Designing Earthing Systems for Onshore Wind Farm Sites

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Abstract

With the demand for renewable power generation increasing and with public pressure stressing a viable alternative to the current thermal and nuclear convention, wind generation has been a growing market in the last couple of decades. This technology is relatively new when compared to the latter implementations and it therefore comes with several challenges. This investigation focusses on designing earthing systems for these wind farm sites and the procedures behind reducing any fault current and consequently large potentials that arise on site and become a threat to human life and damage equipment on site.

This project analyses two wind farm sites, namely Wind Farm A and Wind Farm B. It is noticeable from the Rise of Earth Potential calculations that the first is considered a COLD site as it has a maximum voltage less than 430V (for fault duration greater than 200ms) while the latter is a HOT site as the maximum voltage surpasses that limit. This difference in potentials ultimately affects the earth grid design as it’s evident the HOT site requires a lot more earthing tools in order to lower the ground potential to acceptable limits. The achievement of all the objectives established prior to commencing the project suggests this investigation can be considered successful.
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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho_{app} )</td>
<td>Apparent Resistivity (Ω.m)</td>
</tr>
<tr>
<td>( R_{app} )</td>
<td>Apparent Resistance (Ω)</td>
</tr>
<tr>
<td>( a )</td>
<td>Spacing Between Wenner Soil Probes (m)</td>
</tr>
<tr>
<td>( I )</td>
<td>Fault Current in Amps (A)</td>
</tr>
<tr>
<td>( t )</td>
<td>Operating time of disconnecting device</td>
</tr>
<tr>
<td>( k )</td>
<td>Constant; accounts for resistivity, temperature coefficient and heat capacity</td>
</tr>
<tr>
<td>( S )</td>
<td>Nominal Cross Sectional Area, mm(^2)</td>
</tr>
<tr>
<td>( E_{\text{Step}} )</td>
<td>Step Voltage in Volts (V)</td>
</tr>
<tr>
<td>( E_{\text{Touch}} )</td>
<td>Touch Voltage in Volts (V)</td>
</tr>
<tr>
<td>( R_f )</td>
<td>Ground Resistance of one foot (Ω)</td>
</tr>
<tr>
<td>( R_B )</td>
<td>Human Body Resistance (Ω)</td>
</tr>
<tr>
<td>( I_B )</td>
<td>RMS Magnitude of Current Through Body (A)</td>
</tr>
</tbody>
</table>
“Logic will get you from A to Z; imagination will get you everywhere.”

*Albert Einstein*
1. **Introduction**

With consumers becoming increasingly aware about climate change, there has been greater focus on shifting towards renewables. When this is not possible then companies attempt to make their products as energy efficient as possible. The auto industry for instance is completely drawn to making their cars fuel efficient and invest substantial amounts of money to beat the competition in this research.

The same trend is observed in power generation. The renewable option still occupies a fairly low share on the total production of electricity due to the fact that it is still considered a relatively new technology when compared to the non-renewable alternatives. It was also believed the latter has a significantly larger energy density and this contributed towards its increased popularity. However, the public pressure to undertake a more environmentally considerate approach has resulted in a shift of policy whereby power generation companies investigated how the renewable options could enhance the network and this lead to an increase in the construction of wind farms. As a result of this augmented popularity there has been a boost in the investment of both on shore and off shore wind farms. There are various challenges when constructing a wind farm and this is because it is a relatively new technology in power generation when compared to the thermal and nuclear convention power generation. One of the challenges involves designing the wind farm’s earthing system.

The study of earthing designs can be considered on its own a niche area of research that requires particular care as it is ultimately responsible for people’s safety in the vicinity of the wind farm site\(^1\)\(^2\) and essentially protects any equipment\(^3\) from potential fault currents that may arise and lightning strikes.

In addition to finding this topic highly relevant from an academic perspective, the industrial perspective is equally interesting. There appears to be a more practical approach when addressing this project when the latter point of view is considered. In other words, despite the theory still being relevant in delivering the project, there is a very important factor to consider and this is the cost effectiveness of the various choices presented to the client. For instance, the client will naturally want cut down on the use of copper where possible and use wires with smaller cross sectional areas in order to diminish costs. This experience is extremely beneficial and truly rewarding as it offers a new outlook on delivering projects. The responsibilities entailed in the project are an additional reason why it was considered for this technical investigation.
1.1. Project Overview

This investigation attempts to evaluate the importance and principles behind designing an effective earthing system for wind turbine generators (WTGs) and substations. In addition, the damage that a possible fault current in the wind farm site or even a lightning strike can cause to the equipment is another reason why companies are focused on solving this issue. It is all a matter of following International and National Regulations and Standards imposed by the International Electrotechnical Commission and the British Standards for instance. Furthermore, it is naturally beneficial for the companies as it helps avoid unnecessary costs in the future if a person’s life is at risk or even the equipment in the site is damaged due to a fault.

There are three main considerations when designing an adequate earthing system. The first consists in measuring the site’s soil resistivity, the rockier the site the higher the resistivity. After collecting this on site information and consequently determining the site’s multilayer soil model, the earth grid design is combined in order to obtain the overall site impedance. This impedance is then used to determine the site’s Rise of Earth Potential (RoEP), i.e. the maximum voltage that can arise on site during a phase-earth fault. According to the IEEE Std 367-2012, the Rise of Earth Potential is defined as “The product of a ground electrode impedance, referenced to remote earth, and the current that flows through that electrode impedance” [4]. This is the second main consideration in an earthing design.

The final deliberation involves combining the Rise of Earth Potential with the earth grid design in order to find the touch and step potentials. The earthing design process can be seen in the flow chart below.

It is noticeable that the earthing grid design is an iterative process whereby you determine an initial design and verify whether the output is acceptable, i.e. whether the touch and step potential conforms with the tolerable limits, if not the design will have to be modified.

This earthing report will cover two case studies that will be known as Wind Farm A and Wind Farm B and the purpose of this is to demonstrate the process behind the wind farm’s earth grid.
1.2. Aims and Objectives

Prior to undertaking any project significant milestones must be set defining the main tasks that should be accomplished. There are three main parts to this investigation. The first stage consists in identifying the wind farm site’s average soil model through the obtained resistivity measurements. Subsequently, the Rise of Earth Potential can be determined by applying the known fault current through the calculated system impedance. The Rise of Earth Potential is tremendously important in the design of earthing systems as it establishes the maximum voltage that can arise in the site. The third and last stage involves calculating the touch and step potentials and the ground impedances for the various wind turbine generators (WTGs) and substations.

The main objective consists in achieving the defined milestones and obtaining the desired results for the different sites being considered in this project. Additional objectives include:

- Enhance knowledge on designing earthing systems.
• Understand how each stage complements the next, for instance the Rise of Earth Potential helps determine the touch and step potentials for each turbine.
• Gain experience in dealing with client requests.
• Using practical considerations in theoretical designs.

2. Literature Review

2.1. Soil Resistance and Resistivity

The base of any earthing design is to primarily obtain accurate measurements of the site and this includes soil resistance measurements. The first parameter is particularly relevant to earthing designs as it is directly proportional to the soil resistivity. The purpose of undertaking soil resistivity measurements is to come up with an accurate model of the soil structure at the site that features multiple resistivity layers, i.e. the multilayer theory. The resistivity value (measured in Ohm-metres, Ω-m) is influenced by two main factors, the porosity of the soil and the electrolyte concentration provided there is water within the soil [5].

The resistivity determines a property’s ability to conduct electricity. Good conductors are deemed to have low resistance as they do not impose large obstruction to current flow. Similarly, these materials have low resistivity due to the direct proportionality with the resistance of the material [6].

An accurate measurement of the soil resistance and consequently its resistivity is paramount. Incorrect values lead to an inadequate design and can have hazardous effects to both the people in the site and the equipment. Soil resistivity can vary significantly depending on the nature of the local ground. Typical resistivity values of different soil ground materials are shown below.

<table>
<thead>
<tr>
<th>Type</th>
<th>Resistivity (Ω-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea Water</td>
<td>0.1-10</td>
</tr>
<tr>
<td>Clay</td>
<td>8-70</td>
</tr>
<tr>
<td>Shale, Slate, Sandstone</td>
<td>10-100</td>
</tr>
<tr>
<td>Sand</td>
<td>200-3000</td>
</tr>
<tr>
<td>Ridge Gravel</td>
<td>3000-30000</td>
</tr>
<tr>
<td>Solid Granite</td>
<td>10000-50000</td>
</tr>
<tr>
<td>Ice</td>
<td>10000-100000</td>
</tr>
</tbody>
</table>

*Table 1: Table demonstrating the typical resistivity values for different types of soils and water.* [6]
There are two main methods for measuring a soil’s resistivity on site, the Wenner and the Schlumberger methods \(^7\). The purpose for these measurements is to determine the type of soil that is present in the site which is denoted by the resistivity value; and the number of layers that are present in the subsoil. The Wenner method is the most common technique and in addition to being relatively simple to undertake, it enables the site’s subsoil to be analysed quite accurately by inserting earth rods at the surface \(^8\). This method comprises of inserting four probes that are equally spaced “a” metres apart. The two inner probes are referred to as the potential terminals (P1 and P2) while remaining outer probes are the current terminals (C1 and C2). Figure 1 demonstrates this layout.

\[
\begin{align*}
\text{C1} & \quad \bullet \quad \bullet \quad \bullet \quad \bullet \\
\text{P1} & \quad \bullet \quad \bullet \quad \bullet \quad \bullet \\
\text{P2} & \quad \bullet \quad \bullet \quad \bullet \quad \bullet \\
\text{C2} & \quad \bullet \quad \bullet \quad \bullet \quad \bullet \\
\end{align*}
\]

\(k = 2 \times a\)

\[
\begin{align*}
\text{C1} & \quad \bullet \quad \bullet \quad \bullet \quad \bullet \\
\text{P1} & \quad \bullet \quad \bullet \quad \bullet \quad \bullet \\
\text{P2} & \quad \bullet \quad \bullet \quad \bullet \quad \bullet \\
\text{C2} & \quad \bullet \quad \bullet \quad \bullet \quad \bullet \\
\end{align*}
\]

\(k = n \times (n + 1) \times a\)

**Figure 2:** Figure displaying the Wenner and Schlumberger resistivity measurement techniques respectively \(^9\).

The Schlumberger method, on the other hand, despite having a very similar layout to the Wenner arrangement has in general stationary potential probes while varying the current probes. This technique is more appropriate for smaller areas of soil; however, earthing studies require the analysis of large areas and thus the Wenner method remains the optimal choice as it provides an average for the considered area. By determining the apparent resistance by means of dividing the difference in potential by the current measured on site (\(R_{\text{app}} = \Delta V/I\)), the apparent resistivity can be calculated using the following equations.

Wenner: \[\rho_{\text{app}} = R_{\text{app}} \times 2\pi \times a\]

Schlumberger: \[\rho_{\text{app}} = R_{\text{app}} \times \pi n a (n + 1)\]

This investigation focuses on analysing soil measurements that were collected using the Wenner method. Rather than determining the specific resistivity at that particular point the apparent resistivity is the average resistivity between the surface and depth ‘a’. The average resistivity is more appropriate to determine the site’s multilayer model as it demonstrates the general resistivity each layer has. The specific resistivity, on the other hand, could be an unfair representation of the actual resistivity of each layer.

### 2.2. Earth Grid Design

From the Flow Chart in Figure 1 it is apparent that the earth grid design is of paramount importance. It is what the company is hired to undertake and as previously
acknowledged it is an iterative process whereby its implementation will differ depending on mainly the touch and step potential outputs and whether these voltages comply with the established standards. The design assesses a variety of parameters regarding the site, from the area it covers to the overall impedance of the grid to the type of cables used and their respective ratings \cite{10}. The impedance of the grid is related to the area it covers and the soil resistivity \cite{11}, in fact, the larger the area, the larger the earth grid and therefore the lower the impedance.

The earth grid is used to provide low resistance path for the fault current to return to source and not harm people and damage equipment on site. The earth grid itself is the physical arrangement of the copper that connects the structures on site and the cable screens that follow these copper conductors. The more copper and cables screens used, the lower the impedance as this helps dissipate the current. The impedance of the grid is dependent on the arrangement of the copper and the soil resistivity characteristics. As aforementioned, the higher resistivity sites have a higher resistance and therefore are not as effective in dissipating the fault current. The reason cable screens are used is to lower the longitudinal impedance on site.

The earth grid design uses several formulas to determine the respective earth impedance and potentials that arise on site. For basic designs such as substations that are generally rectangle or a square shaped structures, these calculations could be done manually, however, the copper arrangements that surround the wind farm are very irregularly shaped and therefore computer simulations are required to perform the earthing design more accurately. The formulas for these calculations are found in the IEEE std. 80 \cite{12} and the outlined principles focus on designing earthing systems for AC substations.

The earthing design can go from outlining the copper arrangements throughout the wind farm to calculating the dimensions the copper conductors should have in order to capably transfer the fault current should it occur. The general formula is stated in the BS 7671 that covers all the wiring regulations.

\[ I^2t = k^2S^2 \]

where

\( I \) = Fault Current in Amps
\( t \) = Operating time of disconnecting device (set at 3s, worst case scenario)
\( k \) = Constant; accounts for resistivity, temperature coefficient and heat capacity
\( S \) = Nominal Cross Sectional Area, mm\(^2\)

The earthing design assesses structures that are bonded to the earthing system, in this case, the Wind Turbine Generators. General earthing design is to install conductors as
a perimeter one metre away from any structure to be bonded to the earthing system. This reduces the potentials for anybody touching the structures during an earth fault.

2.3. Fault Current Distribution

In the event of a single phase fault occurring in the wind farm site the current needs to be directed back to the source. The current that passes through the earth grid, which has a finite impedance value, will raise the site’s overall potential with respect to remote earth, known as the Rise of Earth Potential. The fault current path is shown below in Figure 3 for cable connected wind farm.

![Figure 3: Figure displaying the Fault Current Distribution when considering cable connected wind farm](image)

The drawing shown is for cable connected wind farm. However, if wood pole overhead line is considered, then there is no cable screen and therefore $I_{gr} = I_F$.

In principle, the entire fault current should be transferred via the earth mat, however, in reality parallel paths such as the cable screens installed during the earth grid design process (Flow Chart, Figure 1) need to be considered since these also responsible for transferring the current [13]. These parallel paths help dissipate the current by reducing the longitudinal resistance in the site and ultimately decreasing the Rise of Earth Potential. The acknowledgement of these additional components is very significant as it may influence the amount of earthing a site may need. If several parallel paths are available then sites that may be initially considered HOT and have high Rise of Earth Potentials over 430V for fault clearance times greater than 200ms (see next section) may actually be COLD due to the
various components that dissipate the current and thus the site will be overly equipped and
this is unnecessarily costly for the company that is implementing this earthing plan[14].

This investigation considers the transfer of fault current via wood pole overhead lines,
whereby the fault is directed towards the earth mat and transferred towards the source. The
diagram in Figure 3 demonstrates this occurrence. It may be worth noting that the
Distribution Network Operators (DNO) substation is the remote substation while the
rectangular highlighted area represents the substation and wind farm site that is being
designed. The wind farms considered in this report are both connected via wood pole
overhead lines with no earth wire. If higher voltages were to be implemented then the steel
tower lines would have to be included instead and a different scenario would be analysed. It
is noticeable from the diagram that the cable screens have a tremendous impact in lowering
the earth grid’s current. In fact, \( I_{gr} = I_F - I_{scr} \) and resulting in the earth grid current, \( I_{gr} \),
becoming significantly diminished.

2.4. Significant Potentials in Earthing Designs

This section evaluates the potentials that need to be considered in order to design an
effective earthing system. The main potentials that are discussed in this segment are the Rise
of Earth Potential (RoEP), the Touch Potential and the Step Potential. These voltage
calculations are essential as they ultimately help protect human life and the equipment on
site. By calculating the maximum voltage that may arise on site, the earthing designers will
assess how much earthing is needed in order to comply with the acceptable standards, i.e.
lower the voltage so that it doesn’t remain a threat to human life.

2.4.1. Rise of Earth Potential (RoEP)

The IEEE Standard 80-2000 defines the Rise of Earth Potential (RoEP) as “The
Maximum electrical potential that a substation grounding grid can attain relative to a distant
grounding point assumed to be at the potential of remote earth. This voltage, GPR, is equal
to the maximum grid current times the grid resistance.”[12]

The multiplication of the fault current with the grid resistance results in the maximum
voltage that can arise in the considered earth grid. Despite only partially controlling the
amount of current that enters the grid, its effect is diminished by reducing the resistance of the grid so as to decrease the Rise of Earth Potential.

The Rise of Earth Potential is essentially used to determine whether a site is considered to be HOT or COLD. There are various factors that contribute towards this deliberation such as naturally the resistance of the grid which directly influences the maximum potential that can arise in the earth grid, to the international standards which has different maximum allowable Rise of Earth Potentials depending on the equipment’s maximum clearing time which is generally 200ms for wind farm sites. For fault duration greater than 200ms for instance, the maximum potential cannot exceed 430 V, in other words, if the voltage in the considered area surpasses this limit, the site will be considered HOT.

Ground potential tends to expand in a radial manner around the wind turbine generator or the substation, in other words it follows their contours in a radial manner. Moving further away from the earth grid results in the decrease of the earth potential.

### 2.4.2. Touch and Step Potentials

Subsequently to identifying the Rise of Earth Potential, the earthing design evaluates the site’s touch and step potentials and determines their effect on human life and on vital organs, in particular the lungs and heart. It is for that reason that the touch potential for a particular clearing time is always lower than the step potential. If someone touches a conductive object during a fault, the current will travel through the heart and lungs, through the legs down to the ground and this can be very dangerous, even the smallest current at 50Hz can be quite hazardous. The step potential, on the other hand, does not go through these vital organs. The current goes up one leg through the groin and down the other leg. This can be very unpleasant; however, it does not endanger human life to the extent of the previous scenario.

The IEEE std.80-2000 defines the step voltage as “The difference in surface potential experienced by a person bridging a distance of 1m with the feet contacting any grounding object.” The touch voltage on the other hand is the potential difference between the surface potential where the person is standing and the grounded structure that same person is touching. Figure 4 illustrates these principles. It is noticeable from the illustration below
that the person is more vulnerable to touch potentials when closer to the turbine tower than step potentials and requires particular attention when designing the earthing system.

**Figure 4: Figure illustrating the touch and step potentials** \(^{[17]}\).

Britain follows the touch and step regulations imposed by the International Electrotechnical Commission (IEC). By analysing the IEC479 (1984) C1 curve, earthing engineers are able to determine the touch and step potential limits. The graph considers the effect of having soil surfaces with or without stone chippings on these potentials. C1 curve from the IEC479 (1984) can be seen in Appendix A.

Alternatively, the IEEE offers a manual calculation method that varies the potential values with respect to a person’s body weight. It shows a general equation that defines both of these parameters as shown:

\[
E_{\text{Step}} = (R_B + 2R_f) \cdot I_B \tag{12}
\]

\[
E_{\text{Touch}} = (R_B + \frac{R_f}{2}) \cdot I_B \tag{12}
\]

Where
- \(E_{\text{Step}}\) Step Voltage in Volts (V)
- \(E_{\text{Touch}}\) Touch Voltage in Volts (V)
- \(R_f\) Ground Resistance of one foot (Ω)
- \(R_B\) Human Body Resistance (Ω)
- \(I_B\) RMS Magnitude of Current Through Body (A)
2.5. Lightning Protection

This segment analyses the precautions that need to be taken into consideration when designing an earthing system that effectively reduces the excess voltage down to acceptable standards set up by both the IEEE and the International Electrotechnical Commission (IEC).

In a wind farm site, lightning protection is considered for wind turbine generators (WTG’s) rather than substations, since the former is a significantly larger metallic target and thus is more prone to being struck by lightning. Lightning strikes can have quite a hazardous effect on turbines from damaging the blades to ultimately affecting its performance, i.e. affect its electric generation capabilities \[18\]. More specifically it may damage more costly equipment such as the PDP (Primary Distribution Panel) and the TCU (Tower Control Unit) and having to constantly repair these can become a tremendous unnecessary loss for the company responsible for the site’s power generation \[19\].

The main factor to consider when designing an earthing system that successfully protects wind turbine generators from lightning strikes is the total impedance of the wind turbine. The International Electrotechnical Commission (IEC) stipulates that the maximum earth impedance of the turbine base has to be lower than 10Ω. In other words, the earthing resistance of this structure has to be lower than or equal to 10Ω \[20\]. Earthing engineers have to certify that this international standard is fulfilled before connecting the turbine generator to the rest of the system. The IEC 61024 is the International Standard that includes regulations that should protect structures against lighting strikes \[21\][22].

2.6. Standards Used in Designing Wind Farm Earthing Systems in the UK:

The National and International Standards are to provide earthing engineers guidance when undertaking any sort of earthing design. Naturally this technical report considers the standards solely relevant to the UK. Many other countries have their own principles which are slightly different from those considers in Britain. One example is the BS 7430, which is the British Standard’s Code of Practice for Earthing and is solely acknowledged in the UK. This Standard is more of a general Code of Practice that provides recommendations on implementing earthing designs on a variety of electrical installations. It is considered for land-based installations such as LV to HV substations and can’t be applied on offshore constructions, ships, and aircrafts for instance \[23\]. On the other hand, the International
Electrotechnical Commission (IEC) defines regulations for earthing systems that have to considered and accomplished on a global scale. An example that was previously mentioned was the wind turbine lightning protection standard, the IEC 61024 that stipulates a general code of practice concerning lighting protection designs that should be followed at an international level.

The subsequent standard that is equally relevant when designing earthing systems in the UK is the Energy Networks Association ENA TS 41-24. It referred to as the “Guidelines for the design, Installation, Testing and Maintenance of Main Earthing Systems in Substations” [24]. It is primarily used to provide recommendations to determining the maximum allowable touch and step potential limits.

The last guidance manuscript is known as the Energy Networks Association ENA Engineering Recommendation S34 and it assesses the Rise of Earth Potential (RoEP) at substation sites [25]. It goes in accordance with the previous guidance script ENA TS 41-24, that stipulates the touch and step potential allowable limits. By determining the maximum voltage that can arise in an earthing grid, i.e. the Rise of Earth Potential (RoEP) through this guidance specification, the ENA TS 41-24 essentially complements the earthing design by assessing the touch and step potential limits. In other words, both recommendation manuals effectively accompany one another to produce a balanced earthing design.

The Standards considered throughout this investigation include:

- BS 7430 – “Code of Practice for Earthing”[23].
- IEC 61024 – Lightning Protection Standards [22].
- ENA TS 41-24 - “Guidelines for the design, Installation, Testing and Maintenance of Main Earthing Systems in Substations” [24].
3. Case Studies and Implementation of Earthing Design

This section analyses examples of earthing projects undertaken while at placement in Sinclair Knight Merz (SKM) and the procedure behind designing effective earthing systems. There are two case studies that will be evaluated and these shall be known as Wind Farm A and Wind farm B. The reason these two projects were chosen to be included in this report was due to their quite distinct soil measurements and the how these may lead to different procedures being carried out when designing their respective earthing systems. Their geographical dispersion contributed towards this difference in soil models.

3.1. Wind Farm A Analysis

Located in East Midlands of England, this site has a very low resistivity soil model and is surrounded by mainly agricultural land. It is made up of moist soil and this can be identified through the subsequent resistivity results. The wind farm includes nine 1.3MW wind turbine generators (WTG’s) and a switching station comprising of 33kV switchgear together with the appropriate protection and control equipment. The site layout can be seen in Appendix B, and this demonstrates the positioning of the substation relative to all the turbines.

The 33kV switchgear in the switching station a protection tool that de-energises all the electrical equipment on site in the event of a fault occurring. The protection settings involve attributing the switchgear with a maximum clearance time; in this case it was set at 500ms. This information is particularly useful when determining the allowable touch and step potential limits according to the ENA TS 41-24. Having been provided with the site layout, the soil resistance measurements, the fault current measurement and the turbine and switching station dimensions by the contracting company, SKM have been requested to design an appropriate earthing system that capably withstands potential faults and provides a safe environment at the best cost.

The earthing design was undertaken using SES technologies’ grounding/earthing software package, CDEGS (Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis). CDEGS is optimal for these designs as it provides accurate simulations of various component of the site from evaluating soil models to illustrative representations of touch and step potential models.
The design process follows the procedure demonstrated in the Flow Chart in Figure 1. Starting with the analysis of the soil measurements obtained on site and subsequent to finding the overall soil model, the design then goes on to determining the Rise of Earth Potential and the touch and step potentials. The design of the site’s earthing system will depend on whether these potential parameters comply with the established standards.

3.1.1. Wind Farm Soil Model and Resistivity Data

The first stage in any earthing design comprises in assessing the soil measurements gathered on site and using these to determine the wind farm’s average horizontal multi-layer soil model. By inserting the Wenner soil measurements that were determined on site into CDEGS, a plot that illustrates the various soil layers can be obtained. As previously mentioned the Wenner method calculates the apparent resistance by dividing the current probe analysis to the voltage probe measurements (section 2.1). The on-site measurements were provided by the contracting company and can be seen in Appendix C.

The data was inserted into the RESAP module which is a module within the CDEGS program responsible for interpreting Wenner array readings and illustrating these in a plot delineating the soil layer thickness (also known as the depth ‘a’) versus the layer resistivity. The plots have been produced for all wind turbine generators and the switching station for a total of ten individual readings. The average thickness and resistivity for each layer is then calculated for the site’s overall average soil model.

This section is absolutely critical in order to determine the overall soil resistivity which will ultimately determine the overall impedance of the earth design and the resulting Rise of Earth Potential (RoEP). At a first impression it is noticeable the soil appears to be quite moist due to its low resistivity. Subsequent to inputting the soil measurements obtained on site (Appendix C), onto CDEGS, resistivity plots are produced and an example of one of these is shown in Figure 4. All ten plots (nine wind turbine generators and one substation) can be seen in Appendix D.
It is noticeable from the above graph that there are clearly outlined three main horizontal layers with different resistivity values, the middle layer being significantly lower than the remaining sections. This is made apparent through the graph’s points of inflection. The point of inflection indicates a new layer and the software clearly portrays three main layers going from high, low to medium resistivity respectively. The direct proportionality between the apparent resistivity and the apparent resistance described in section 2.1 suggests this soil is highly conductive and thus offers a lower impedance path for all the fault current resulting in lower potentials. After obtaining a graphical analysis for all the necessary locations on site, i.e. all the turbines and substation, a table specifying the various resistivity values and soil thicknesses was created and from that an average soil model was identified, since it’s essentially the average of every layer’s thickness and resistivity. This can be verified in Table 2.
Layer | Turbine 1 | Turbine 2 | Turbine 3 | Turbine 4
---|---|---|---|---
| Thickness (m) | ρ (Ωm) | Thickness (m) | ρ (Ωm) | Thickness (m) | ρ (Ωm) | Thickness (m) | ρ (Ωm)
1 | 1.08 | 48.12 | 0.98 | 22.84 | 0.98 | 56.42 | 1.87 | 28.99
2 | 13.29 | 13.60 | 20.45 | 12.98 | 16.61 | 13.17 | 11.57 | 10.95
3 | Infinite | 33.26 | Infinite | 80.95 | Infinite | 54.44 | Infinite | 49.78
Layer | Turbine 5 | Turbine 6 | Turbine 7 | Turbine 8
---|---|---|---|---
| Thickness (m) | ρ (Ωm) | Thickness (m) | ρ (Ωm) | Thickness (m) | ρ (Ωm) | Thickness (m) | ρ (Ωm)
1 | 0.67 | 69.00 | 0.70 | 102.38 | 0.81 | 48.25 | 0.46 | 49.54
2 | 8.20 | 11.19 | 15.06 | 18.74 | 12.26 | 15.13 | 15.20 | 14.07
3 | Infinite | 42.18 | Infinite | 49.35 | Infinite | 84.48 | Infinite | 388.27
Layer | Turbine 9 | Switching Station | Met Mast | Overall Average Soil Model
---|---|---|---|---
| Thickness (m) | ρ (Ωm) | Thickness (m) | ρ (Ωm) | Thickness (m) | ρ (Ωm) | Thickness (m) | ρ (Ωm)
1 | 2.00 | 29.28 | 0.63 | 62.64 | 0.50 | 80.49 | 0.72 | 55.83
3 | Infinite | 34.85 | Infinite | 171.18 | Infinite | 97.57 | Infinite | 107.30

Table 2: Table demonstrating the site’s various soil thicknesses and resistivity values using CDEGS.

A general soil model pattern is observed among all the site’s structures. The primary factor to notice is the consistency of the soil that appears to have three main horizontal layers throughout the entire wind farm site. In addition, it is worth noting how the shape remains fairly regular between the various structures, in other words, the apparent resistivity has a sort of positive parabolic shape as can be seen in Figure 4. This suggests that the middle layer is a very moist and damp soil particularly when compared to its surroundings.

The most striking reading however is turbine 8’s third layer resistivity which is significantly larger than the remaining measurements. The reason for this is possibly because when the software analyses the data it essentially guesses where the resistivity plot tails off and from the data that was given it has to extrapolate the graph and determine where the next layer may be. This figure doesn’t appear to correspond with the remaining results and therefore this assumption can be made whereby the program guessed where the resistivity would tail off. Further measurements with wider probe spacing would provide a more accurate model of the lower layers. However, as the result is higher than the other measurements it can be considered a worst case scenario.

An additional structure appears to be included in this site, namely the Met Mast. The reason it was not previously acknowledged is due to the fact that it is not in fact bonded to the earthing system and will not see a potential rise during a phase to earth fault.
3.1.2. Earth Grid Design

This section details the copper conductor arrangement on site together with the cable screens, in addition to the type of copper conductor used and its burial depth used in the design. As aforementioned, the earth grid design by itself is an iterative process whereby the design may need to be modified depending on the outputs generated at a later stage.

The first task in the earth grid design is to determine what size of copper conductor would be appropriate to install on site and at what depth the cables would be laid. The standard that stipulates the wiring regulations is the BS 7671. It was previously acknowledged that the formula that determines whether the copper conductor is sufficient is

$$I^2t = k^2S^2.$$  

As verified in the next section, the contractors stipulate the fault current is 1670 Amps and therefore any cable with a fault rating above this value is adequate for installation. For the conductors that will be buried across the site linking the various structures, copper conductors with 50mm$^2$ cross sectional area (S) are considered. If the operating time (t) is 3secs and k is a constant, 199.19, value from the BS 7671, it means the fault current rating is 5.75kA, significantly larger than the site’s 1670A fault current. Similarly, if the standard 40x4mm (160mm$^2$) copper tape is considered for the substation and the operating time and constant parameters are kept the same, then these result in a fault current rating of 18.4kA again significantly higher than the 1670A fault current. The turbines will use the 50mm$^2$ copper conductors as it can capably withstand the fault current. The copper arrangement throughout the site will be analysed to a greater extent in section 3.1.4, Rise of Earth Potential since the cable layout will essentially outline any possible HOT zones in the site (Appendix E). Since the earth grid design is an iterative process, the copper conductors that connect the structures on site are buried at approximately 1m as an initial part of the design. The copper conductors are buried in the same trench as the 33kV power cables (1m). The tape should be buried one metre around the perimeter of the substation at a depth of 1m. As aforementioned the turbines have two rings, namely the inner and outer rings. The contractor offers the layout of the turbine and these can be seen in section 3.1.5, Touch and Step Potentials (Appendix F). The inner ring is 9m diameter and is buried at 0.8m while the outer foundation ring has a diameter of 17m and buried at a depth of 1.5m. This is the initial design however it’s prone to change depending on the potential outputs and whether these comply with the established standards.
3.1.3. Fault Current Analysis

Identifying the maximum voltage that can arise in a wind farm site during a phase to earth fault, i.e. the Rise of Earth Potential (RoEP) is essential to protect both human life in the vicinity and the equipment on site. In order to obtain this value, the overall impedance of earthing design has to be found together with the maximum single phase fault current. The single phase current is always used rather than the three phase current because the three-phase fault effectively becomes its own neutral and therefore no resultant current flows into the earth grid. The single phase current, on the other hand, has its only return path to the DNO transformer neutral via the earth grid as shown in Figure 3. The fault current value was provided by the contractors since they did the calculations.

The maximum fault current that was calculated by the contractors at the 33kV switchgear in the substation was 1670 Amps. In addition, its maximum clearance time is 500ms which can be adequate given the large area and low resistivity of the site that will help dissipate the fault current.

Since the site is connected via a 33kV wood pole overhead line all the fault current will return via the earth grid (see section 2.3).

3.1.4. Determining the Rise of Earth Potential (RoEP)

The Rise of Earth Potential (RoEP) defines the maximum voltage that can arise in the site. It stipulates whether the site in consideration is HOT or COLD. Nevertheless, prior to determining this potential, the standard safety limits need to be noted. In other words, the maximum voltage limits, whether it be the maximum Rise of Earth Potential or the touch and step potentials need to be appropriately established. In order for the earthing design to be effective, it needs to comply with these standards accordingly. Table 3 demonstrates the considered safety limits.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Touch Potential (500 ms) (See Appendix A)</td>
<td>300 Volts*</td>
</tr>
<tr>
<td>Step Potential (500 ms) (See Appendix A)</td>
<td>900 Volts*</td>
</tr>
<tr>
<td>Max Rise of Earth Potential for COLD site (fault duration &gt; 200ms)</td>
<td>430 Volts</td>
</tr>
<tr>
<td>Max Impedance of turbine base (for lightning protection)</td>
<td>10 Ω</td>
</tr>
</tbody>
</table>

*Table 3: Table demonstrating the safety limit criteria in an earthing system design*
*Touch and Step potential limits were obtained from the C1 Curve of the IEC 479 (Appendix A) and used the body impedances from the EA TS 41-24. The values shown correspond to the surfaces without stone chippings. If stone chippings were included these potential limits would increase to 380V to 1300V respectively.

The analysis of the Rise of Earth Potential (RoEP) was performed using the MALZ module in the CDEGS software. The MALZ section is where the earth grid design model is created and it includes soil model and fault current inputs.

By modelling the earth grid design in the appropriate multilayer soil model, the wind farm site’s overall Earth Impedance can be found. Subsequently, the MALZ model then uses this impedance and multiplies it with the maximum fault current in order to determine the Rise of Earth Potential. The site has to be accurately drawn onto the program, i.e. has to be drawn to scale and this gives an illustrated representation of where potential HOT zones may be located. This is otherwise known as the site’s copper arrangements and it is essential to mark the conductor tracks and the cable screens since these are ultimately the main carriers of current and act as an effective earthing mat to the fault current. The site layout that was drawn into the program can be seen in Appendix E.

Since the switchgear has protection settings greater than 200ms, the safety criterion in Table 3 establishes that the maximum Rise of Earth Potential for a COLD site is 430V, i.e. anything over this voltage is considered a HOT site.

After inserting this information onto CDEGS and drawing the site shown in Appendix B into the program, the following Earth Impedance was calculated:

\[(0.12 \angle 20.79^\circ) \Omega\]

Consequently, by multiplying this impedance by the 1670A fault current, the following Rise of Earth Potential was calculated:

**195.3 Volts**

It is noticeable from Table 3 that in order for a site to be considered HOT, the Rise of Earth Potential would have to be greater than 430V (for a fault duration greater than 200ms). This information therefore confirms that this wind farm site is in fact COLD since it does not exceed the established safety limit. This can be explained mainly by the site large area that capably dissipates the fault current that arises and the soil low resistivity that is an effective conductor of the current and offers a low impedance path away from all the main structures on site, thus protecting people in the vicinity and any electrical equipment. The site’s illustrated representation of the Rise of Earth Potential together with the programs report with
the calculations performed in order to determine the Rise of Earth Potential and the Earth Impedance can be seen in Appendix E.

3.1.5. Evaluating Touch and Step Potentials

It was previously verified that the Rise of Earth Potential was of 195.3 Volts suggesting the site is in fact considered COLD as it’s significantly lower than the 430V safety limit for fault durations lower than 200ms. Since the maximum voltage on site is additionally lower than the allowable touch and step potential limits as verified in Table 3, there is reason to believe that naturally these limits won’t be surpassed. In fact, the touch and step potentials are never greater than the Rise of Earth Potential (see Figure 4), meaning that the site’s actual touch and step voltages will be lower than the 195.3V. The Rise of Earth Potential represents the maximum potential that can arise on site while the touch potential for instance solely the difference in potential between the ground and the turbine tower which is never greater than the Rise of Earth Potential. Therefore, there is reason to believe the touch and step potentials will not surpass the allowable limits.

Figure 6: Figure illustrating the Turbine 6’s Touch Potential. Note the maximum value is 157.808V but it’s not in an area of concern, i.e. it’s far from turbine tower.

Figure 5 demonstrates the touch potential for Turbine 6 and compared to the remaining structures, it recorded this highest voltage. It represents the worst case and the maximum voltage remains significantly lower than the allowable touch and step potential limits imposed by the C1 curve in the IEC 479. The reason the touch potential was chosen as an example over the step potential was because step potentials generally have lower voltages. Despite having a higher limit, the maximum step potential generally never exceeds the touch potential and in this case there is no exception. Figure 4 in page 10 demonstrates the reasoning behind this statement, i.e. the potential difference between the surface and the
Designing Earthing Systems for Onshore Wind Farm Sites

person touch the turbine tower is greater than the potential difference known as the step potential. Appendix F includes the site structures’ various touch and step potentials and by analysing them individually, it is noticeable that the worst step potential is registered in Turbine 1 that had a maximum voltage of 42.924V.

3.1.6. Lightning Protection Analysis

It is acknowledged that there are two main ways current is injected into the earth grid. Either some sort of fault in an overhead line tower or a lightning strike hitting one of the turbines on site. In addition to increasing the earth potential, lightning strikes can damage the blades of the turbine, its PDP (Primary Distribution Panel) and its TCU (Tower Control Unit). The IEC 61024 establishes that the maximum impedance in turbine’s base should be 10Ω. This can be also verified in Table 3 that demonstrates the safety limit criteria.

Lightening protection only considers local areas to the turbine. With the lightning frequency being very high, implies the longitudinal impedance will also become very high resulting in the lightning strike becoming dissipated in the local earth mat.

This section essentially uses the MALZ module in CDEGS to verify whether the turbine bases in this site actually go beyond the regulatory 10Ω.

The following table was created demonstrating the impedance at the base of each of the wind turbine generators.

<table>
<thead>
<tr>
<th>Wind Turbine Generator</th>
<th>Impedance of Earthing System (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WTG 1</td>
<td>0.88</td>
</tr>
<tr>
<td>WTG 2</td>
<td>0.65</td>
</tr>
<tr>
<td>WTG 3</td>
<td>0.95</td>
</tr>
<tr>
<td>WTG 4</td>
<td>0.73</td>
</tr>
<tr>
<td>WTG 5</td>
<td>0.91</td>
</tr>
<tr>
<td>WTG 6</td>
<td>1.29</td>
</tr>
<tr>
<td>WTG 7</td>
<td>0.99</td>
</tr>
<tr>
<td>WTG 8</td>
<td>0.86</td>
</tr>
<tr>
<td>WTG 9</td>
<td>0.77</td>
</tr>
</tbody>
</table>

*Table 4: Table demonstrating the impedance at the base of each wind turbine generator*

The above table confirms that all turbines have impedances that remain significantly lower than the 10Ω standard imposed by the IEC 61024 suggesting that this earthing design is quite effective since it effectively complies with all the regulations and reduces any potential fault current to acceptable limits.
3.2. Wind Farm B Analysis

This particular site is located in Scotland near Glasgow and it consists of five 2.3MW Wind Turbine Generators (WTGs), a switching station that includes 33kV switchgear with a maximum fault clearance time of 750ms and the appropriate control and protection equipment. The primary factor that is noticeable when conducting a preliminary analysis of the site is the high resistivity terrain that is present which contrasts to the soil type available in the previous site. This naturally indicates that the site appears to be rockier and thus remains a poor conductor of current. Appendix G demonstrates the site layout that includes the substation and its connection to the five wind turbines.

The 33kV switchgear has a maximum clearance time of 750ms which is quite a significant difference to the switchgear in the previous site (500ms). This means that the allowable touch and step potentials will be lower as a smaller voltage for a longer time period can be as hazardous as a large voltage in a small time frame. Much like the previous scenario, the site layout, the soil measurements, the fault current measurements and the turbine and substation dimensions were provided by the contracting company. SKM have been requested to design an earthing system for this particular site and this report lays out the fundamental observations and evaluations made when undertaking this project.

3.2.1. Wind Farm Soil Model and Resistivity Data

The procedure behind designing an earthing system for a wind farm is generally the same, i.e. the process is essentially a recurrence of the previous case study. Much like the last scenario, the first stage always involves determining the site’s overall average soil model.

The on-site measurements were performed by the contractor and the Wenner method was used to collect the data. These readings calculate the apparent resistance of the soil underneath the location where each structure is meant to be constructed. These measurements can be seen in Appendix H.

The apparent resistance readings obtained on-site are then inserted into the RESAP module in CDEGS and plots are created describing the soil resistivity and thickness (depth ‘a’) under each structure. There are an overall of seven plots, five represent the wind turbines, the substation and an average soil plot. It is evident that the site is not particularly large
considering the type of soil present and the available switchgear equipment an obvious contrast when compared to the previous site.

The resistivity plots for this wind farm site can be seen in Appendix I and these include the five turbines, the substation and the calculated overall soil model.

Figure 7: Figure illustrating the soil model for the area surrounding the Turbine A2 (Appendix I).

The above plot clearly demonstrates the area underneath the second turbine, Turbine A2, has three horizontal soil layers with different thicknesses and resistivity values. When compared to the previous site, it is noticeable that the resistivity is considerably higher. This implies that the soil offers a high impedance path for the current and this ultimately leads to the implementation of more earthing tools in order to reduce the excess current to acceptable standards. Despite including all graphical displays in Appendix I, the subsequent table reveals the various resistivity and thickness values for the turbines and substation on site. In addition, it calculates the average soil model for the entire site which is used when determining the site’s overall impedance and ultimately the Rise of Earth Potential.
<table>
<thead>
<tr>
<th>Layer</th>
<th>Turbine A1</th>
<th>Turbine A2</th>
<th>Turbine A3</th>
<th>Turbine OE1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thickness (m)</td>
<td>Thickness (m)</td>
<td>Thickness (m)</td>
<td>Thickness (m)</td>
</tr>
<tr>
<td></td>
<td>ρ (Ωm)</td>
<td>ρ (Ωm)</td>
<td>ρ (Ωm)</td>
<td>ρ (Ωm)</td>
</tr>
<tr>
<td>1</td>
<td>1.47</td>
<td>307.43</td>
<td>2.67</td>
<td>435.09</td>
</tr>
<tr>
<td>2</td>
<td>3.01</td>
<td>87.35</td>
<td>23.22</td>
<td>42.28</td>
</tr>
<tr>
<td>3</td>
<td>9.09</td>
<td>254.90</td>
<td>Infinite</td>
<td>267.21</td>
</tr>
<tr>
<td>4</td>
<td>Infinite</td>
<td>152.69</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Layer</th>
<th>Turbine OE2</th>
<th>Substation</th>
<th>Overall Average Soil Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thickness (m)</td>
<td>Thickness (m)</td>
<td>Thickness (m)</td>
</tr>
<tr>
<td></td>
<td>ρ (Ωm)</td>
<td>ρ (Ωm)</td>
<td>ρ (Ωm)</td>
</tr>
<tr>
<td>1</td>
<td>0.92</td>
<td>250.10</td>
<td>0.85</td>
</tr>
<tr>
<td>2</td>
<td>3.81</td>
<td>957.96</td>
<td>6.32</td>
</tr>
<tr>
<td>3</td>
<td>Infinite</td>
<td>57.18</td>
<td>Infinite</td>
</tr>
</tbody>
</table>

Table 5: Table demonstrating the site’s various soil thicknesses and resistivity values using CDEGS.

From the above table it can be verified that despite the first three turbines, A1, A2 and A3 having the same positive parabolic shape, the remaining structures appear to have varying soil measurements. One parameter is fairly consistent, however, and this is the high resistivity of the soil.

The overall average soil model has a significantly higher resistance than the previous site, in addition to having slower switchgear equipment that lowers the allowable potential limits even further in comparison to the previous site.

3.2.2. Earth Grid Design

Much like the previous site, this section essentially outlines the standard design for this wind farm from cable arrangements, to the size of the cable and its respective burial depth.

The first section comprises in assessing viable cable sizes for this particular application. According to the information given by the contractors it can be verified that the fault current is 1966 Amps (next section), slightly larger than the current in previous site. The wiring regulations in the BS 7671 stipulate the formula to determine a cable’s appropriateness for the application in consideration, \( I^2t = k^2S^2 \). Using the same parameter as in the previous case, i.e. have the operating time, \( t \), at 3 secs and the constant, \( k \), at 199.19, then given the copper conductor is 50mm\(^2\) results in the fault current rating to be equal to 5.75kA, significantly larger than the fault current measured on site. This indicates this conductor should be capable of withstanding the fault current should it arise. This conductor
will be used to connect the structures on site and become part of the turbine rings. It should be buried at 1m; however, if necessary this may be subject to changes depending on the outputs.

The substation should comprise of copper tape that will be buried one metre around its perimeter again at a depth of 1m. The copper tape is 40x4mm, with a cross sectional area of 160mm$^2$. Assuming the parameters remain the same results in the fault current rating, I, to be equal to 18.4kA, larger than the fault current calculated on site, suggesting its use is adequate for this particular application.

The turbines have two rings, namely the inner and outer rings that comprise of 50mm$^2$ copper conductors. According to the contractor, the inner ring has a diameter of 7.5m while the outer foundation ring has 20.5m diameter. In addition, both conductor rings are buried at 0.6m which differs from Wind Farm A where the foundation ring was buried at a significantly larger depth (Appendix K).

The copper arrangement throughout the site will be analysed to a greater extent in section 3.2.4, Rise of Earth Potential, where the layout and physical arrangement of the copper conductors will demonstrate which areas on site have the highest potentials (Appendix J). In addition, the turbines’ and substation physical layout can be seen in the Touch and Step Potential section which analyses where are the areas of concern regarding elevated potentials on each of these structures (Appendix L).

3.2.3. Fault Current Analysis

As aforementioned the fault current is essential together with the average soil model to determine the Rise of Earth Potential. This is a typical $V=IR$ situation whereby the entire fault current is multiplied by the earth impedance to give the maximum potential that can arise in the earth grid. The maximum fault current that was calculated was 1966 Amps, larger than the previous site current. Furthermore, the maximum fault clearance time was 750ms and this effectively leads to lower limits for touch and step potentials.

This investigation assumes that the entire fault current is carried by the earth mat. This is in fact a simulation of the worst case scenario.
3.2.4. Determining the Rise of Earth Potential (RoEP)

The Rise of Earth Potential is the product of the overall earth grid impedance and the simulated fault current. It is equivalent to a V=IR scenario in this case whereby the maximum potential that can arise on site is dependent on the maximum fault current.

When assessing the standard safety limits shown in Table 5, it is noticeable that the touch and step potential boundaries are quite different from Wind Farm A. The 33kV switchgear in this site is significantly slower than the one considered in the last case study. This ultimately leads to lower allowable touch and step potential limits, since people and the equipment are exposed to this high voltage for a longer period of time. The safety limit criteria can be verified in Table 5.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Touch Potential (750 ms)</td>
<td>175 Volts*</td>
</tr>
<tr>
<td>Step Potential (750 ms)</td>
<td>540 Volts*</td>
</tr>
<tr>
<td>Max Rise of Earth Potential for COLD site (fault duration &gt; 200ms)</td>
<td>430 Volts</td>
</tr>
<tr>
<td>Max Impedance of turbine base (for lightning protection)</td>
<td>10 Ω</td>
</tr>
</tbody>
</table>

*The Touch and Step Potential limits were obtained from the C1 curve stipulated in the IEC479 (Appendix A) and using the body impedances from the EA TS 41-24. The values shown in the table correspond to surfaces without stone chippings. The inclusion of stone chippings would result in the increase of the potential limits to 240V and 780V respectively.

The site’s Rise of Earth Potential was determined by using the MALZ module in the CDEGS software. The directly proportionality between the apparent resistance and the apparent resistivity suggests that this earth mat has a very high impedance that will influence the magnitude of the Rise of Earth Potential. In addition, the fault current calculated on site is also greater than the current found on the previous site and this will similarly contribute towards a larger Rise of Earth Potential.

The criteria in Table 6 establishes that for any fault duration greater than 200ms, the maximum Rise of Earth Potential for a COLD site is 430V, in other words, any site with a maximum voltage greater than 430V will be considered HOT.

The first step to identifying this maximum potential is to draw the site layout shown in Appendix G onto the program. The substation and the five wind turbine generators are interlinked via bare copper conductors and insulated cable screens. While the bare copper conductors are able to directly reduce the earth impedance as these make up the earth grid,
the cable screens provide the fault current with a low impedance path to this grid. On a related note, the reason why these sites tend to cover a large area is because it is desirable to extend the bare copper conductors throughout the site. The more ground it covers, the larger the earth mat and the lower the ground impedance. This site however, has fewer turbines and is small in area in comparison to Wind Farm A and therefore it is expected to have larger impedance.

The Rise of Earth Potential plot demonstrates the highest potentials on site and can be seen in Appendix J. There are two plots that portray the same information, one that shows the Rise of Earth Potential over the entire wind farm site and the other that focuses over what appears to be the area with the highest potentials, i.e. closer to the substation and the first two turbines, A1 and A2. The latter plot can be seen below and this illustrative display establishes that this site is considered HOT as there are numerous locations that surpass the 430V potential limit.

From the figure above it is noticeable that the areas highlighted in pink to red colour denote voltages that are greater than the 430V limit. This is a primary indication that the site is indeed HOT and therefore requires particular attention when designing the site’s earthing system. The above figure above also highlights the structures that may need more earthing tools when it comes to lowering the touch and step potentials. It appears that the substation and turbine A2 have a large area of potentials greater than 430V.

Subsequent to analysing the graphical display, a more precise evaluation of the site’s characteristics is necessary. By inputting the average soil model and the earth grid design into
the MALZ module within CDEGS, the earth impedance is primarily obtained and this was calculated as:

\[(0.40 \angle 14.27^\circ) \Omega\]

The product of this impedance and the fault current results in the maximum potential that can arise on site, i.e. the Rise of Earth Potential. This was determined to be:

**791.87 Volts**

This potential is significantly higher than both the standard safety limits shown in Table 6 and the Rise of Earth Potential in the previous COLD site. As expected the calculations performed by the software confirm the site’s classification as a HOT site since it is substantially larger than the 430V threshold. This occurrence is in fact predictable since the firstly area covered by the bare copper conductors is not very large in comparison to Wind Farm A. This contributes towards higher impedance as verified in the above calculation where the earth impedance is 0.4Ω, considerably larger than the 0.12Ω seen in the previous site. In addition, the fault current is greater and this also contributes towards a larger overall potential. The high resistivity was also a clear indicator that the site could in fact be deemed HOT.

**3.2.5. Evaluating Touch and Step Potentials**

The last section helped confirm which sections on site would have the highest potentials and from Figure 8, it was noticeable that this included the substation and turbine A2. Table 6 demonstrates the established standard touch and step potential limits for 33kV switchgears with maximum fault duration of 750ms. This information is obtained from the C1 curve of the IEC 479 and uses body impedances from the EA TS 41-24. The table indicates that the maximum touch voltage is 175 Volts while the step voltage is 540 Volts.

The very large Rise of Earth Potential countered by the very low allowable potential limits suggested that the process behind designing safe turbines and substation would prove to be a challenge.

When firstly considering the turbine earthing design, it may be worth noting what is acknowledged as relevant from an earthing perspective. As aforementioned the turbine has two rings and these are buried underneath the turbine tower suggesting there is no danger of considering the potential caused by touching the actual rings. Touch potentials are concerned with people touching the main tower during a fault. Touch potentials consider voltages up to
one metre away from the tower which is outlined by the inner ring. The contractors sent forward a design specification for the turbines that included three connectors between the inner and outer rings. This is shown in Appendix K. This design was initially used; however, it was not adequate since voltages greater than 175V were verified at least one metre away from the tower. The Figure below demonstrates the turbine A2 (Appendix G) and it is noticeable that the three conductor scenario is not optimal since the potential limit is exceeded.

![Diagram](image)

**Figure 9: Figure illustrating Turbine A2’s initial Touch Potential**

It can be verified from the above Figure, that despite including the turbine’s steel reinforcement foundation bars in order to help lower the potentials, the actual touch potential is still far from the acceptable limits and additional earthing tools need to be included in the design.

Subsequently, four connections were tried on the worst case turbine rather than solely three; however, this implementation still didn’t lower the touch potential to the intended level. The touch and step potential plots for all the turbines can be seen in Appendix L.

In order to get the potentials down to the appropriate level, six connectors between the inner and the outer rings were carried out and a 60 metre conductor that simulates the connection between the outer ring of the turbine and another turbine on site was designed. Turbine A2 was tested using this earthing design and the following result was achieved.
The design for a substation is naturally very different from the turbine design. Despite having the same potential limit, i.e. 175 Volts, it is essential to maintain a low voltage within the substation since it can possibly have people inside and a variety of electrical equipment that needs to be protected from a fault. After receiving a substation layout from the contractors and running the simulation through CDEGS it is noticeable that the initial design had to be altered in order to accommodate the large Rise of Earth Potential countered by the small potential limit imposed by the IEC479 standard.

The final design has to obviously lower the potential on the far right hand side that displayed 300 – 430V inside the substation, which is excessive. In fact a few conductors were placed in that location the voltage in that region, earth rods were placed in the across the outside of the substation and two metre conductors pointing outwards were also connected in the corners of the substation. The reason steel reinforcement bars were not included in the region shown in

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**Figure 10:** Figure illustrating Turbine A2’s Touch Potential including 6 connectors and 60m conductor

**Figure 11:** Figure illustrating Substation’s initial Touch Potential
pink was because the design specification given by the contractors specified the top of that region was for the transformer/generator compound and therefore no earthing conductors could go beneath it. The final design is shown below in Figure 11. It is possible to verify from this graphical display that the potentials were drastically reduced and the substation appears to be safe from the inside. This process is still not complete however, as the contractor will have to be contacted in relation to the placement of the transformer/generator compound. It is visible this area still exceeds the established 175 Volts and thus this confirms the real life challenge of designing earthing systems for HOT sites.

The step potentials, on the other hand, don’t encounter a lot of problems mainly because it has a considerably larger potential limit as seen in Table 6. Appendix L demonstrates all the step potential plots for the turbines and the substation on site. It can be verified that all plots comply with the potential standards imposed by the IEC 479 and thus this part of the design can be considered successful.
3.2.6. **Lightning Protection Analysis**

The IEC 61024 establishes that the earth impedance below these structures should be a maximum of 10Ω and by using the MALZ module within CDEGS it was possible to confirm that these turbines were indeed complying with these international standards. The following results were obtained.

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*Table 7: Table demonstrating the impedance at the base of each wind turbine generator*
4. Discussion

The purpose of this investigation was to evaluate the various earthing design techniques used for wind farm sites. This report therefore focussed on comparing the differences between a site with a relatively high soil resistivity and a site with a relatively low soil resistivity. It was confirmed that the former case study was significantly more challenging due to and the associated larger Rise of Earth Potential and resulting increase in touch and step potentials.

An effective earthing system design considers a wide range of factors, from measuring soil resistance to calculating touch and step potentials and lightning protection considerations. During the years its implementation has become increasingly important since it can ultimately help save human lives in the vicinity of the site and protect electrical equipment from large fault currents that may arise. The subsequent sections discuss the individual case studies in greater depth and effectively compare different earthing design techniques used at each site.

4.1. Wind Farm A Evaluation

The first case described the necessary design procedures when considering a site with a low soil resistivity. The first task is to determine suitable soil models derived from the on-site soil resistance measurement performed by the client. The Wenner method was used to gather the relevant information, and this is the optimal method, as verified in the Literature Review, section 2.1. This measurement technique is particularly useful to cover large areas, it provides a more qualitative and informative display of the type of soil present on site whereas the alternative Schlumberger method is more adequate for smaller areas and is therefore not ideal for his type of application.

When analysing the type of soil in more detail, it is noticeable that the apparent resistivity is predominantly low throughout the site. When soil measurements were carried out underneath each structure, the consistency of the soil is the most striking factor. As well as verifying that all readings have three horizontal layers, it is also worth noting that a positive parabolic shape can be seen under each structure (Appendix D). The main point that can be made is the fact that these low resistivity values contributes towards low overall site impedance that ultimately results in a low Rise of Earth Potential. Having a low resistivity suggests the soil has low resistance and thus offers the fault current a low impedance path.
back to source. These readings help explain the subsequent low Rise of Earth Potentials and the relative simplicity when designing an earthing system in terms of touch and step potentials especially when compared to Wind Farm B.

When compared to the Wind farm B site, it is noticeable that the calculated earth impedance is significantly lower, i.e. it was calculated to be $0.12\,\Omega$, a large contrast with the $0.4\,\Omega$ measured in Wind Farm B. As well as this being due to the low resistivity soil, an additional factor that contributed towards this diminished impedance was the broader area that the site extended to. In other words, the bare copper conductors that connected all the structures on site were occupying a larger area and this resulted in an earthing grid that had a very expansive cross sectional area.

The Rise of Earth Potential is the parameter that defines whether a site is considered HOT or COLD. The standards in Table 3 establish the criteria that must be followed when designing an earthing system with a maximum fault clearance time of 500ms. As well as defining the allowable touch step potential limits; it also refers to the maximum voltage that can arise in a COLD site provided the fault duration is greater than 200ms, which is the case. It states that if the Rise of Earth Potential is greater than 430V, then the site is considered HOT. With 195.3 Volts, the site is clearly COLD. The direct $V=IZ$ relationship between the earth impedance and the Rise of Earth Potential contributed towards the latter being substantially diminished in the COLD site case. It can be seen that the Rise of Earth Potential was determined to be 195.3 Volts which is a lot smaller than the value calculated in the latter site, 791.87 Volts. This is due to two fundamental aspects. The first is the average soil model previously evaluated, that demonstrated a low resistivity and together with the site’s large area this contributed towards low earth impedance. The next factor was the lower fault current. The combination of these explains the tremendous difference between the sites’ Rise of Earth Potentials because as discussed, the alternate site has both a larger earth impedance and fault current.

The next step involves designing earthing systems for the individual turbines and substation on site according to the respective tolerable touch and step potentials established by the C1 curve in the IEC 479. Table 3 demonstrates that the tolerable touch and step potentials for this particular site is 300 Volts and 900 Volts respectively (Appendix A). These boundaries are indeed larger than the actual Rise of Earth Potential suggesting that the actual touch and step potentials will be less than 195.3 Volts and therefore within the allowable potential limits. The reason these potential limits are particularly high is due to the relatively
fast fault clearance time (500ms). Figure 6 portrays turbine 6’s touch plot, representing the worst case scenario and it is noticeable that it is clearly within the acceptable potential limit. The step potential limits are even higher and these also comply with the standards. These plots can be seen in Appendix F for reference.

The final step assesses whether the turbines are capable of withstanding a possible lightning strike. The IEC 61024 establishes that the turbine base’s maximum impedance should be $10\Omega$. Table 4 displays the results obtained and it is possible to notice that the impedance of the earthing system under each turbine on site is significantly lower than the standard $10\Omega$ therefore complying with the IEC 61024.

The overall earthing design implemented for this site consistently fulfils the requirements established by the various standard committees and as a result this earthing system can be considered to be a successful implementation.

4.2. Wind Farm B Evaluation

The Wind Farm B site design was a lot more challenging due to its high resistivity soil, slower fault clearance time (750ms) and larger phase to earth fault current. The combination of these factors contributed towards augmented Rise of Earth Potential and touch and step potentials. The larger the potential, the more complex the design and the more copper electrode will be required to decrease this voltage to within the tolerable limits.

When primarily assessing the soil resistance section it is possible to verify a significant increase in the resistivity values when compared to Wind Farm A. Despite also having an average soil model that consists of three layers, it is noticeable that the wind farm site is located in a rockier area. The direct correlation resistivity and resistance suggests the site has fairly high impedance that counters the flow of current and therefore is not ideal when dissipating any excessive fault current. This is a factor in the calculation of the Rise of Earth Potential which determines whether a site is considered HOT or COLD. However, these high resistivity values may also contribute towards that assessment, and it’s a preliminary analysis of the soil’s possible conductivity.

Similarly to having higher soil impedance, the site also has a larger fault current (1966 Amps) when compared to Wind Farm A (1670 Amps). In addition, the allowable touch potential for instance decreased from 300 Volts to 175 Volts and this is due to the slower clearance time (750ms).
Judging from the previous indications it was legitimate to expect a larger Rise of Earth Potential compared to the previous site mainly due to the type of soil and fault current. The first calculation established the overall earth impedance and naturally this value was considerably larger than the impedance value for the COLD site. This is due to the direct correlation between soil resistivity and its resistance. The average soil model revealed a consistent high resistivity in all layers on site and this contributed towards the augmented impedance value. The Rise of Earth Potential is equivalent to the V=IR relationship whereby the multiplication of the fault current with the earth impedance calculates the maximum voltage that can arise on site.

The touch and step potential section was clear demonstration that the earth grid design is indeed an iterative process whereby subsequent to setting up a basic generalized design, the output was appeared to be constantly surpassing the allowable potential limits. Generally the initial design doesn’t include the turbine tower’s steel reinforcement bars which help to provide an equipotential zone within the tower, however, since the site was considered HOT in the Rise of Earth Potential section, it was predicted that its inclusion could be necessary. In addition, rather than interconnecting the turbine rings with three conductors, as was the initial consideration, six copper conductors were in the end necessary so as to reduce the touch potentials one metre away from the turbine tower below the 175V limit. A 60m conductor was also included and this simulates the connection to another structure on the site and ultimately reduced the local touch potential. The substation was also subject to quite a few changes. Other than the copper tape installed in the perimeter of building, radial conductors, 2m long were also necessary in order to reduce the touch and step potentials. Much like the turbine scenario, the steel reinforcement bars present in the foundation slab were included in order to lower these potentials to acceptable limits. These two cases were clear demonstrators of the iterative side of earthing design whereby engineers start off with a general model and change these with respect to the potential outputs.

The final section analyses the lightning protection mechanism and it can be verified from the results that these remain below the standard 10Ω imposed by the IEC 61024 proving the design was successful from lightning protection perspective.
5. Conclusion

The purpose of this placement was to primarily gain a better insight of how to approach a given project from an industrial perspective. In other words, it stressed the importance of meeting deadlines, working as part of team in order to meet customer specifications and ultimately work on projects that have particular budgets allocated to them. This is quite a distinct way of approaching tasks especially when compared to the student perspective.

In addition, this placement helped enhance knowledge regarding the design of onshore wind farm earthing systems. With the current demand in renewable energies increasing, and with society shifting towards a more environmentally considerate mentality, this project is quite relevant to current affairs and it’s one the reasons this investigation seems particularly enticing.

Prior to commencing this investigation, several aims and objectives were set outlining several theoretical and practical tasks that had to be accomplished. This technical report essentially helps prove these goals were achieved as the knowledge obtained concerning the actual design of the earthing system and the calculations that determine the overall impedance and Rise of Earth Potential for instance are clearly defined. In addition, practical experience was obtained, i.e. knowledge on the earthing software CDEGS was augmented.

Having analysed both case studies, it is apparent that despite numerous initial differences, such as the soil models, fault currents and the switchgear maximum fault clearance times, the earth grid design always starts with the same starts with the same basic model and this is eventually subject to change depending on the various potential outputs. From the results obtained it can be verified that Wind Farm A was a COLD site whereas Wind Farm B was a HOT site and the fact that the first site was greater in area and thus had a larger earth grid that helped dissipate the fault current contributed towards this lower Rise of Earth Potential. In addition, it can be verified that Wind Farm A also has lower soil resistivity when compared to the latter site and this suggests the site has lower soil impedance ultimately resulting in a lower Rise of Earth Potential. Therefore, there are several reasons as to why these two sites end up with different designs, however, the important factor to note is that these start under the same principles.
In conclusion, this investigation can be considered successful as firstly valuable industrial experience was obtained and practical and theoretical knowledge regarding the design of earthing systems was enhanced.
References


Appendices

Appendix A: C1 Curve – IEC 479
Appendix B: Wind Farm A – Site Layout
### Resistivity Test Results/Analysis

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**Project:** Roade Wind Farm

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</table>
Appendix D:

Part 1: Images of RESAP Module Within CDEGS

Part 2: Wind Farm A – Graph Plots of Resistivity

Wind Turbine Generator 1 (WTG 1)
Wind Turbine Generator 2 (WTG 2)

Wind Turbine Generator 3 (WTG 3)
Wind Turbine Generator 4 (WTG 4)

Metric/Logarithmic X and Y

Inter-Electrode Spacing (meters)

Wind Turbine Generator 5 (WTG 5)

Metric/Logarithmic X and Y

Inter-Electrode Spacing (meters)
Wind Turbine Generator 6 (WTG 6)

Wind Turbine Generator 7 (WTG 7)
Wind Turbine Generator 8 (WTG 8)

Wind Turbine Generator 9 (WTG 9)
Met Mast

![Graph of Metric/Logarithmic X and Y](image)

Substation

![Graph of Metric/Logarithmic X and Y](image)
Average

Metric/Logarithmic X and Y

Legend

- Measured data
- Computer results curve
- Trench

Measurement Method: Werner

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<th>Thickness (m)</th>
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Apparent Resistivity (Ohm-meters) vs. Inter-Electrode Spacing (meters)
Appendix E: Wind Farm A – Rise of Earth Potential

Report #1:

DATE OF RUN (START)= DAY 8 / Month 10 / Year 2013
STARTING TIME= 26:14:42:72

--------------- N A L Z (SYSTEM INFORMATION SUMMARY) ----------------

Run ID: ... mode
System of units: ................. Metric
Earth Potential/Magnetic Field Calculations: Potentials
Number of Energization Source Busses: .......... 1
Current Injected in Reference Source Bus: 1637 amps
Energization Scaling Factor (SPLITS/FCOST/specified): 1.0000
Number of Original Conductors: ....... 205
Number of Frequency Values to be Analyzed: ....... 1
Power Source Frequency: ................. 50.000 Hertz
Impedance Values are Based on: ................... 50.000 Hertz
Total Length of Conductor Network: .......... 6402.3 meters

CHARACTERISTICS OF MEDIA SURROUNDING NETWORK

Air layer: Resitivity: ................. 0.100000E+13 ohm-meters
Relative Permittivity: ................. 1.00000
Relative Permeability: ................. 1.00000

>> SOIL TYPE: Multi-Layer Horizontal

LAYER RESISTIVITY [ (ohm-meter) ] RELATIVE PERMITTIVITY PERMEABILITY [ (meters) ] THICKNESS [ (meters) ]

1 15.8344 1.00000 1.00000 0.718189
2 15.8344 1.00000 1.00000 0.2496
3 107.296 1.00000 1.00000 Infinite

Case Number: ................. 1
Frequency for This Case: .......... 50.000 Hertz
GPR of Reference Source Bus (# 1)... Magn.: 193.3434 Volts
Angle: 20.790687 degrees

Impedance of Grounding System: ................. Magn.: ...

End of Report #1
Appendix F: Wind Farm A – Touch and Step Potential Touch Potentials

Wind Turbine Generator 1 (WTG 1)

Wind Turbine Generator 2 (WTG 2)
Wind Turbine Generator 3 (WTG 3)

Wind Turbine Generator 4 (WTG 4)

Wind Turbine Generator 5 (WTG 5)
Wind Turbine Generator 6 (WTG 6)

Wind Turbine Generator 7 (WTG 7)

Wind Turbine Generator 8 (WTG 8)
Wind Turbine Generator 9 (WTG 9)

Step Potentials
Wind Turbine Generator 1 (WTG 1)

Wind Turbine Generator 2 (WTG 2)
**Wind Turbine Generator 3 (WTG 3)**

![Diagram](Image1)

**Wind Turbine Generator 4 (WTG 4)**

![Diagram](Image2)

**Wind Turbine Generator 5 (WTG 5)**

![Diagram](Image3)
Wind Turbine Generator 6 (WTG 6)

Wind Turbine Generator 7 (WTG 7)

Wind Turbine Generator 8 (WTG 8)
Wind Turbine Generator 9 (WTG 9)

![Diagram of Gradient Step Voltage Magn. (V/M)]
Appendix G: Wind Farm B – Site Layout
### Appendix H: Wind Farm B – On site Soil Measurements

<table>
<thead>
<tr>
<th>Probe Spacing (metres)</th>
<th>WTGA1 Resistance (Ohms)</th>
<th>WTGA2 Resistance (Ohms)</th>
<th>WTGA3 Resistance (Ohms)</th>
<th>WTGOE1 Resistance (Ohms)</th>
<th>WTGOE2 Resistance (Ohms)</th>
<th>Substation Resistance (Ohms)</th>
<th>Average Soil Resistance (Ohms)</th>
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<td>0.18</td>
<td>0.31</td>
<td>0.29</td>
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Appendix I: Wind Farm B – Soil Resistivity Plots

Wind Turbine Generator A1 (WTG A1)

Wind Turbine Generator A2 (WTG A2)
Wind Turbine Generator A3 (WTG A3)

Wind Turbine Generator OE1 (WTG OE1)
Wind Turbine Generator OE2 (WTG OE2)

Substation
Appendix J: Wind Farm B – Rise of Earth Potential

Potential Profile Magnitude (Volts)

Legend:
- Maximum Value: 532.044
- Minimum Value: 35.102
- Colors represent potential magnitudes:
  - < 800.00
  - ≤ 650.00
  - ≤ 430.00
  - ≤ 200.00
  - ≤ 100.00

Potential Profile Magnitude (Volts)
DATE OF RUN (START) = DAY 15 / MONTH 10 / YEAR 2013
STARTING TIME = 15:45:48/73

------------- M A L Z (SYSTEM INFORMATION SUMMARY) ------------
Run ID. ........................................ sitecontour
Earth Potential/Magnetic Field calculations : Potentials = Magnetic Fields
Number of Energization Source Waves ........ 1
Current Injected in Reference Source Bus........ 1966 Amps
Energization Scaling Factor (SPLITS/FCDIST/specified).... 1.0000
Number of Original Conductors .............. 291
Number of Frequency values to be Analyzed... 1
Power Source Frequency....................... 50.000 Hertz
Impedance Values are Based On................ 50.000 Hertz
Total Length of Conductor Network .......... 3763.1 meters
1

CHARACTERISTICS OF MEDIA SURROUNDING NETWORK
----------------------------------------------------------
AIR LAYER : Resistivity......................... 0.19000E+13 ohm-meters
Relative Permittivity,.. 1.00000
Relative Permeability,.. 1.00000

>>> SOIL TYPE : Multi-Layer Horizontal

<table>
<thead>
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<th>Layer Resistivity (ohm-meter)</th>
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<th>Permeability</th>
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Case Number............................ 1
Frequency for this Case.............. 50.000 Hertz
GPR of Reference Source bus (# 1)..... Magn. : 791.4735 Volts
Angle : 14.26648 degrees

Impedance of Grounding System........ Magn. : 0.4027841 Ohms
Angle : 14.26648 degrees

End of Report #1
Appendix K: Wind Farm B – Contractor’s Turbine Specification
Appendix L: Wind Farm B – Touch and Step Potentials

Touch Potentials

Wind Turbine Generator A1 (WTG A1)

3 Conductors:

6 Conductors:
**Wind Turbine Generator A2 (WTG A2)**

3 Conductors:

---

**Wind Turbine Generator A3 (WTG A3)**

3 Conductors:
6 Conductors:

Wind Turbine Generator OE1 (WTG OE1)
3 Conductors:

6 Conductors:
Wind Turbine Generator OE2 (WTG OE2)

3 Conductors:

6 Conductors:
Substation

Trial 1:

Trial 2:
Trial 3:

Step Potentials
The main trials were performed on the touch potentials section since its design will be adequate for the step potentials. It can be verified the 6 connector design developed in the previous section also step potential limits.

Wind Turbine Generator A1 (WTG A1)
6 connectors:
Wind Turbine Generator A2 (WTG A2)
6 connectors:

Wind Turbine Generator A3 (WTG A3)
6 connectors:

Wind Turbine Generator OE1 (WTG OE1)
6 connectors:
Wind Turbine Generator OE2 (WTG OE2)
6 connectors:

Substation