where the worst case fault condition for that location actually occurs for a fault at a different grounding point. For example Figure 6.1 suggests that the riskiest time to be standing at WTG B09 is actually when there is a fault at B08.

Obviously all locations for this site are well under the safety thresholds (Max touch 66.9% and max step 38.9%) however this is not always the case as soils can vary widely with location. Also it is worth noting that red cells typically tend to be rare and extremely close to the diagonal value. This being said making sure that all diagonals are beneath the threshold will likely ensure that 99% of the site is also below the threshold; however assuming this can fail to capture the 1% that could be a safety risk.

In this way this matrix approach can be used to prove that due to the large size of the grounding system and the subsequent failing of the traditional equipotential assumption, transferred potentials can easily exist even on sites with good soil and should be accounted for.

6.2 Thesis Contribution

This thesis has provided a general review of grounding design theory, described the unique challenges to grounding design introduce by WPPs, provided basic methodology for the “safe” design of a wind farm grounding design, and provided a case study for reference of one such real world design. This information is currently not readily available as WPP grounding is a new area of study and very little has been published concerning it. The main contribution of this thesis has been to offer a summary of grounding design practices that provides both general information of power system grounding as well detailed information on how grounding design pertains specifically to wind power plants. In addition, this work has been used in pushing forward the creation of a guide or standard for wind power plant grounding. This thesis may serves as an introduction to Wind Power Plant grounding for personal safety as well as an easily accessible starting point for future research.

6.3 Future Work:

WPP Grounding is a relatively unknown field of design. With wind energy rapidly on the rise there is much work needed to ensure new WPP are designed safely. Currently there is no IEEE or IEC standard or guide for WPP grounding design for personal safety. An IEEE standard or guide should be created to both disseminate the design requirements unique to WPPs and to provide acceptable methods of design that can be agreed upon or referenced by industry. As there is no standard or guide there is very little information on the relationship between key design factors. Detailed research is required to determine special design relationships between varying particular factors. For instance: “What is the effect on Touch and Step potentials if the trench bare ground is removed?”, “Is the inclusion of the turbine rebar an acceptable practice and how does it affect safety.”, or “Statistically what is an acceptable number of soil samples to ensure safe design?”. All these research topics and more could greatly impact industry practice and through it the viability of WPPs. Lastly the current electric codes do not account for several factors unique to WPPs (many mentioned in this thesis). These codes should be updated to accurately account for new renewable technologies. All these challenges provide a broad field of opportunity for future work that will be needed to standardize the wind energy industry, create a more viable fiscal environment for WPPs, and most importantly to ensure their safe construction.

In Summary, WPPs are a rapidly growing technology that introduce several unique challenges to grounding design for the purpose of personal safety. These challenges can create unforeseen and at times unintuitive implications across large extents of land within publicly accessible areas. It is a necessity that those designing WPP grounding systems are aware of these challenges and consider them when evaluating the personal safety of a WPP. Currently there is no standard on wind farm grounding for personal safety which has caused confusion and misunderstanding over the topic throughout the industry with no governing or reference to follow. This research has given a basic description of these unique challenges, a method for their safe consideration, and real world examples of their existence. As populations increase, power system infrastructures grow, and the space between continues to shrink, the dedication to safety becomes more and more vital. It is crucial that all new technologies are understood first and foremost as they relate to the safety of the individuals in contact with them and WPP provide perhaps one of the most vivid illustrations.

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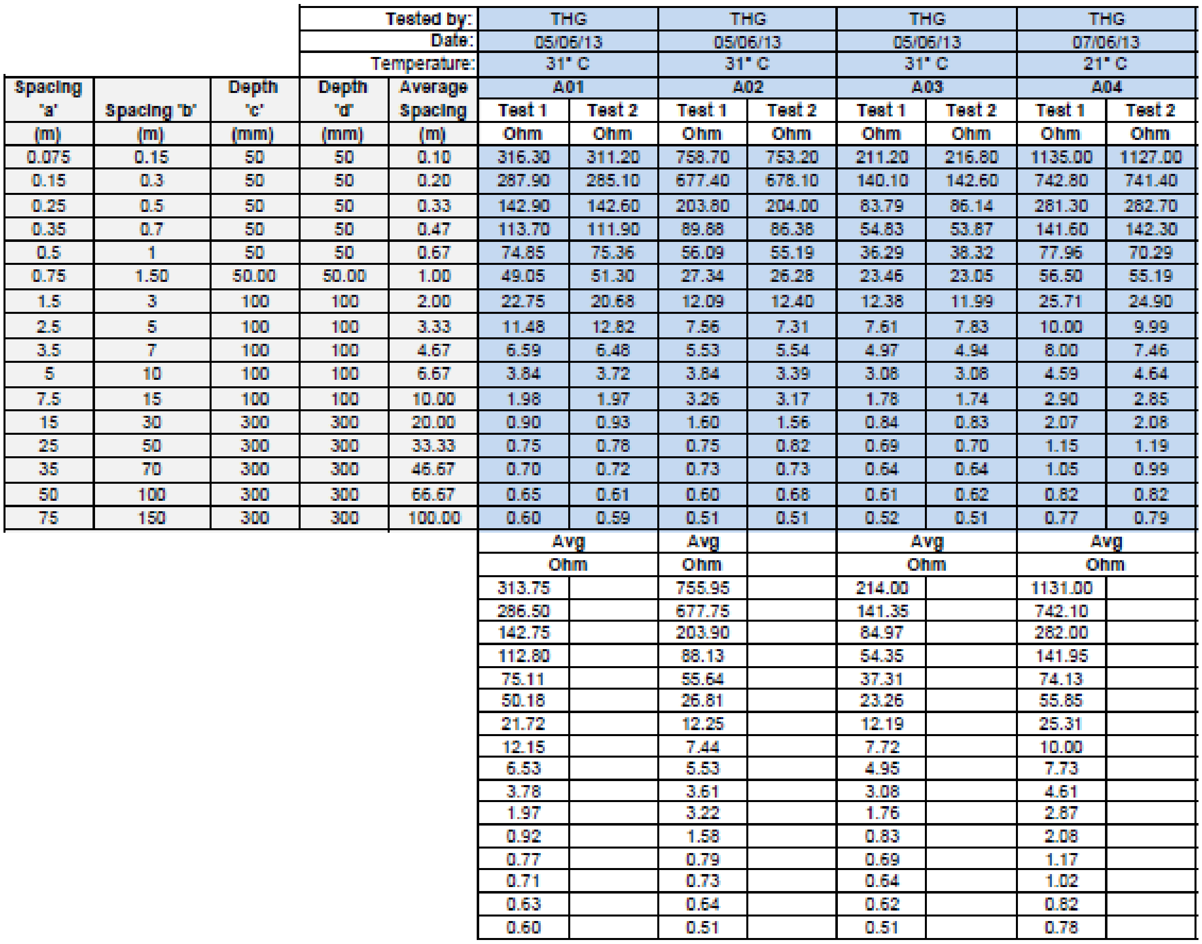
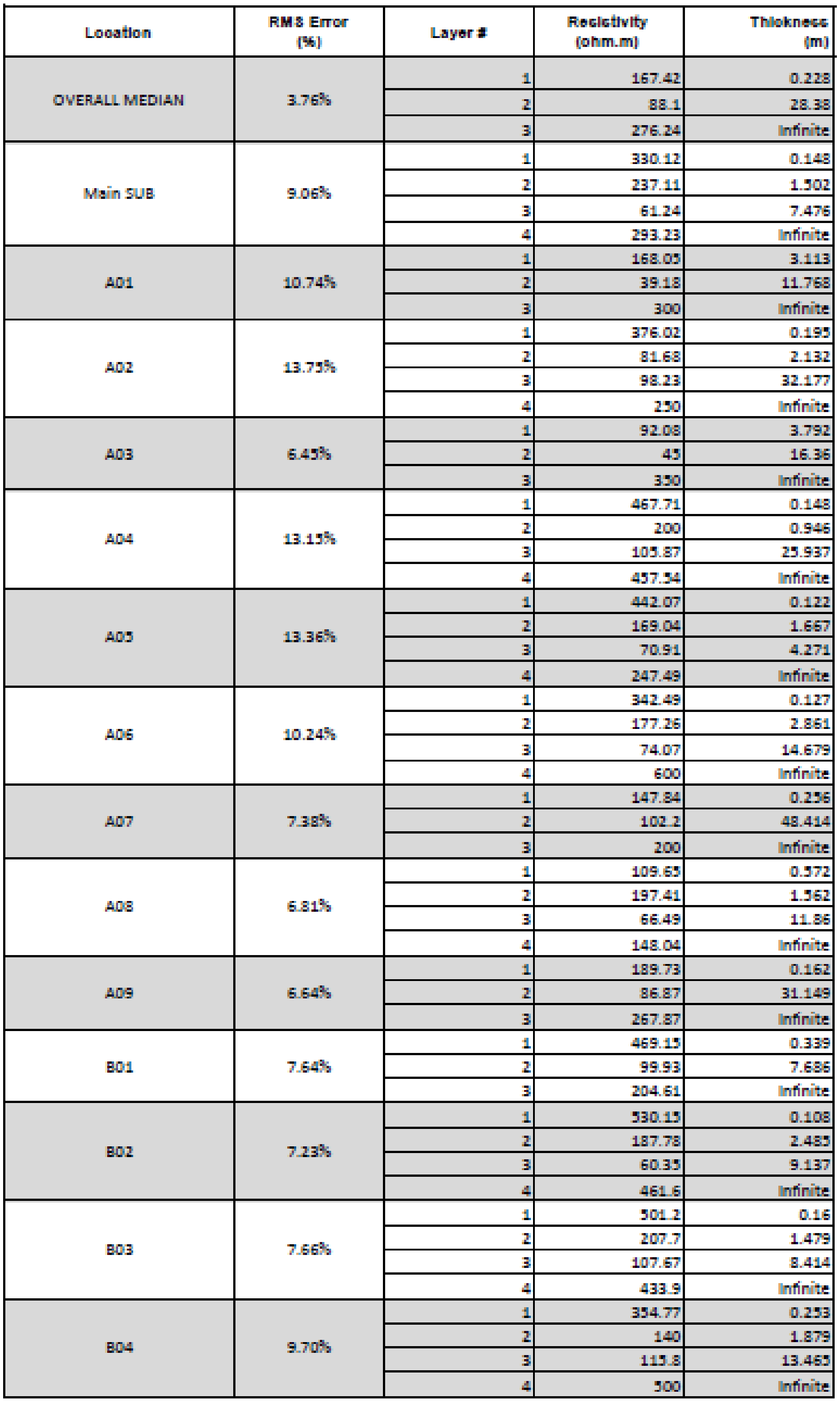
APPENDIX 1: GOUND RESISTANCE MEASUREMENTS



				Tested by:	THG		THG		THG		THG	
				Date:	05/06/13		05/06/13		05/06/13		07/06/13	
				Temperature:	31° C		31° C		31° C		21° C	
Spacing 'a'	Spacing 'b'	Depth 'c'	Depth 'd'	Average Spacing	A01		A02		A03		A04	
					Test 1	Test 2	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2
(m)	(m)	(mm)	(mm)	(m)	Ohm	Ohm	Ohm	Ohm	Ohm	Ohm	Ohm	Ohm
0.075	0.15	50	50	0.10	316.30	311.20	758.70	753.20	211.20	216.80	1135.00	1127.00
0.15	0.3	50	50	0.20	287.90	285.10	677.40	678.10	140.10	142.60	742.80	741.40
0.25	0.5	50	50	0.33	142.90	142.60	203.80	204.00	83.79	86.14	261.30	262.70
0.35	0.7	50	50	0.47	113.70	111.90	89.88	86.38	54.83	53.87	141.60	142.30
0.5	1	50	50	0.67	74.85	75.36	56.09	55.19	36.29	38.32	77.96	70.29
0.75	1.50	50.00	50.00	1.00	49.05	51.30	27.34	26.28	23.46	23.05	56.50	55.19
1.5	3	100	100	2.00	22.75	20.68	12.09	12.40	12.38	11.99	25.71	24.90
2.5	5	100	100	3.33	11.48	12.82	7.56	7.31	7.61	7.83	10.00	9.99
3.5	7	100	100	4.67	6.59	6.48	5.53	5.54	4.97	4.94	8.00	7.46
5	10	100	100	6.67	3.84	3.72	3.84	3.39	3.08	3.08	4.59	4.64
7.5	15	100	100	10.00	1.98	1.97	3.26	3.17	1.78	1.74	2.90	2.85
15	30	300	300	20.00	0.90	0.93	1.60	1.56	0.84	0.83	2.07	2.08
25	50	300	300	33.33	0.75	0.78	0.75	0.82	0.69	0.70	1.15	1.19
35	70	300	300	46.67	0.70	0.72	0.73	0.73	0.64	0.64	1.05	0.99
50	100	300	300	66.67	0.65	0.61	0.60	0.68	0.61	0.62	0.82	0.82
75	150	300	300	100.00	0.60	0.59	0.51	0.51	0.52	0.51	0.77	0.79

Avg		Avg		Avg		Avg	
Ohm		Ohm		Ohm		Ohm	
313.75		755.95		214.00		1131.00	
286.50		677.75		141.35		742.10	
142.75		203.90		84.97		262.00	
112.80		88.13		54.35		141.95	
75.11		55.64		37.31		74.13	
50.18		26.81		23.26		55.85	
21.72		12.25		12.19		25.31	
12.15		7.44		7.72		10.00	
6.53		5.53		4.95		7.73	
3.78		3.61		3.08		4.61	
1.97		3.22		1.76		2.87	
0.92		1.58		0.83		2.08	
0.77		0.79		0.69		1.17	
0.71		0.73		0.64		1.02	
0.63		0.64		0.62		0.82	
0.60		0.51		0.51		0.78	

APPENDIX 2: SOIL RESISTIVITY COMPUTER MODEL DATA



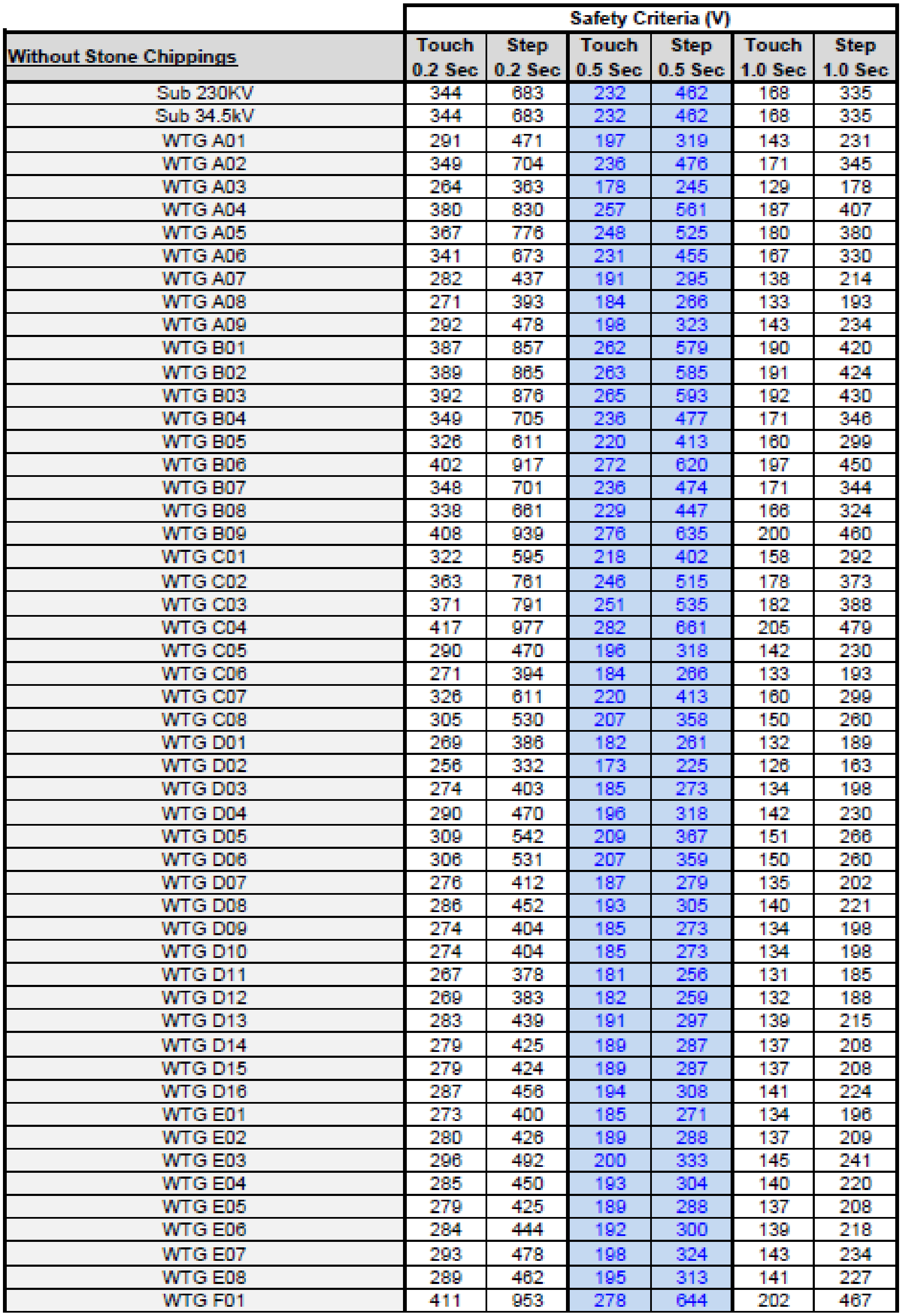
Location	RMS Error (%)	Layer #	Resistivity (ohm.m)	Thickness (m)
OVERALL MEDIAN	3.76%	1	167.42	0.228
		2	88.1	28.38
		3	276.24	Infinite
Main SUB	9.06%	1	330.12	0.148
		2	237.11	1.502
		3	61.24	7.476
		4	293.23	Infinite
A01	10.74%	1	168.05	3.113
		2	39.18	11.768
		3	300	Infinite
A02	13.75%	1	376.02	0.195
		2	81.68	2.132
		3	98.23	32.177
		4	250	Infinite
A03	6.45%	1	92.08	3.792
		2	45	16.36
		3	350	Infinite
A04	13.15%	1	467.71	0.148
		2	200	0.946
		3	105.87	25.937
		4	457.54	Infinite
A05	13.36%	1	442.07	0.122
		2	169.04	1.667
		3	70.91	4.271
		4	247.49	Infinite
A06	10.24%	1	342.49	0.127
		2	177.26	2.861
		3	74.07	14.679
		4	600	Infinite
A07	7.38%	1	147.84	0.256
		2	102.2	48.414
		3	200	Infinite
A08	6.81%	1	109.65	0.572
		2	197.41	1.562
		3	66.49	11.86
		4	148.04	Infinite
A09	6.64%	1	189.73	0.162
		2	86.87	31.149
		3	267.87	Infinite
B01	7.64%	1	469.15	0.339
		2	99.93	7.686
		3	204.61	Infinite
B02	7.23%	1	530.15	0.108
		2	187.78	2.485
		3	60.35	9.137
		4	461.6	Infinite
B03	7.66%	1	501.2	0.16
		2	207.7	1.479
		3	107.67	8.414
		4	433.9	Infinite
B04	9.70%	1	354.77	0.253
		2	140	1.879
		3	115.8	13.465
		4	500	Infinite

APPENDIX 3: SOIL RESITIVITY PROFILES

Soil Resistivity Profile – Site Median

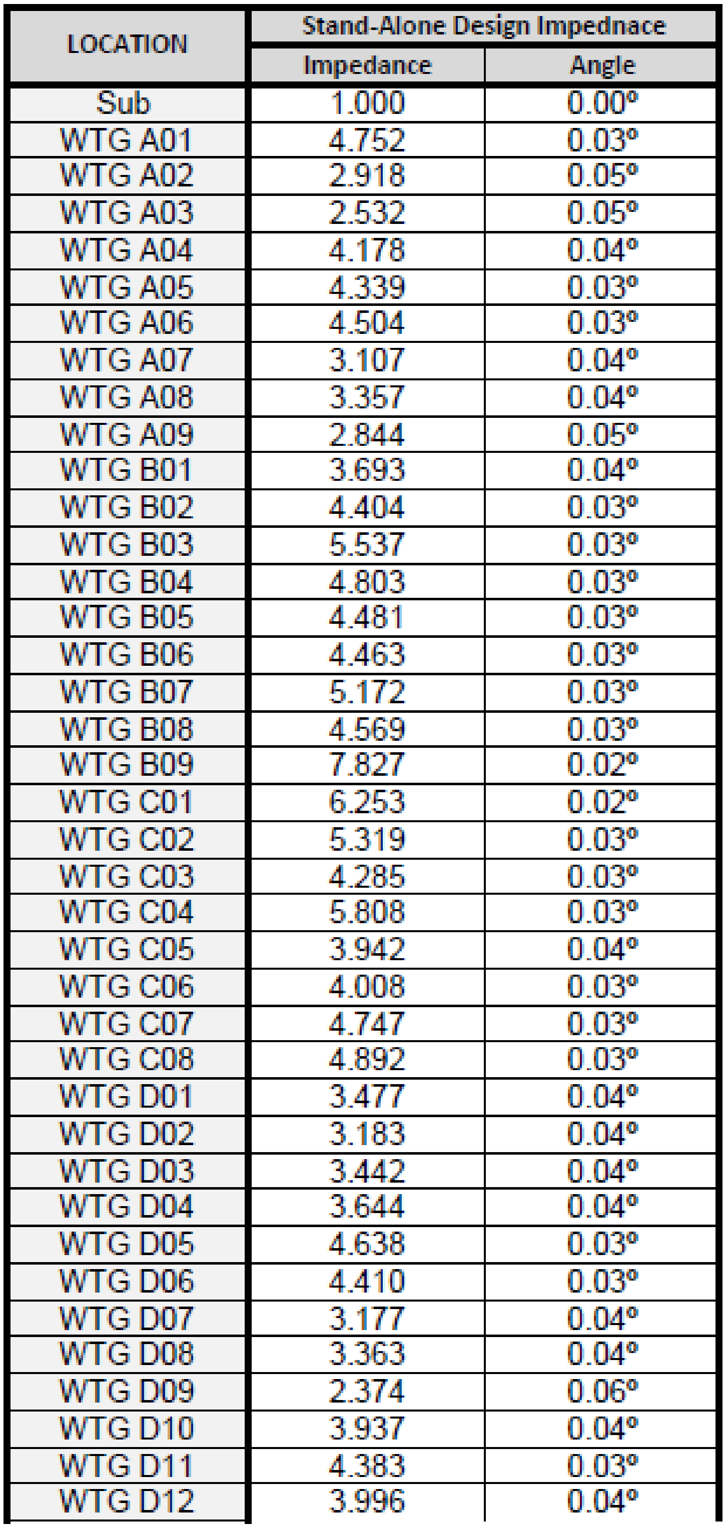
Soil Resistivity Profile – Sub Station

APPENDIX 4: SAFETY CRITERIA



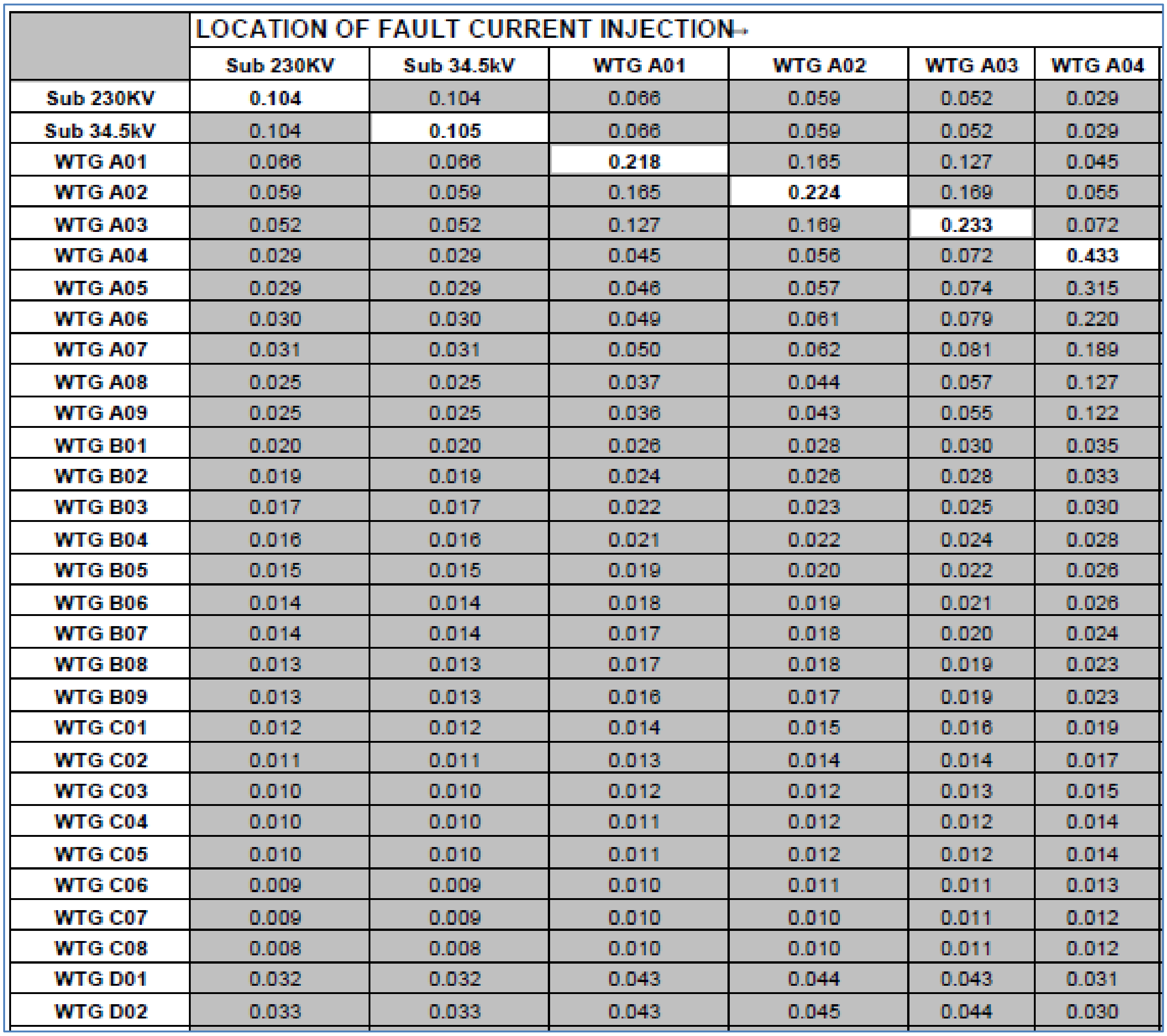
	Safety Criteria (V)					
Without Stone Chippings	Touch 0.2 Sec	Step 0.2 Sec	Touch 0.5 Sec	Step 0.5 Sec	Touch 1.0 Sec	Step 1.0 Sec
Sub 230KV	344	683	232	462	168	335
Sub 34.5kV	344	683	232	462	168	335
WTG A01	291	471	197	319	143	231
WTG A02	349	704	236	476	171	345
WTG A03	264	363	178	245	129	178
WTG A04	380	830	257	561	187	407
WTG A05	367	776	248	525	180	380
WTG A06	341	673	231	455	167	330
WTG A07	282	437	191	295	138	214
WTG A08	271	393	184	266	133	193
WTG A09	292	478	198	323	143	234
WTG B01	387	857	262	579	190	420
WTG B02	389	865	263	585	191	424
WTG B03	392	876	265	593	192	430
WTG B04	349	705	236	477	171	346
WTG B05	326	611	220	413	160	299
WTG B06	402	917	272	620	197	450
WTG B07	348	701	236	474	171	344
WTG B08	338	661	229	447	166	324
WTG B09	408	939	276	635	200	460
WTG C01	322	595	218	402	158	292
WTG C02	363	761	246	515	178	373
WTG C03	371	791	251	535	182	388
WTG C04	417	977	282	661	205	479
WTG C05	290	470	196	318	142	230
WTG C06	271	394	184	266	133	193
WTG C07	326	611	220	413	160	299
WTG C08	305	530	207	358	150	260
WTG D01	269	386	182	261	132	189
WTG D02	256	332	173	225	126	163
WTG D03	274	403	185	273	134	198
WTG D04	290	470	196	318	142	230
WTG D05	309	542	209	367	151	266
WTG D06	306	531	207	359	150	260
WTG D07	276	412	187	279	135	202
WTG D08	286	452	193	305	140	221
WTG D09	274	404	185	273	134	198
WTG D10	274	404	185	273	134	198
WTG D11	267	378	181	256	131	185
WTG D12	269	383	182	259	132	188
WTG D13	283	439	191	297	139	215
WTG D14	279	425	189	287	137	208
WTG D15	279	424	189	287	137	208
WTG D16	287	456	194	308	141	224
WTG E01	273	400	185	271	134	196
WTG E02	280	426	189	288	137	209
WTG E03	296	492	200	333	145	241
WTG E04	285	450	193	304	140	220
WTG E05	279	425	189	288	137	208
WTG E06	284	444	192	300	139	218
WTG E07	293	478	198	324	143	234
WTG E08	289	462	195	313	141	227
WTG F01	411	953	278	644	202	467

APPENDIX 5.1: STAND-ALONE IMPEDANCE



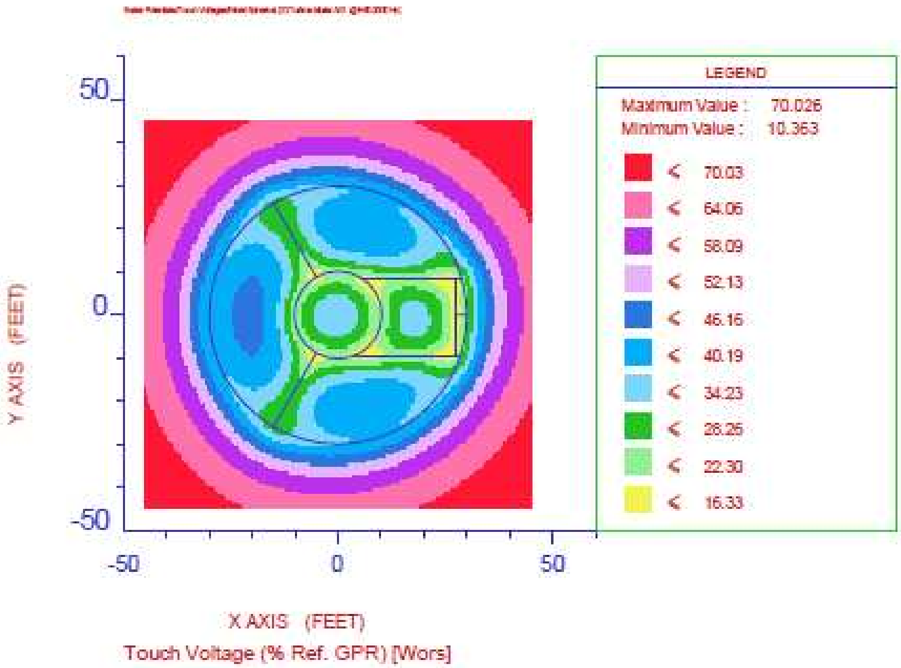
LOCATION	Stand-Alone Design Impednace	
	Impedance	Angle
Sub	1.000	0.00º
WTG A01	4.752	0.03º
WTG A02	2.918	0.05º
WTG A03	2.532	0.05º
WTG A04	4.178	0.04º
WTG A05	4.339	0.03º
WTG A06	4.504	0.03º
WTG A07	3.107	0.04º
WTG A08	3.357	0.04º
WTG A09	2.844	0.05º
WTG B01	3.693	0.04º
WTG B02	4.404	0.03º
WTG B03	5.537	0.03º
WTG B04	4.803	0.03º
WTG B05	4.481	0.03º
WTG B06	4.463	0.03º
WTG B07	5.172	0.03º
WTG B08	4.569	0.03º
WTG B09	7.827	0.02º
WTG C01	6.253	0.02º
WTG C02	5.319	0.03º
WTG C03	4.285	0.03º
WTG C04	5.808	0.03º
WTG C05	3.942	0.04º
WTG C06	4.008	0.03º
WTG C07	4.747	0.03º
WTG C08	4.892	0.03º
WTG D01	3.477	0.04º
WTG D02	3.183	0.04º
WTG D03	3.442	0.04º
WTG D04	3.644	0.04º
WTG D05	4.638	0.03º
WTG D06	4.410	0.03º
WTG D07	3.177	0.04º
WTG D08	3.363	0.04º
WTG D09	2.374	0.06º
WTG D10	3.937	0.04º
WTG D11	4.383	0.03º
WTG D12	3.996	0.04º

APPENDIX 5.2: NETWORK IMPEDANCE

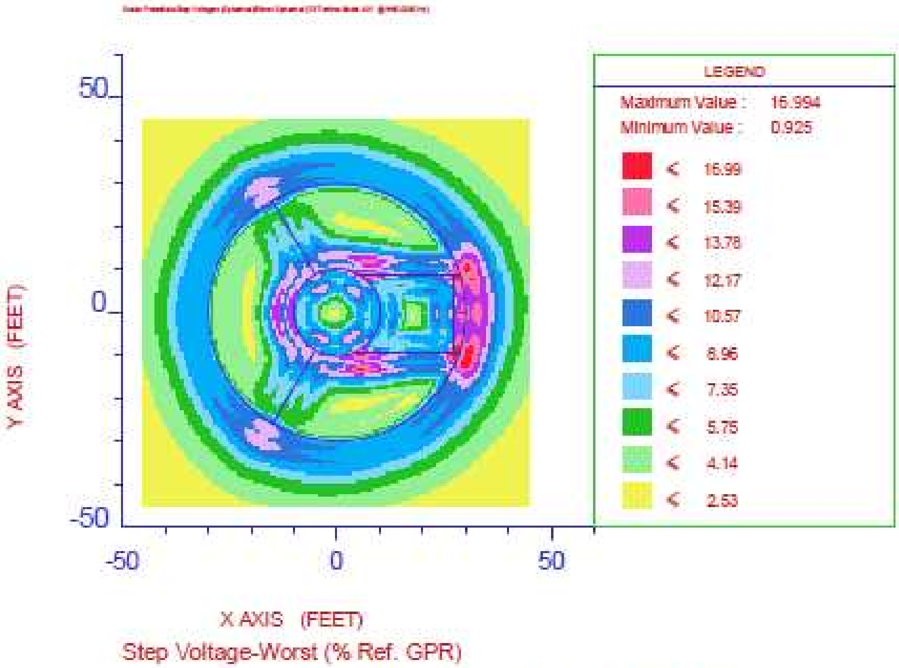


	LOCATION OF FAULT CURRENT INJECTION→					
	Sub 230KV	**Sub 34.5kV**	**WTG A01**	**WTG A02**	**WTG A03**	**WTG A04**
Sub 230KV	**0.104**	0.104	0.066	0.059	0.052	0.029
Sub 34.5kV	0.104	**0.105**	0.066	0.059	0.052	0.029
WTG A01	0.066	0.066	**0.218**	0.165	0.127	0.045
WTG A02	0.059	0.059	0.165	**0.224**	0.169	0.055
WTG A03	0.052	0.052	0.127	0.169	**0.233**	0.072
WTG A04	0.029	0.029	0.045	0.056	0.072	**0.433**
WTG A05	0.029	0.029	0.046	0.057	0.074	0.315
WTG A06	0.030	0.030	0.049	0.061	0.079	0.220
WTG A07	0.031	0.031	0.050	0.062	0.081	0.189
WTG A08	0.025	0.025	0.037	0.044	0.057	0.127
WTG A09	0.025	0.025	0.036	0.043	0.055	0.122
WTG B01	0.020	0.020	0.026	0.028	0.030	0.035
WTG B02	0.019	0.019	0.024	0.026	0.028	0.033
WTG B03	0.017	0.017	0.022	0.023	0.025	0.030
WTG B04	0.016	0.016	0.021	0.022	0.024	0.028
WTG B05	0.015	0.015	0.019	0.020	0.022	0.026
WTG B06	0.014	0.014	0.018	0.019	0.021	0.026
WTG B07	0.014	0.014	0.017	0.018	0.020	0.024
WTG B08	0.013	0.013	0.017	0.018	0.019	0.023
WTG B09	0.013	0.013	0.016	0.017	0.019	0.023
WTG C01	0.012	0.012	0.014	0.015	0.016	0.019
WTG C02	0.011	0.011	0.013	0.014	0.014	0.017
WTG C03	0.010	0.010	0.012	0.012	0.013	0.015
WTG C04	0.010	0.010	0.011	0.012	0.012	0.014
WTG C05	0.010	0.010	0.011	0.012	0.012	0.014
WTG C06	0.009	0.009	0.010	0.011	0.011	0.013
WTG C07	0.009	0.009	0.010	0.010	0.011	0.012
WTG C08	0.008	0.008	0.010	0.010	0.011	0.012
WTG D01	0.032	0.032	0.043	0.044	0.043	0.031
WTG D02	0.033	0.033	0.043	0.045	0.044	0.030

APPENDIX 6: TOUCH & STEP POTENTIAL PLOTS

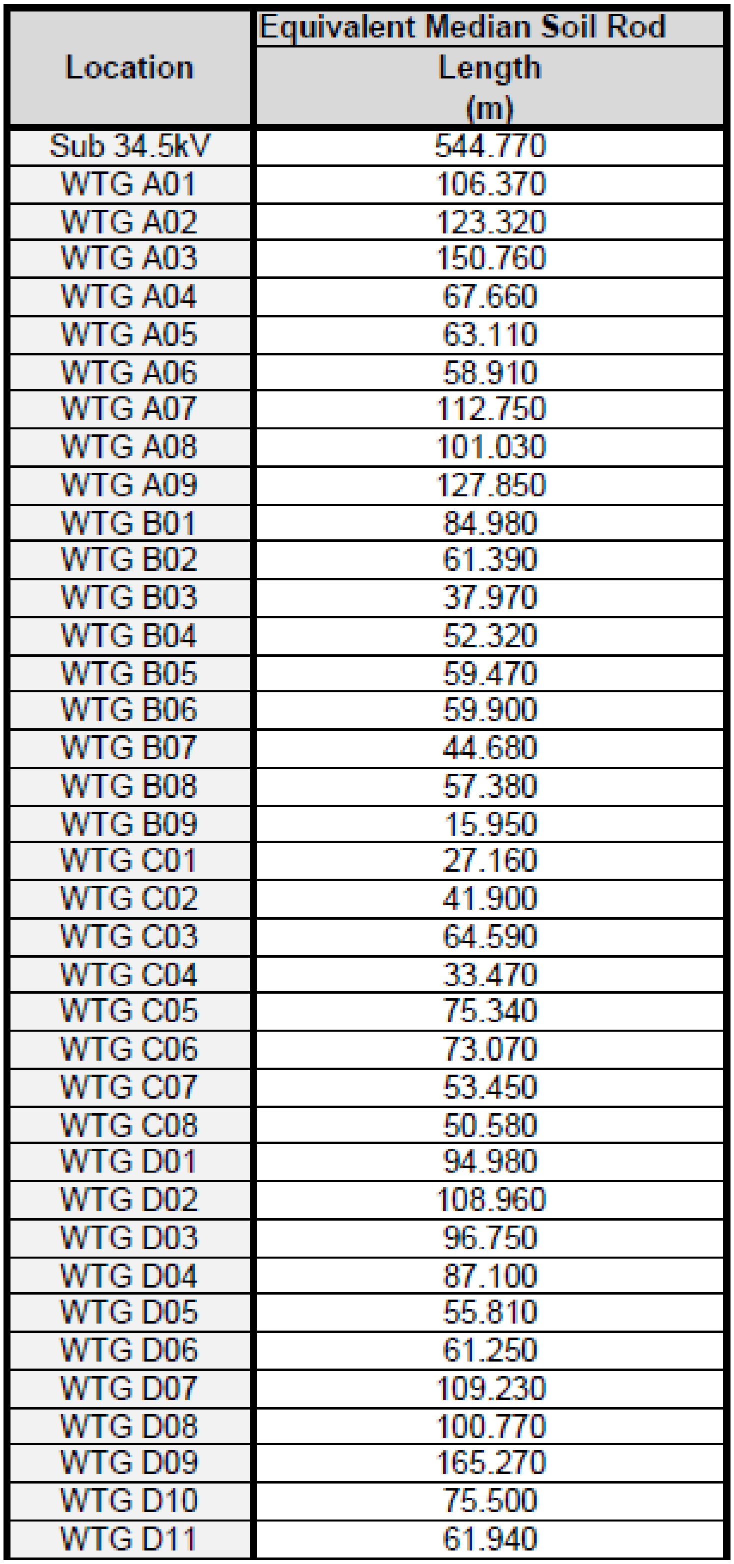


Touch Potential Plot – Turbine No. A01



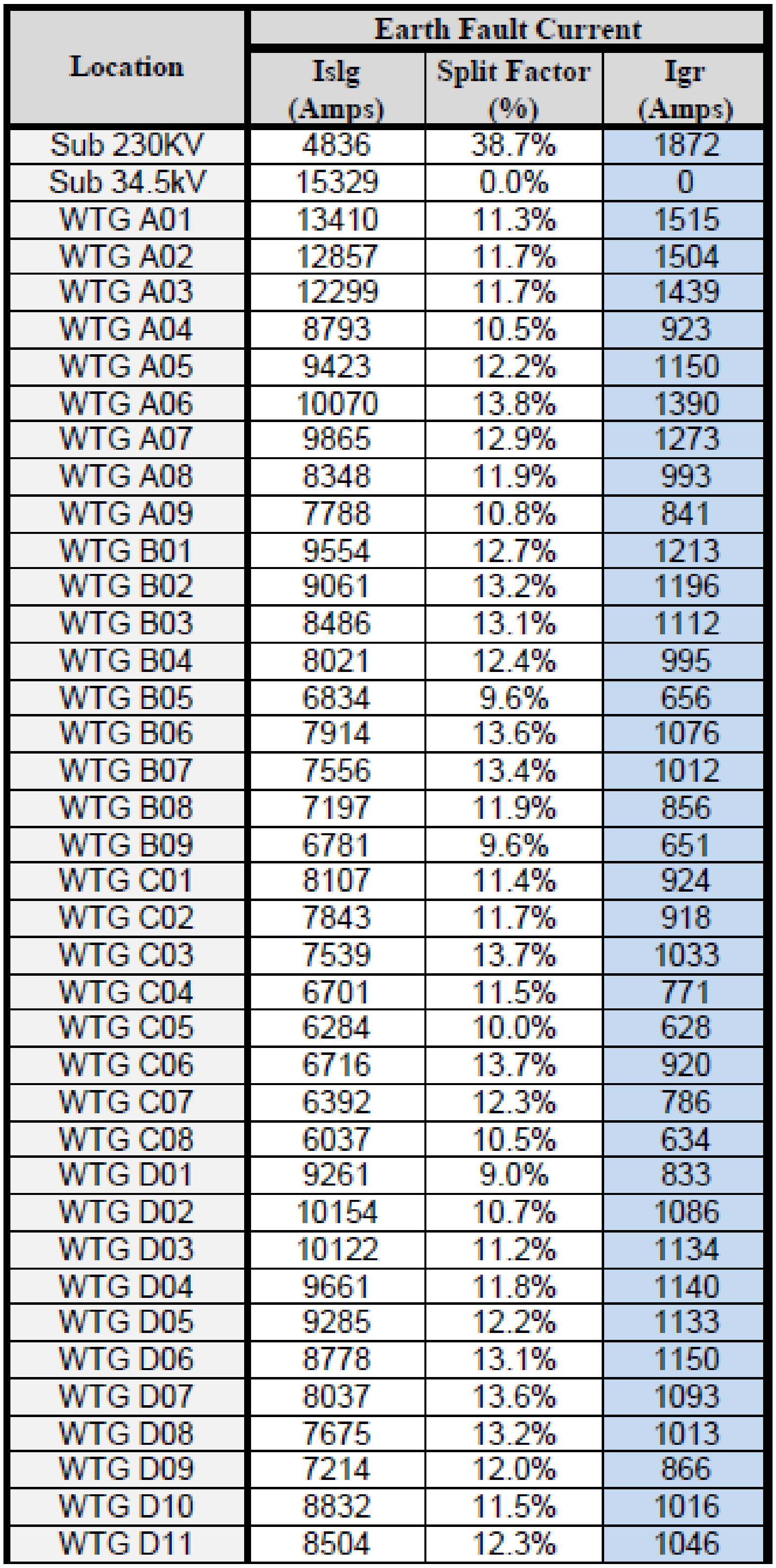
Step Potential Plot – Turbine No. A01

APPENDIX 7: EQUIVALENT ROD LENGTHS



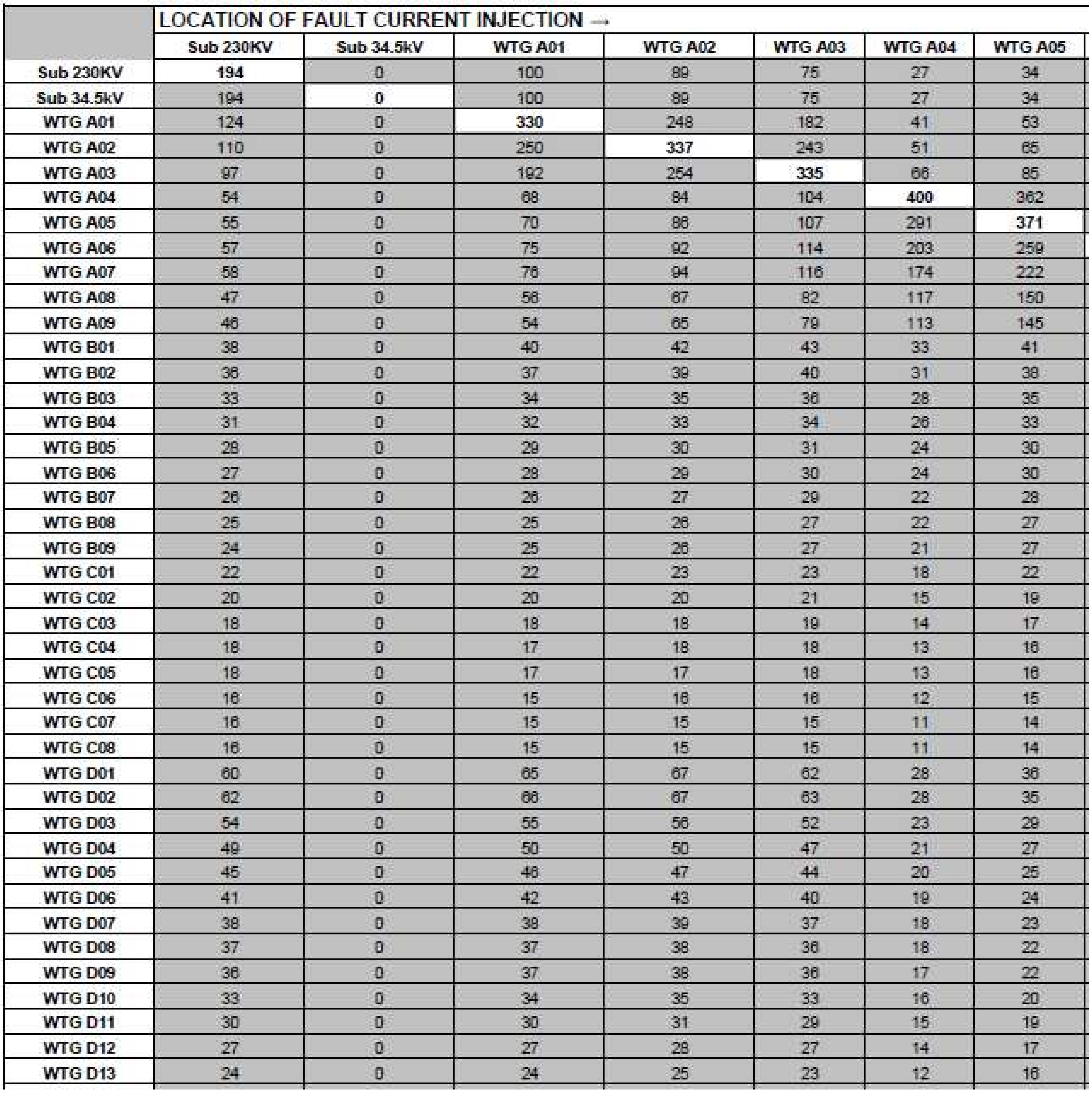
Location	Equivalent Median Soil Rod Length (m)
Sub 34.5kV	544.770
WTG A01	106.370
WTG A02	123.320
WTG A03	150.760
WTG A04	67.660
WTG A05	63.110
WTG A06	58.910
WTG A07	112.750
WTG A08	101.030
WTG A09	127.850
WTG B01	84.980
WTG B02	61.390
WTG B03	37.970
WTG B04	52.320
WTG B05	59.470
WTG B06	59.900
WTG B07	44.680
WTG B08	57.380
WTG B09	15.950
WTG C01	27.160
WTG C02	41.900
WTG C03	64.590
WTG C04	33.470
WTG C05	75.340
WTG C06	73.070
WTG C07	53.450
WTG C08	50.580
WTG D01	94.980
WTG D02	108.960
WTG D03	96.750
WTG D04	87.100
WTG D05	55.810
WTG D06	61.250
WTG D07	109.230
WTG D08	100.770
WTG D09	165.270
WTG D10	75.500
WTG D11	61.940

APPENDIX 8: FAULT CURRENT SCHEDULE



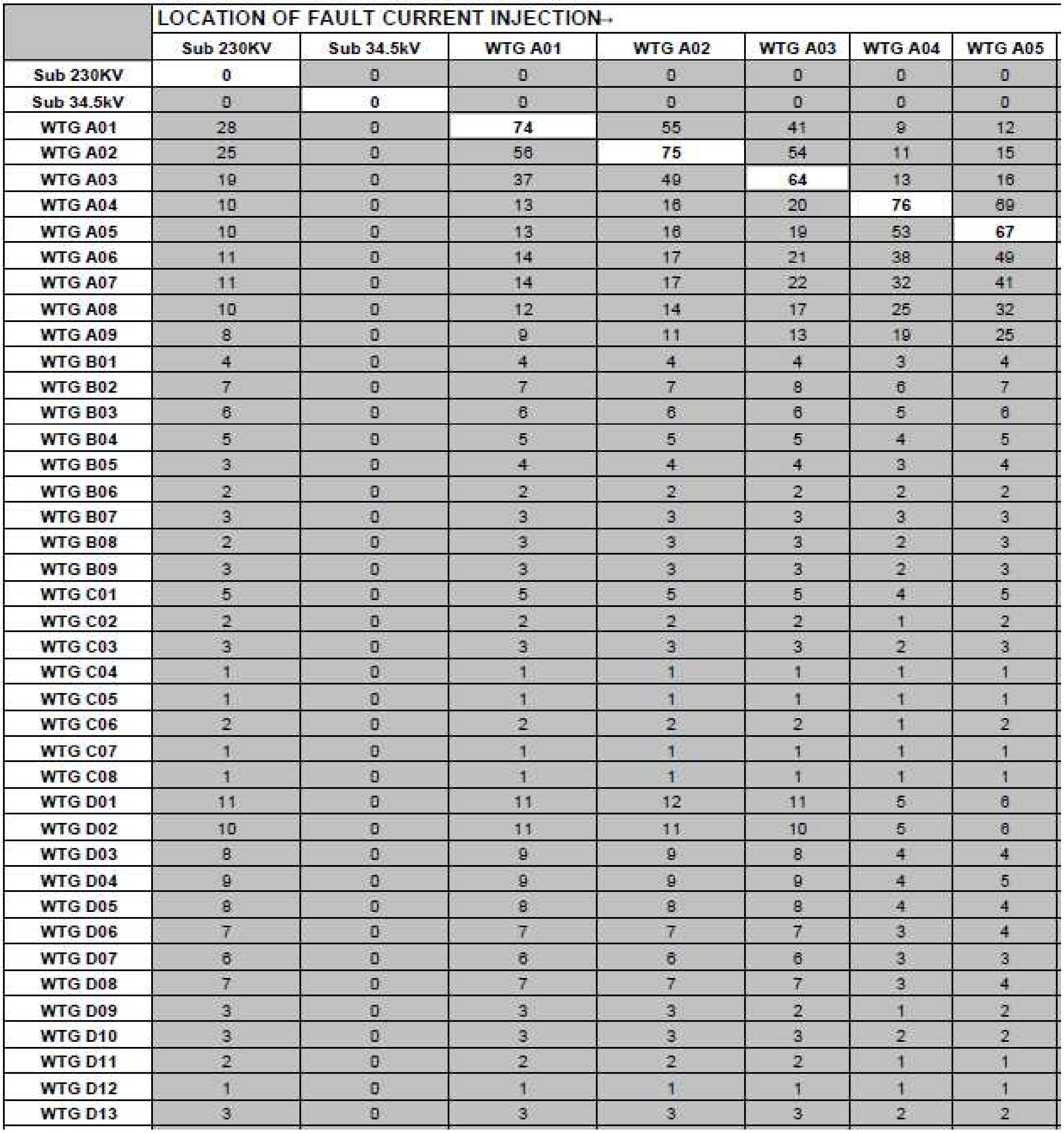
Location	Earth Fault Current		
	Islg (Amps)	Split Factor (%)	Igr (Amps)
Sub 230KV	4836	38.7%	1872
Sub 34.5kV	15329	0.0%	0
WTG A01	13410	11.3%	1515
WTG A02	12857	11.7%	1504
WTG A03	12299	11.7%	1439
WTG A04	8793	10.5%	923
WTG A05	9423	12.2%	1150
WTG A06	10070	13.8%	1390
WTG A07	9865	12.9%	1273
WTG A08	8348	11.9%	993
WTG A09	7788	10.8%	841
WTG B01	9554	12.7%	1213
WTG B02	9061	13.2%	1196
WTG B03	8486	13.1%	1112
WTG B04	8021	12.4%	995
WTG B05	6834	9.6%	656
WTG B06	7914	13.6%	1076
WTG B07	7556	13.4%	1012
WTG B08	7197	11.9%	856
WTG B09	6781	9.6%	651
WTG C01	8107	11.4%	924
WTG C02	7843	11.7%	918
WTG C03	7539	13.7%	1033
WTG C04	6701	11.5%	771
WTG C05	6284	10.0%	628
WTG C06	6716	13.7%	920
WTG C07	6392	12.3%	786
WTG C08	6037	10.5%	634
WTG D01	9261	9.0%	833
WTG D02	10154	10.7%	1086
WTG D03	10122	11.2%	1134
WTG D04	9661	11.8%	1140
WTG D05	9285	12.2%	1133
WTG D06	8778	13.1%	1150
WTG D07	8037	13.6%	1093
WTG D08	7675	13.2%	1013
WTG D09	7214	12.0%	866
WTG D10	8832	11.5%	1016
WTG D11	8504	12.3%	1046

APPENDIX 9: GROUND POTENTIAL RISE MATRIX



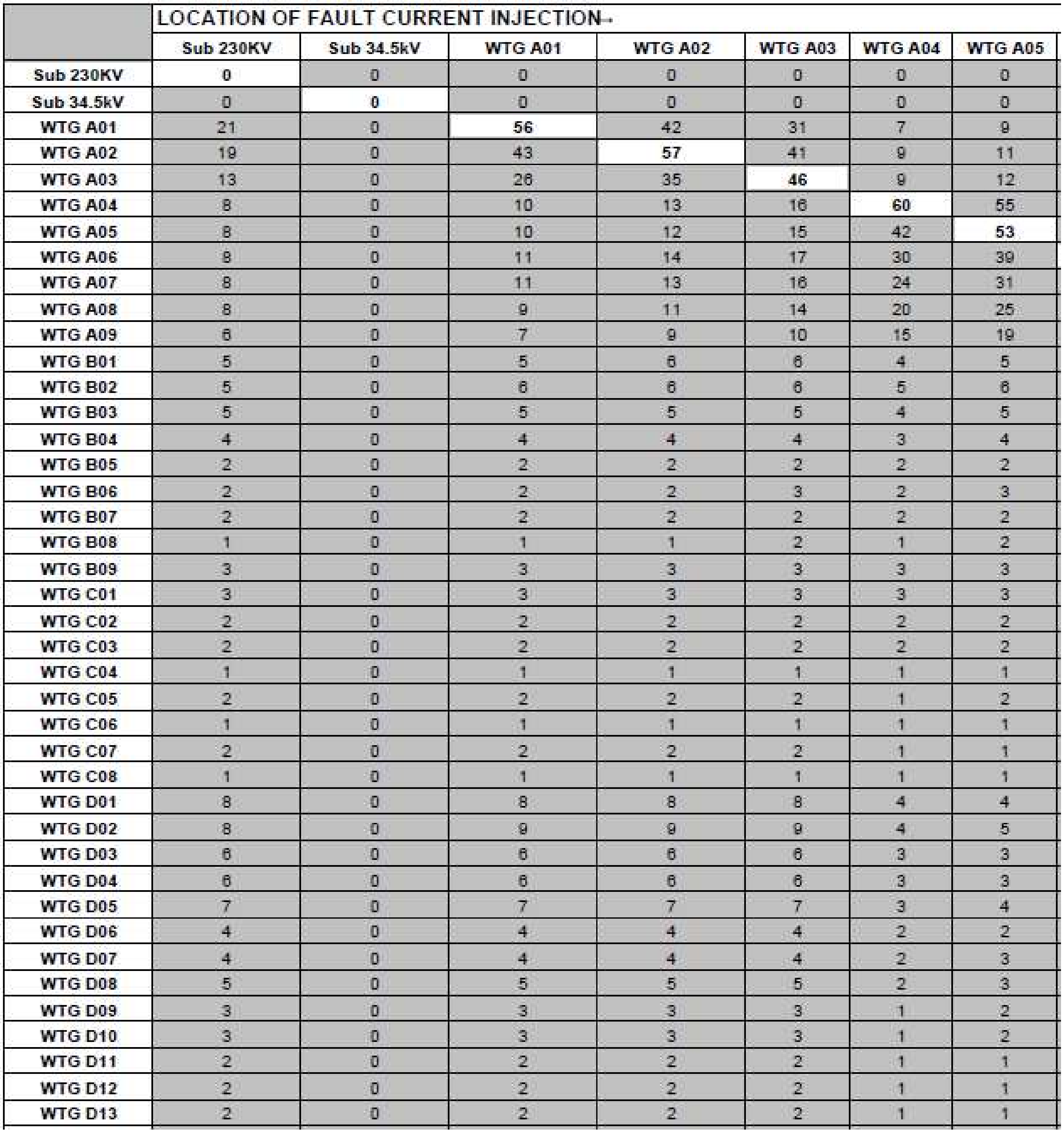
	LOCATION OF FAULT CURRENT INJECTION →						
	Sub 230KV	Sub 34.5kV	WTG A01	WTG A02	WTG A03	WTG A04	WTG A05
Sub 230KV	**194**	0	100	89	75	27	34
Sub 34.5kV	194	**0**	100	89	75	27	34
WTG A01	124	0	**330**	248	182	41	53
WTG A02	110	0	250	**337**	243	51	65
WTG A03	97	0	192	254	**335**	66	85
WTG A04	54	0	68	84	104	**400**	362
WTG A05	55	0	70	86	107	291	**371**
WTG A06	57	0	75	92	114	203	259
WTG A07	58	0	76	94	116	174	222
WTG A08	47	0	56	67	82	117	150
WTG A09	46	0	54	65	79	113	145
WTG B01	38	0	40	42	43	33	41
WTG B02	36	0	37	39	40	31	38
WTG B03	33	0	34	35	36	28	35
WTG B04	31	0	32	33	34	26	33
WTG B05	28	0	29	30	31	24	30
WTG B06	27	0	28	29	30	24	30
WTG B07	26	0	26	27	29	22	28
WTG B08	25	0	25	26	27	22	27
WTG B09	24	0	25	26	27	21	27
WTG C01	22	0	22	23	23	18	22
WTG C02	20	0	20	20	21	15	19
WTG C03	18	0	18	18	19	14	17
WTG C04	18	0	17	18	18	13	16
WTG C05	18	0	17	17	18	13	16
WTG C06	16	0	15	16	16	12	15
WTG C07	16	0	15	15	15	11	14
WTG C08	16	0	15	15	15	11	14
WTG D01	60	0	65	67	62	28	36
WTG D02	62	0	66	67	63	28	35
WTG D03	54	0	55	56	52	23	29
WTG D04	49	0	50	50	47	21	27
WTG D05	45	0	46	47	44	20	25
WTG D06	41	0	42	43	40	19	24
WTG D07	38	0	38	39	37	18	23
WTG D08	37	0	37	38	36	18	22
WTG D09	36	0	37	38	36	17	22
WTG D10	33	0	34	35	33	16	20
WTG D11	30	0	30	31	29	15	19
WTG D12	27	0	27	28	27	14	17
WTG D13	24	0	24	25	23	12	16

APPENDIX 10.1: TOUCH VOLTAGE MATRIX



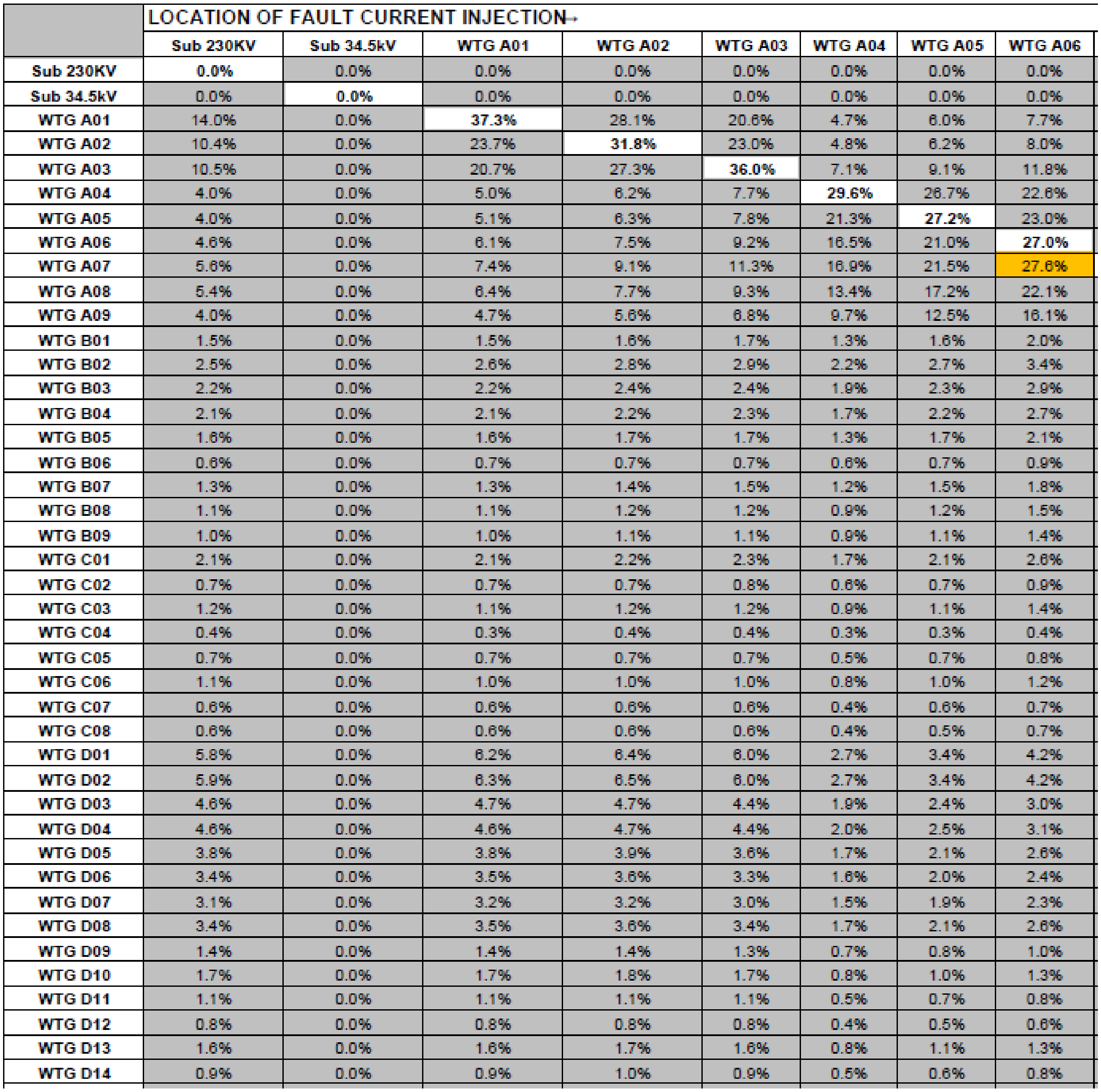
	LOCATION OF FAULT CURRENT INJECTION→						
	Sub 230KV	Sub 34.5kV	WTG A01	WTG A02	WTG A03	WTG A04	WTG A05
Sub 230KV	0	0	0	0	0	0	0
Sub 34.5kV	0	0	0	0	0	0	0
WTG A01	28	0	74	55	41	9	12
WTG A02	25	0	56	75	54	11	15
WTG A03	19	0	37	49	64	13	16
WTG A04	10	0	13	16	20	76	69
WTG A05	10	0	13	16	19	53	67
WTG A06	11	0	14	17	21	38	49
WTG A07	11	0	14	17	22	32	41
WTG A08	10	0	12	14	17	25	32
WTG A09	8	0	9	11	13	19	25
WTG B01	4	0	4	4	4	3	4
WTG B02	7	0	7	7	8	6	7
WTG B03	6	0	6	6	6	5	6
WTG B04	5	0	5	5	5	4	5
WTG B05	3	0	4	4	4	3	4
WTG B06	2	0	2	2	2	2	2
WTG B07	3	0	3	3	3	3	3
WTG B08	2	0	3	3	3	2	3
WTG B09	3	0	3	3	3	2	3
WTG C01	5	0	5	5	5	4	5
WTG C02	2	0	2	2	2	1	2
WTG C03	3	0	3	3	3	2	3
WTG C04	1	0	1	1	1	1	1
WTG C05	1	0	1	1	1	1	1
WTG C06	2	0	2	2	2	1	2
WTG C07	1	0	1	1	1	1	1
WTG C08	1	0	1	1	1	1	1
WTG D01	11	0	11	12	11	5	6
WTG D02	10	0	11	11	10	5	6
WTG D03	8	0	9	9	8	4	4
WTG D04	9	0	9	9	9	4	5
WTG D05	8	0	8	8	8	4	4
WTG D06	7	0	7	7	7	3	4
WTG D07	6	0	6	6	6	3	3
WTG D08	7	0	7	7	7	3	4
WTG D09	3	0	3	3	2	1	2
WTG D10	3	0	3	3	3	2	2
WTG D11	2	0	2	2	2	1	1
WTG D12	1	0	1	1	1	1	1
WTG D13	3	0	3	3	3	2	2

APPENDIX 10.2: STEP VOLTAGE MATRIX



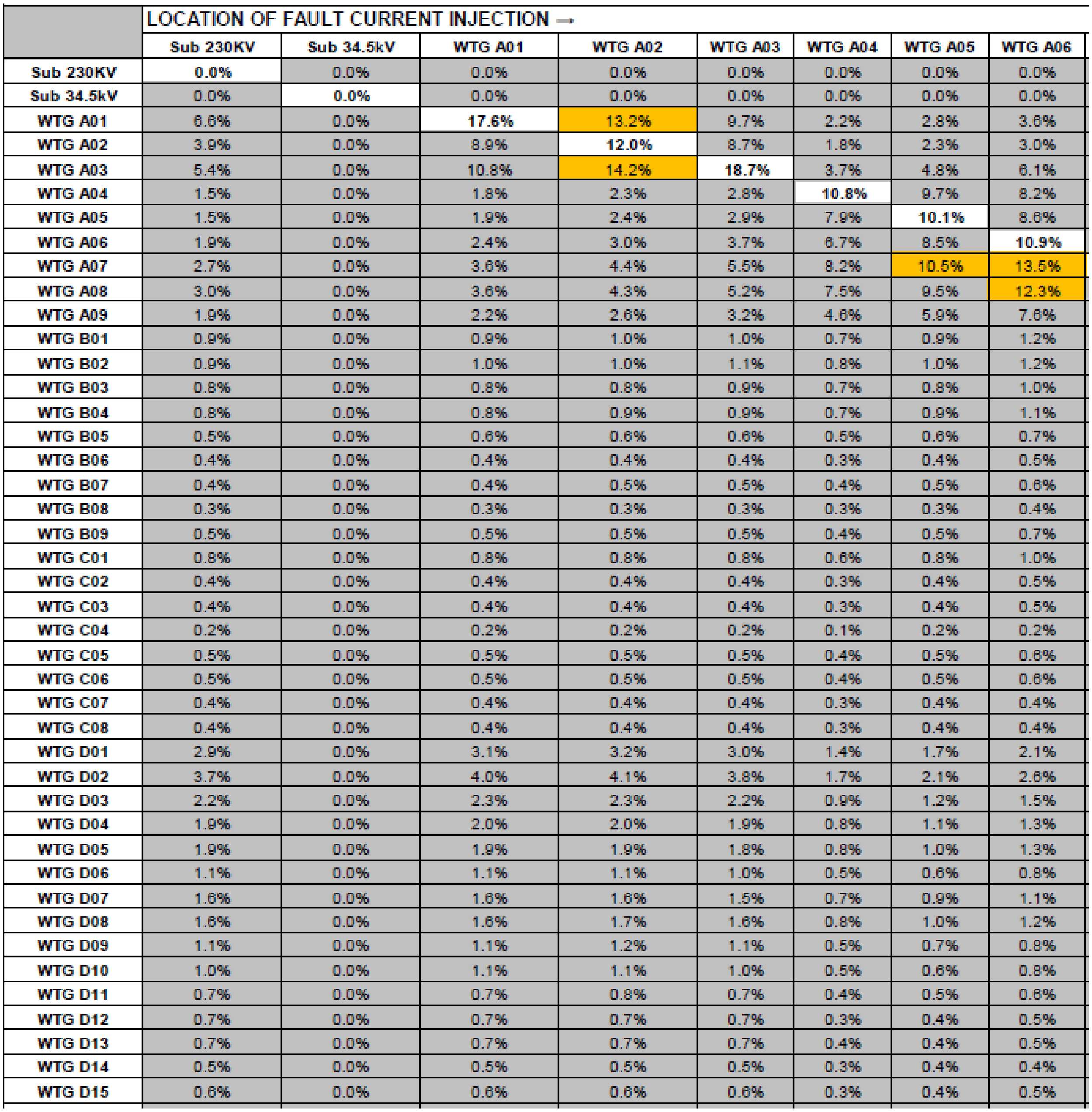
	LOCATION OF FAULT CURRENT INJECTION→						
	Sub 230KV	Sub 34.5kV	WTG A01	WTG A02	WTG A03	WTG A04	WTG A05
Sub 230KV	0	0	0	0	0	0	0
Sub 34.5kV	0	0	0	0	0	0	0
WTG A01	21	0	56	42	31	7	9
WTG A02	19	0	43	57	41	9	11
WTG A03	13	0	26	35	46	9	12
WTG A04	8	0	10	13	16	60	55
WTG A05	8	0	10	12	15	42	53
WTG A06	8	0	11	14	17	30	39
WTG A07	8	0	11	13	16	24	31
WTG A08	8	0	9	11	14	20	25
WTG A09	6	0	7	9	10	15	19
WTG B01	5	0	5	6	6	4	5
WTG B02	5	0	6	6	6	5	6
WTG B03	5	0	5	5	5	4	5
WTG B04	4	0	4	4	4	3	4
WTG B05	2	0	2	2	2	2	2
WTG B06	2	0	2	2	3	2	3
WTG B07	2	0	2	2	2	2	2
WTG B08	1	0	1	1	2	1	2
WTG B09	3	0	3	3	3	3	3
WTG C01	3	0	3	3	3	3	3
WTG C02	2	0	2	2	2	2	2
WTG C03	2	0	2	2	2	2	2
WTG C04	1	0	1	1	1	1	1
WTG C05	2	0	2	2	2	1	2
WTG C06	1	0	1	1	1	1	1
WTG C07	2	0	2	2	2	1	1
WTG C08	1	0	1	1	1	1	1
WTG D01	8	0	8	8	8	4	4
WTG D02	8	0	9	9	9	4	5
WTG D03	6	0	6	6	6	3	3
WTG D04	6	0	6	6	6	3	3
WTG D05	7	0	7	7	7	3	4
WTG D06	4	0	4	4	4	2	2
WTG D07	4	0	4	4	4	2	3
WTG D08	5	0	5	5	5	2	3
WTG D09	3	0	3	3	3	1	2
WTG D10	3	0	3	3	3	1	2
WTG D11	2	0	2	2	2	1	1
WTG D12	2	0	2	2	2	1	1
WTG D13	2	0	2	2	2	1	1

APPENDIX 11.1: TOUCH VOLTATGE % OF SAFETY



	LOCATION OF FAULT CURRENT INJECTION→							
	Sub 230KV	Sub 34.5kV	WTG A01	WTG A02	WTG A03	WTG A04	WTG A05	WTG A06
Sub 230KV	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Sub 34.5kV	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
WTG A01	14.0%	0.0%	37.3%	28.1%	20.6%	4.7%	6.0%	7.7%
WTG A02	10.4%	0.0%	23.7%	31.8%	23.0%	4.8%	6.2%	8.0%
WTG A03	10.5%	0.0%	20.7%	27.3%	36.0%	7.1%	9.1%	11.8%
WTG A04	4.0%	0.0%	5.0%	6.2%	7.7%	29.6%	26.7%	22.6%
WTG A05	4.0%	0.0%	5.1%	6.3%	7.8%	21.3%	27.2%	23.0%
WTG A06	4.6%	0.0%	6.1%	7.5%	9.2%	16.5%	21.0%	27.0%
WTG A07	5.6%	0.0%	7.4%	9.1%	11.3%	16.9%	21.5%	27.6%
WTG A08	5.4%	0.0%	6.4%	7.7%	9.3%	13.4%	17.2%	22.1%
WTG A09	4.0%	0.0%	4.7%	5.6%	6.8%	9.7%	12.5%	16.1%
WTG B01	1.5%	0.0%	1.5%	1.6%	1.7%	1.3%	1.6%	2.0%
WTG B02	2.5%	0.0%	2.6%	2.8%	2.9%	2.2%	2.7%	3.4%
WTG B03	2.2%	0.0%	2.2%	2.4%	2.4%	1.9%	2.3%	2.9%
WTG B04	2.1%	0.0%	2.1%	2.2%	2.3%	1.7%	2.2%	2.7%
WTG B05	1.6%	0.0%	1.6%	1.7%	1.7%	1.3%	1.7%	2.1%
WTG B06	0.6%	0.0%	0.7%	0.7%	0.7%	0.6%	0.7%	0.9%
WTG B07	1.3%	0.0%	1.3%	1.4%	1.5%	1.2%	1.5%	1.8%
WTG B08	1.1%	0.0%	1.1%	1.2%	1.2%	0.9%	1.2%	1.5%
WTG B09	1.0%	0.0%	1.0%	1.1%	1.1%	0.9%	1.1%	1.4%
WTG C01	2.1%	0.0%	2.1%	2.2%	2.3%	1.7%	2.1%	2.6%
WTG C02	0.7%	0.0%	0.7%	0.7%	0.8%	0.6%	0.7%	0.9%
WTG C03	1.2%	0.0%	1.1%	1.2%	1.2%	0.9%	1.1%	1.4%
WTG C04	0.4%	0.0%	0.3%	0.4%	0.4%	0.3%	0.3%	0.4%
WTG C05	0.7%	0.0%	0.7%	0.7%	0.7%	0.5%	0.7%	0.8%
WTG C06	1.1%	0.0%	1.0%	1.0%	1.0%	0.8%	1.0%	1.2%
WTG C07	0.6%	0.0%	0.6%	0.6%	0.6%	0.4%	0.6%	0.7%
WTG C08	0.6%	0.0%	0.6%	0.6%	0.6%	0.4%	0.5%	0.7%
WTG D01	5.8%	0.0%	6.2%	6.4%	6.0%	2.7%	3.4%	4.2%
WTG D02	5.9%	0.0%	6.3%	6.5%	6.0%	2.7%	3.4%	4.2%
WTG D03	4.6%	0.0%	4.7%	4.7%	4.4%	1.9%	2.4%	3.0%
WTG D04	4.6%	0.0%	4.6%	4.7%	4.4%	2.0%	2.5%	3.1%
WTG D05	3.8%	0.0%	3.8%	3.9%	3.6%	1.7%	2.1%	2.6%
WTG D06	3.4%	0.0%	3.5%	3.6%	3.3%	1.6%	2.0%	2.4%
WTG D07	3.1%	0.0%	3.2%	3.2%	3.0%	1.5%	1.9%	2.3%
WTG D08	3.4%	0.0%	3.5%	3.6%	3.4%	1.7%	2.1%	2.6%
WTG D09	1.4%	0.0%	1.4%	1.4%	1.3%	0.7%	0.8%	1.0%
WTG D10	1.7%	0.0%	1.7%	1.8%	1.7%	0.8%	1.0%	1.3%
WTG D11	1.1%	0.0%	1.1%	1.1%	1.1%	0.5%	0.7%	0.8%
WTG D12	0.8%	0.0%	0.8%	0.8%	0.8%	0.4%	0.5%	0.6%
WTG D13	1.6%	0.0%	1.6%	1.7%	1.6%	0.8%	1.1%	1.3%
WTG D14	0.9%	0.0%	0.9%	1.0%	0.9%	0.5%	0.6%	0.8%

APPENDIX 11.2 STEP VOLTAGE % OF SAFETY



	LOCATION OF FAULT CURRENT INJECTION →							
	Sub 230KV	Sub 34.5kV	WTG A01	WTG A02	WTG A03	WTG A04	WTG A05	WTG A06
Sub 230KV	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Sub 34.5kV	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
WTG A01	6.6%	0.0%	17.6%	13.2%	9.7%	2.2%	2.8%	3.6%
WTG A02	3.9%	0.0%	8.9%	12.0%	8.7%	1.8%	2.3%	3.0%
WTG A03	5.4%	0.0%	10.8%	14.2%	18.7%	3.7%	4.8%	6.1%
WTG A04	1.5%	0.0%	1.8%	2.3%	2.8%	10.8%	9.7%	8.2%
WTG A05	1.5%	0.0%	1.9%	2.4%	2.9%	7.9%	10.1%	8.6%
WTG A06	1.9%	0.0%	2.4%	3.0%	3.7%	6.7%	8.5%	10.9%
WTG A07	2.7%	0.0%	3.6%	4.4%	5.5%	8.2%	10.5%	13.5%
WTG A08	3.0%	0.0%	3.6%	4.3%	5.2%	7.5%	9.5%	12.3%
WTG A09	1.9%	0.0%	2.2%	2.6%	3.2%	4.6%	5.9%	7.6%
WTG B01	0.9%	0.0%	0.9%	1.0%	1.0%	0.7%	0.9%	1.2%
WTG B02	0.9%	0.0%	1.0%	1.0%	1.1%	0.8%	1.0%	1.2%
WTG B03	0.8%	0.0%	0.8%	0.8%	0.9%	0.7%	0.8%	1.0%
WTG B04	0.8%	0.0%	0.8%	0.9%	0.9%	0.7%	0.9%	1.1%
WTG B05	0.5%	0.0%	0.6%	0.6%	0.6%	0.5%	0.6%	0.7%
WTG B06	0.4%	0.0%	0.4%	0.4%	0.4%	0.3%	0.4%	0.5%
WTG B07	0.4%	0.0%	0.4%	0.5%	0.5%	0.4%	0.5%	0.6%
WTG B08	0.3%	0.0%	0.3%	0.3%	0.3%	0.3%	0.3%	0.4%
WTG B09	0.5%	0.0%	0.5%	0.5%	0.5%	0.4%	0.5%	0.7%
WTG C01	0.8%	0.0%	0.8%	0.8%	0.8%	0.6%	0.8%	1.0%
WTG C02	0.4%	0.0%	0.4%	0.4%	0.4%	0.3%	0.4%	0.5%
WTG C03	0.4%	0.0%	0.4%	0.4%	0.4%	0.3%	0.4%	0.5%
WTG C04	0.2%	0.0%	0.2%	0.2%	0.2%	0.1%	0.2%	0.2%
WTG C05	0.5%	0.0%	0.5%	0.5%	0.5%	0.4%	0.5%	0.6%
WTG C06	0.5%	0.0%	0.5%	0.5%	0.5%	0.4%	0.5%	0.6%
WTG C07	0.4%	0.0%	0.4%	0.4%	0.4%	0.3%	0.4%	0.4%
WTG C08	0.4%	0.0%	0.4%	0.4%	0.4%	0.3%	0.4%	0.4%
WTG D01	2.9%	0.0%	3.1%	3.2%	3.0%	1.4%	1.7%	2.1%
WTG D02	3.7%	0.0%	4.0%	4.1%	3.8%	1.7%	2.1%	2.6%
WTG D03	2.2%	0.0%	2.3%	2.3%	2.2%	0.9%	1.2%	1.5%
WTG D04	1.9%	0.0%	2.0%	2.0%	1.9%	0.8%	1.1%	1.3%
WTG D05	1.9%	0.0%	1.9%	1.9%	1.8%	0.8%	1.0%	1.3%
WTG D06	1.1%	0.0%	1.1%	1.1%	1.0%	0.5%	0.6%	0.8%
WTG D07	1.6%	0.0%	1.6%	1.6%	1.5%	0.7%	0.9%	1.1%
WTG D08	1.6%	0.0%	1.6%	1.7%	1.6%	0.8%	1.0%	1.2%
WTG D09	1.1%	0.0%	1.1%	1.2%	1.1%	0.5%	0.7%	0.8%
WTG D10	1.0%	0.0%	1.1%	1.1%	1.0%	0.5%	0.6%	0.8%
WTG D11	0.7%	0.0%	0.7%	0.8%	0.7%	0.4%	0.5%	0.6%
WTG D12	0.7%	0.0%	0.7%	0.7%	0.7%	0.3%	0.4%	0.5%
WTG D13	0.7%	0.0%	0.7%	0.7%	0.7%	0.4%	0.4%	0.5%
WTG D14	0.5%	0.0%	0.5%	0.5%	0.5%	0.3%	0.4%	0.4%
WTG D15	0.6%	0.0%	0.6%	0.6%	0.6%	0.3%	0.4%	0.5%