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Solutions and Calculation Methodologies for Earthing Systems in Wind Farms and PV Plants

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Resumo

A segurança e a eficiência das instalações elétricas são as duas questões mais importantes na concepção de um projeto de energia renovável. Portanto, é altamente relevante compreender os fatores que levam a um dimensionamento adequado das redes de terras. Com o crescimento exponencial dos parques eólicos e dos parques solares fotovoltaicas, é importante estudar os métodos e tecnologias para garantir que as redes de terras conseguem cumprir bem a sua função: proteger as pessoas e os equipamentos. A influência de vários parâmetros dos quais dependem as redes de terras, como a resistência do solo, a magnitude da corrente de curto-circuito, o tempo de exposição à corrente de curto-circuito, a profundidade da rede de terras, a sua estrutura e características, são os parâmetros mais importantes que serão estudados para entender como otimizá-los. Neste estudo, será testada a comparação entre diversos métodos de cálculo de redes de terras em parques eólicos e solares fotovoltaicas para melhor entender quais métodos utilizar para cada caso, e como podem ser melhorados no futuro.

Abstract

The safety and efficiency of electrical installations are the two most important issues when designing a renewable energy project. Therefore, it is highly relevant to understand the factors that lead to an appropriate sizing of earthing systems. With the exponential growth of wind and solar photovoltaic plants, it is important to study the methods and technologies to ensure that the earthing systems manage to do their job properly: protect people and equipment. The influence of various parameters on which earthing systems are dependent, such as ground resistance, magnitude of the short-circuit current, time of exposure to fault, how deep the ground grid is buried, its structure and features, are the most important parameters that will be studied in order to understand how to optimize them. In this study, the comparison between various calculation methods for the earthing systems in wind and photovoltaic plants will be tested to better understand which methods to use for each case, and how they can be improved in the future.

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Abrevittions and Symbols

List of abreviattions

GPR	Ground Potential Rise
LV	Low Voltage
MV	Medium Voltage
RMSE	Root-Mean-Square Error
RSSPTS	Regulamento de Segurança de Subestações e Postos de Transformação e Seccionamento
RTIEBT	Regras Técnicas de Instalações Elétricas de Baixa Tensão
TCAP	Heat capacity of the conductor per unit volume

Symbol list

A	Area occupied by the mesh
a	Spacing
b	Radius of the foot
C^r	Correction factor
C_s	Constant
D_f	Depreciation factor
E_{step}	Step voltage
E_{touch}	Touch voltage
h	Depth at which the conductor is buried
I	Current
I_f	Total fault current
I_G	Maximum current flowing through the earthing system
I_g	Symmetrical current flowing through the earthing system
I_o	Zero-sequence fault current
I_1	Current injected by the substation under consideration into the transmission line through the earth wire

I_2	Current received by the adjacent substation through the earth wire of the transmission line
I_L	Current injected by the substation under consideration into the transmission line through the phase conductor
I_r	Current injected by the adjacent substation into the transmission line through the phase conductor
k	Constant
L_T	Buried conductor length
R	Resistance
R_g	Earthing grid resistance
R_{g1}	Adjacent substation's equivalent resistance
R_{Ti}	Resistance of one pole of the transmission line
S_f	Split factor
S_{min}	Minimum cable cross-section
T_a	Room temperature
T_m	Conductor melting temperature
t_f	Duration of the fault
V	Voltage
X/R	Ratio of the system inductive reactance to resistance
Z_{eq}	Equivalent resistance of the network connected to the grounding system
Z_{m1}	Impedance of the path created in case of a phase-to-neutral short circuit
Z_{ph}	Impedance of the phase conductor
$Z_{S\ i+1}$	Impedance of the span between poles
ρ	Resistivity of the soil
ρ_1	Electrical resistivity of the first layer
ρ_2	Electrical resistivity of the second layer
ρ_s	Resistivity of the layer in contact with the surface

Chapter 1

Introduction

In recent years, the awareness of the general public on how climate change will affect future generations had a big impact on the need of switching from a society depending mainly on non-renewable energy to a cleaner and more responsible way to produce energy. With the constant increase in the number of photovoltaic plants and wind farms, it's important to make sure the system is safe and can respond effectively when a short-circuit happens, either from natural causes, or human errors.

When electricity moved from laboratories to the public in the 19th century, the issue of safety was one of the biggest problems as people were afraid of having electricity in their homes and still didn't see it as a basic need. So, safety with regard to electricity has always been the most important aspect. Back in the 19th century, grids were relatively simple, and as the demand for electricity grew, so did the complexity of earthing systems. Among the general population, earth grids are best known for draining currents from lightning strikes, since these phenomena are recurrent and cause concern due to the visual impact of this type of currents.

With the worsening of global warming, renewable energies have become a clean alternative to fossil fuels, namely solar energy and wind energy. Since photovoltaic plants and wind farms are getting bigger and more powerful, the ground grid will need to be more robust in order to protect the system from bigger short-circuit currents. Thus, since these systems have different structures, their earthing systems will also have different structures, which can be studied in order to increase their efficiency and reduce their costs.

Due to the increase in the size of the electrical systems, it was necessary to increase the protection measures of the systems. In 1836-1837 a german scientist named Carl August Steinheil discovered that the ground conductor could be used as a return path to complete the circuit, making the return wire unnecessary. The earth grids have thus become a fundamental part of various day-to-day installations, such as the electrical installations in our homes.

Introduction

Earthing systems present challenges as photovoltaic and wind systems need to be safe, but also efficient and cost effective. By studying different methods of grounding, the system can improve its reliability when the ground grid works properly.

Chapter 2

Validation of the Grounding System

Although the principle of grounding systems is always very similar, there are several systems with different functions. The best-known systems are: electrical grounding, signal grounding, radio frequency (RF) grounding, lightning grounding, and finally electrostatic discharge (ESD) grounding.

Electrical grounding is used to protect people and equipment from electrical shock and to provide a path for fault current to flow in the event of a fault or short circuit. This is the grounding system on which the work will be based on.

Signal ground is used to establish a common reference point for electrical signals in a circuit or system. Signal grounding is important to maintain the integrity and accuracy of transmitted signals.

Radio frequency (RF) grounding is used in circuits and systems to provide a low impedance path for RF currents and reduce the risk of RF interference. RF grounding systems may include a combination of conductive and inductive elements to provide the desired impedance characteristics.

Electrostatic discharge (ESD) grounding is a type of grounding system used to protect electronic devices and systems from damage caused by electrostatic discharge. ESD grounding systems typically include conductive materials and grounding straps that are used to dissipate any built-up static electricity.

2.1 - Damage Caused by the Passage of Electric Current in the Human Body

Electric shock is defined as a sudden violent response to electric current flow through any part of a human's body. Electrocution is death caused by electric shock. [11]

The effects current can have on humans and animals depends on factors like the magnitude and duration of the current, and in which specific circumstances it happens. Some of the

potential effects of current on humans and animals include shock, which is a sudden and potentially dangerous flow of current through the body, which can result in difficulty breathing, muscle spasms, and even cardiac arrest which can lead to death. Some of the other effects are burns, which is the most common and the severity can range from mild to severe, neurological effects that are caused by the flow of current through the brain which may result in symptoms such as confusion, dizziness, and loss of consciousness, and in extreme it can cause long-term or even permanent damage to the nerves and brain. In last, muscular tension also happens frequently, causing, for example, the hand to close involuntarily when touching a live mass or cable, which can aggravate the consequences of electric shock.

The path that the current travels will also influence the consequences of the electric shock. For example, if the path that the current takes passes between the left hand and the feet, it will be more serious than if it passes between the right hand and the feet. This is because the heart is located on the left side of the human body, and current can interfere with the normal functioning of the heart, disrupting the normal electrical signals that control the contraction of the heart, leading to abnormal heart rhythm, known as arrhythmia.

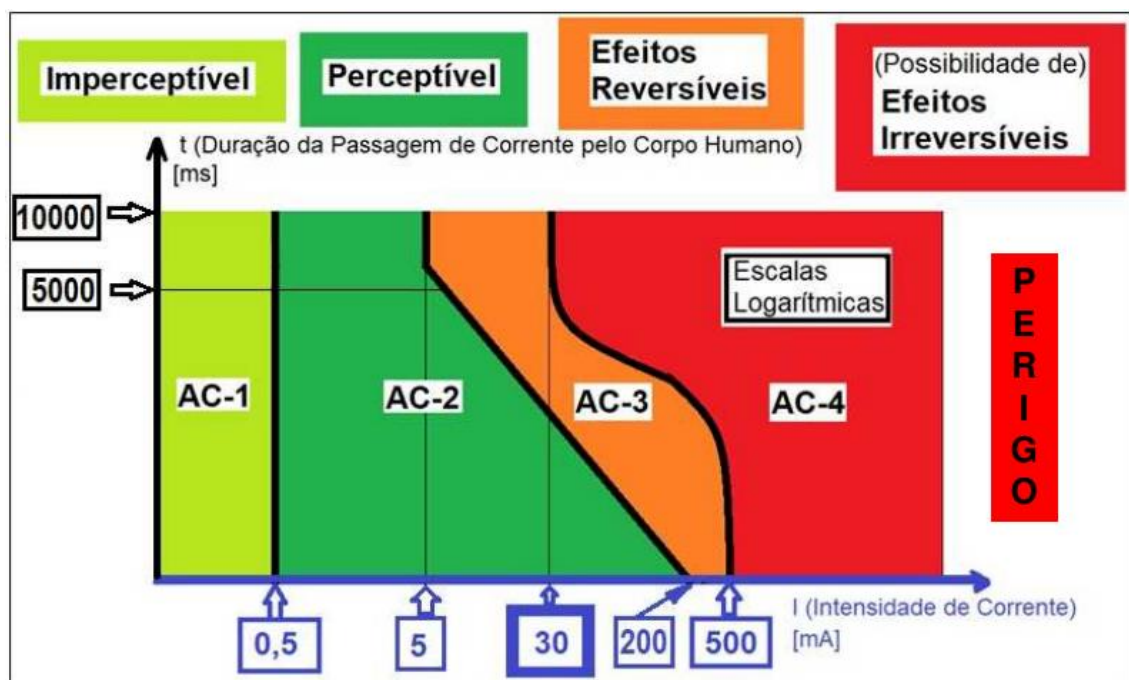


Figure 2.1 - Danger of current passing through the human body over time [1]

There are some ways to prevent faults and consequently electrical shocks from occurring in the grounding grids. Since the state of the ground electrode and its connections can degrade over time, leading to an increase in the earth resistance of the system, regular maintenance is a way to prevent faults from happening.

2.2 - Grid Parameters

Fault current is an electrical current that flows through an electrical power system when a fault or abnormal condition occurs, such as a short circuit or ground fault. When a fault occurs, the fault current can cause equipment damage, power interruptions, electrical fires, or even electrocution in extreme cases, if the system isn't properly protected.

Understanding why fault currents occur and implementing appropriate protection measures is essential for the grounding system to be able to maintain the safety and reliability of people and electrical power systems.

There are several types of short-circuits that can happen:

- **Phase-to-phase short circuit:** This type of fault occurs when two phase conductors come into contact with each other, bypassing the load and creating a direct low resistance path between the phases. They can cause high levels of fault current and can result in equipment damage and even electrical fires. Despite not being directly related to the grounding system, they can cause equipment malfunction, and consequently pass the current to the grounding system. They are more common than the three-phase short circuits, but less common than phase-to-ground short circuits.
- **Phase-to-ground short circuit:** This occurs when a phase conductor encounters a grounded surface, such as a metal casing or the earth. This creates a low resistance path between the phase conductor and the ground, which can cause fault current to flow through the ground and can lead to equipment damage and electrical hazards. Phase-to-ground short circuits are the most common since only one line needs to deteriorate or break, which can cause a connection to the ground. This scenario can happen, for example, if a tree is teared down due to harsh weather and ends up falling into an electrical wire.
- **Phase-to-Phase-to-Ground short circuit:** A phase-to-phase-to ground short circuit occurs when two phases of the system come in contact with each other and one of those phases comes in contact with the ground. This is a rarer case than the phase-to-ground short circuit, but also more dangerous.
- **Phase-to-Phase-to-Phase-to-Ground short circuit:** This type of fault occurs when all three phase conductors come into contact with each other or with a grounded surface simultaneously, creating a direct low resistance path between all three phases. This type of short circuit can cause extremely high levels of fault current and can result in

severe damage to equipment and electrical hazards. However, this scenario is the least likely to happen because of the conditions necessary for it to happen.

Fault currents can occur in a system due to various reasons. Some of these are presented below.

- Inappropriate conductor sizing: If the wiring is improperly installed or maintained, it can lead to insulation breakdown, which can cause a phase-to-phase short circuit.
- Mechanical damage: Physical damage to the conductors or insulation, such as crushing or cutting.
- Equipment failure: If equipment, such as motors or transformers, fails due to insulation breakdown or other issues, it can create a phase-to-phase short circuit.
- Human error: Accidentally crossing or connecting two or more phase conductors can also cause a phase-to-phase short circuit.

The effects of short circuit currents can sometimes be reduced by introducing a current limiting reactor in the installation. The current limiting reactor is an inductive component that allows limiting the short-circuit current, usually to a value between 100 A and 1000 A, producing an acceptable voltage drop during normal operation, and high enough voltage drop during a fault to reduce the short-circuit current. However, the maximum current allowed by the resistance must be high enough to trigger the circuit breaker that protects the installation. This component helps to reduce system damage and its stability. However, it increases the complexity of the system and its cost.

Although short circuits can appear in many places on installations, there are places that are more likely to happen than others, which are the cases worth studying for the sizing of the grounding systems.

In substations, the line gantry of the transmission lines are highly likely to suffer a short circuit, so this will be the first place where the occurrence of defects will be simulated in the practical part of this dissertation.

In PV plants, the short circuit may occur at transformer stations. Despite its fault current being much lower than the fault current in the substation, this is also a case to consider and will also be studied.

Finally, in wind farms, faults can occur directly in one of the wind turbines, due to atmospheric discharges or defects in the primary of the turbine's transformer. Again, this case will also be studied.

Chapter 3

Soil Model Study

Earthing systems are designed to protect people and equipment against high electrical currents in the systems, draining them to the ground, where the resistance should be closest to zero, which is preferable for the passage of current. The grounding system is also used as a reference to connect equipment. Due to the difference in potential between certain equipment and a human or other equipment, there is a displacement of particles carrying an electric charge, that is, an electric current.

3.1 - Location

The performance and efficiency of grounding systems are directly related to the ability of the soil to drain the fault current, and therefore, choosing the location of the system's implementation is crucial.

3.2 - Location of Wind Farms

Wind farms are typically installed in mountainous regions where strong wind is more common, which allows the turbines to produce as much energy as possible. However, in these regions the soil is rocky, which causes the soil resistivity to be very high. In order to reduce the resistance of the grounding system, the upper soil layer can be replaced by soil with least resistivity, or ground enhancement material (GEM) can be used to reduce the overall resistance of the system. This last topic is covered in more detail in chapter 7.

Furthermore, when a wind farm is built in a mountain, the risk of a lightning strike the wind turbine is very high. The lightning current flows through the blades, rotor and tower, which can damage the components of the turbine if the grounding system isn't properly sized [12].

3.3 - Location of Solar Parks

PV plants can have a big dimension, so it is necessary to take several measures over the entire land and create a soil model suitable for the implementation area.

Temperature and humidity also influence the performance of the grounding system as can be seen in the next section.

3.4 - Solar Park Location

Grounding grids depend on factors like the soil electrical resistivity, the ground fault current and its duration, therefore a study of the soil where we want to build the system is crucial. While many factors come into play in determining the overall effectiveness of the grounding system, the resistance of the earth itself (earth resistivity) can significantly impact the overall impedance of the grounding system and therefore it is important to obtain an accurate measurement of the soil resistivity [13]. Several factors, such as moisture content, mineral content, soil type, soil contaminants, etc., to determine the overall resistivity of the earth. In general, the higher the soil moisture content, the lower the soil's resistivity. Systems designed for areas which typically have very dry soil and arid climates may need to use enhancement materials or other means to achieve lower resistivities. Thus, the size and structure of the grounding system will be highly dependent on the soil resistivity.

3.5 - Temperature Effects

Temperature can also affect soil resistivity. This is because the electrical conductivity of soil is primarily dependent on the presence of moisture and the movement of ions through that moisture [14].

High temperatures can cause evaporation, reducing the moisture content of the soil, which tends to increase resistivity as the number of ions available for conduction decreases.

On the other hand, cold temperature can increase soil resistivity. This is because at low temperatures, the moisture content of soil tends to decrease due to freezing or decreased evaporation rates. As a result, the number of ions available for conduction decreases, which leads to a higher resistivity.

3.6 - Water Content Effects

Moisture refers to the presence of water or other liquids in the form of small droplets or particles in the air, on a surface, or in a substance. Water is a good conductor of electricity to some extent. When comparing it to metals, like copper or aluminium, it's not very conductive. The presence of ions in water it's what gives it the capability of conducting electricity. Since a

richer mineral content in water means higher concentration of dissolved salts, waters with high mineral content have a greater ability to conduct electric energy.

This is the reason the water content in the soil will affect its resistivity, not only by the quantity of liquid present, but also by the mineral content.

3.7 - Geotechnical Study

In order to get the soil resistivity values, it is necessary to carry out a geotechnical study, where several measures are made at different spacings. Depending on the size of the installation, the measures need to include most of the soil of the installation. For substations the measures are taken in places close to one another, while for PV plants and wind farms need to be taken in several distant places of the installation. This can be done through different methods. The first one is the Wenner Four Electrode Method and it's the most used method due to its simpler resistivity formula and implementation in the field.

3.7.1 - Wenner Four Electrode Method

In order to obtain more reliable values, normally several resistivity tests are carried out, with different spacings, in places close to the first test. To make these measures, the Wenner four-electrode method is the most commonly used. The method is named after its inventor, the American geophysicist Frank Wenner. This method consists in placing four pins along a straight line at equal distances, depths and injecting a current into the ground through two outer electrodes and measuring the resulting voltage drop across the two inner electrodes.

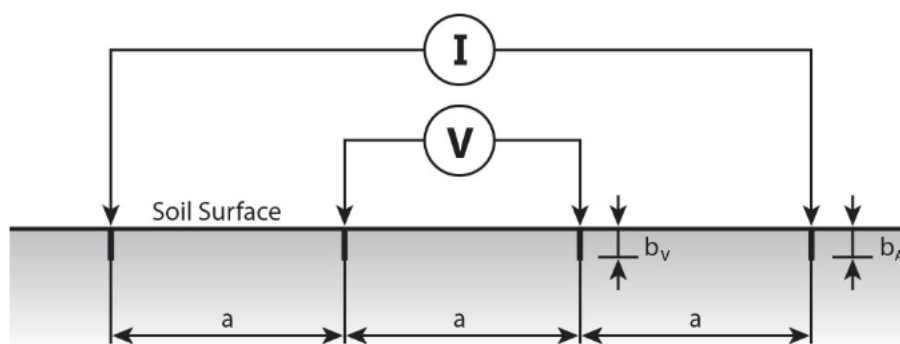


Figure 3.1 - Wenner Four Electrode Method [2]

To use this method properly, the presented steps should be followed:

- Choosing an appropriate location for the test, where the soil should be relatively homogeneous and free from any large conductive objects or moisture.

- Four electrodes are inserted into the soil, forming a straight line, and the distance between two electrodes is noted as "d".
- A current, typically in the range of 10 to 100 milliamperes, is injected into the ground through the two outer electrodes, and the resulting voltage drop is measured across the two inner electrodes using a voltmeter.
- The electrode spacing is increased, and the current and voltage measures are repeated for several different electrode spacings.

Using the Wenner formula, the resistivity of the soil is calculated by:

$$\rho = \frac{2\pi aV}{I} \quad (3.1)$$

Where:

- ρ is the resistivity of the soil in ohm per meter [$\Omega \cdot m$];
- a is the electrode spacing in meters [m];
- V is the voltage drop in volts [V];
- I is the injected current in amperes [A].

The resistivity values are plotted against the corresponding electrode spacings on a graph, and a curve is fitted to the data.

The curve's slope is proportional to the resistivity of the soil, and this value can be used to determine the soil's electrical properties.

The ratio between depth and spacing is usually between 1:1 and 1:2.

3.7.2 - Schlumberger Method

The Schlumberger method is also used to determine the electrical resistivity of the soil. However, the distance between the two inner electrodes is different from the distance between the outer electrodes and the inner electrodes, making it harder to implement than the Wenner Four Electrode Method.

Contrary to what happens in the Wenner method, in the Schlumberger method the positions of the electrodes are changed during the test.

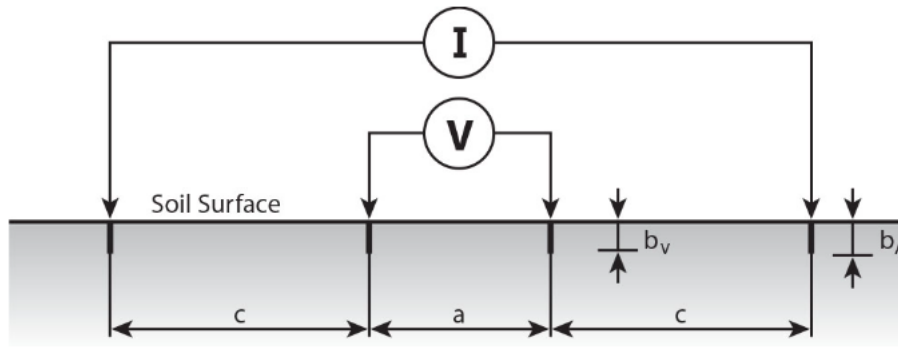


Figure 3.2 - Schlumberger Method [2]

For this method, the apparent resistivity can be calculated as shown in equation 1.2.

$$\rho = \pi \times \frac{c \times (a+c) \times V}{a} \times \frac{V}{I} \quad (3.2)$$

Where:

- ρ is the resistivity of the soil in ohm per meter [$\Omega \cdot m$];
- a is the electrode spacing in meters [m];
- V is the voltage drop in volts [V];
- I is the injected current in amperes [A].

Similar to what happens with the Wenner Four Electrode Method, the ratio between depth and spacing is usually between 1:1 and 1:2.

3.7.3 - Root Mean Square Error (RMSE)

After obtaining soil resistivity values for different depths and locations close to the future grounding grid, it is necessary to correct these values, eliminating those with the greatest measure error.

The root mean square error method, or root mean square deviation method, is one of the most commonly used methods to evaluate the quality of predictions, which in this case, will be the soil resistivity values. The result of this method allows to find the group of measures with the least error. The lower the error the most accurate the measures will be, which is essential to ensure the safe and effective operation of the grounding system.

The formula for calculating the root-mean-square error (RMSE) is as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (Predicted_i - Actual_i)^2}{N}} \quad (3.3)$$

Where:

- Predicted_i are the predicted values;
- Actual_i are the actual values;
- N is the number of observations available for analysis.

3.7.4 - Surface Material

Grounding systems are designed to provide a low impedance path for unwanted currents by flowing them to the ground, which reduces the risk of electrical hazards and helps electrical equipment to work properly.

The use of a protective layer above-ground can help isolate a person from an electric shock by increasing the resistance between the surface of the ground and the person or equipment in contact with it. Due to a higher resistivity when comparing it to the soil, the electric current drained into the soil will have difficulty to go beyond the gravel layer, which increases the tolerable touch and step voltages, reducing the risk of electric shock. For this matter, the most common materials are granite gravel and limestone gravel.

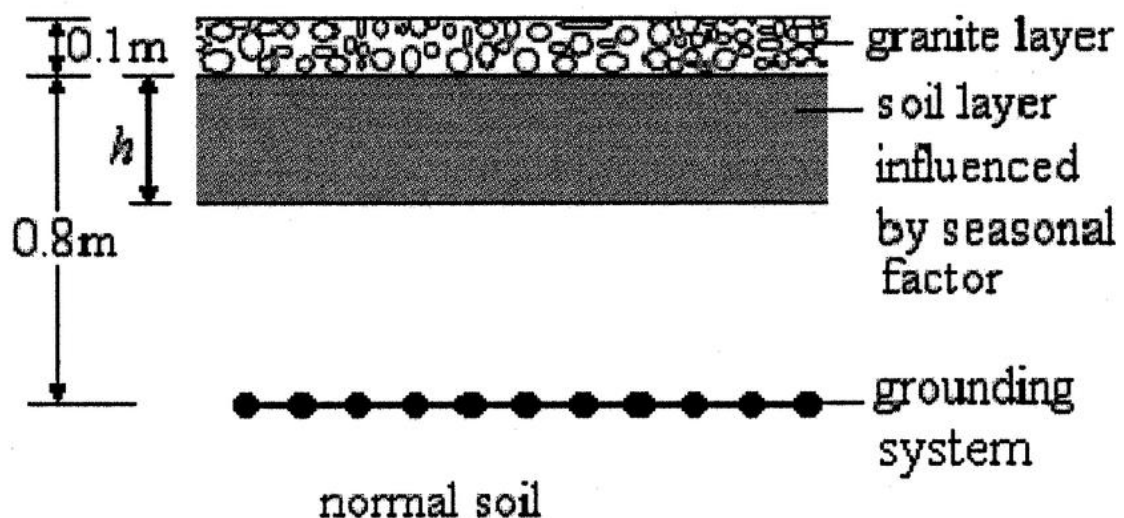


Figure 3.3 - Soil layers [3]

Gravel is a type of loose, granular material that consists of rock fragments or small stones. Gravel can be found naturally in rivers, streams and oceans, or it can be produced by crushing larger stones. This material is often used on infrastructures that we come across daily, including roads, bridges, railways, and even landscapes. Gravel can be made up by various types of rocks, including granite and limestone, which are the most relevant for grounding systems. This layer has normally a thickness between 0.05m and 0.15m.

Gravel is widely used in substations due to its high efficiency, and less used in solar parks or wind farms due to their large size, which also translates into a high cost. With regard to wind farms, a layer of concrete is introduced into the foundation of each wind turbine, which, although being buried, it will act as a surface layer in terms of protecting people in the turbine from dangerous voltages [15].

Limestone gravel has a high resistivity, approximately 3000 $\Omega\cdot\text{m}$, which makes it a good material for the above-ground layer. It is also a durable and hard material, known for its ability to resist corrosion and erosion.

For a scenario in which the grounding system has very high maximum touch and step voltages and it is not possible to validate it with limestone gravel, granitic gravel is normally used, which has a higher resistivity of 5000 $\Omega\cdot\text{m}$.

The first gravel to be tested is the limestone gravel as it's usually the least expensive one. In extreme cases, bituminous asphalt can be used, as it has a resistivity of 10000 $\Omega\cdot\text{m}$. However, its cost is even higher than the cost of granitic gravel.

The resistivity of each material will vary depending on if the material is dry or wet.

Table 7—Typical surface material resistivities

Number	Description of surface material (U.S. state where found)	Resistivity of sample, Ω -m	
		Dry	Wet
1	Crusher run granite with fines (NC)	140×10^6	1300 (ground water, 45 Ω -m)
2	1½ in (0.04 m) crusher run granite (GA) with fines	4000	1200 (rain water, 100 Ω -m)
3	¾ in to 1 in (0.02 m to 0.025 m) granite (CA) with fines	---	6513 (10 minutes after 45 Ω -m water drained)
4	No. 4 (1 in to 2 in) (0.025 m to 0.05 m) washed granite (GA)	1.5×10^6 to 4.5×10^6	5000 (rain water, 100 Ω -m)
5	No. 3 (2 in to 4 in) (0.05 m to 0.1 m) washed granite (GA)	2.6×10^6 to 3×10^6	10 000 (rain water, 100 Ω -m)
6	Size unknown, washed limestone (MI)	7×10^6	2000 to 3000 (ground water, 45 Ω -m)
7	Washed granite, similar to ¾ in (0.02 m) gravel	2×10^6	10 000
8	Washed granite, similar to pea gravel	40×10^6	5000
9	No. 57 (¾ in) (0.02 m) washed granite (NC)	190×10^6	8000 (ground water, 45 Ω -m)
10	Asphalt	2×10^6 to 30×10^6	10 000 to 6×10^6
11	Concrete	1×10^6 to 1×10^9 ^a	21 to 200

^aOven-dried concrete (Hammond and Robson [B79]). Values for air-cured concrete can be much lower due to moisture content.

Figure 3.4 - Surface Material Resistivities [19]

Figure 3.5 shows the soil modeling flowchart.

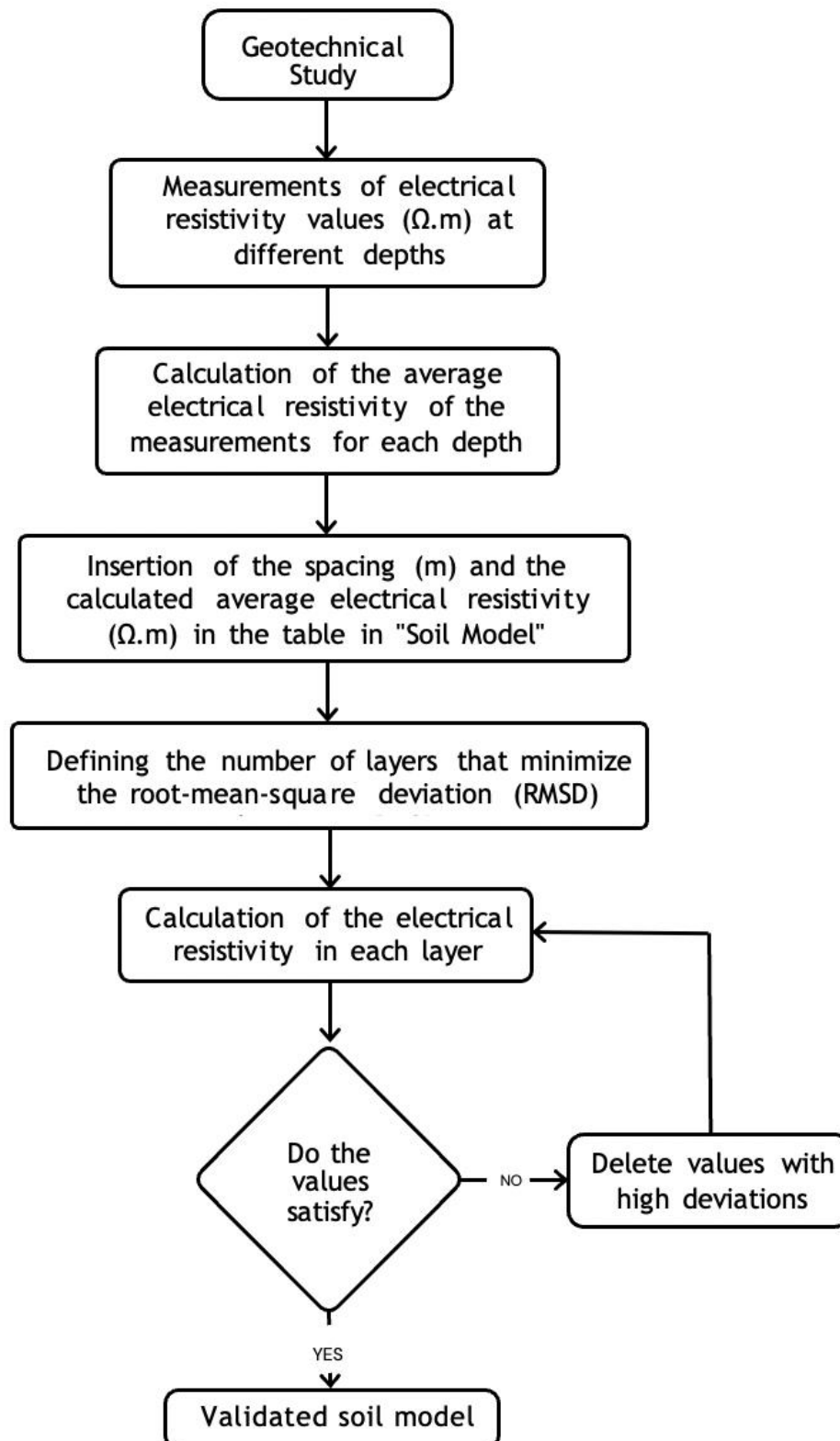


Figure 3.5 - Soil Model Flowchart [4]

Chapter 4

Accidental Circuits

After getting parameters relevant to this study, such as the earth fault current, fault duration, resistivity of the various soil layers, and considered resistance of the human body (may be 50kg or 70kg), the maximum allowable step and touch voltages can now be calculated.

4.1 - Touch Voltage

The touch voltage is the potential difference between an earthed metallic structure and a point on the ground surface at a distance equal to the normal maximum horizontal distance that it can touch, approximately 1 meter [16].

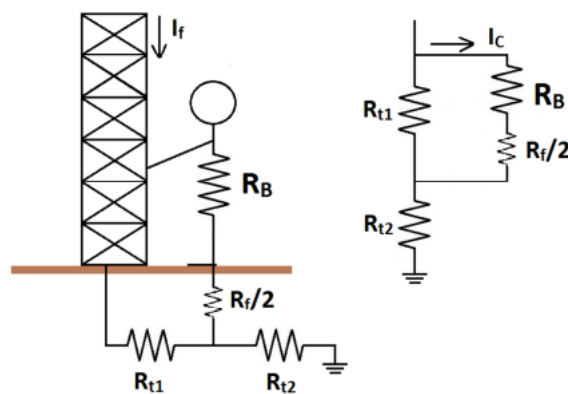


Figure 4.1 - Touch Voltage Equivalent Circuit [5]

4.2 - Step Voltage

The step voltage is the potential difference between two points on the ground surface, separated by a distance of one step, assumed to be 1 meter, in the direction of the maximum potential gradient [16].

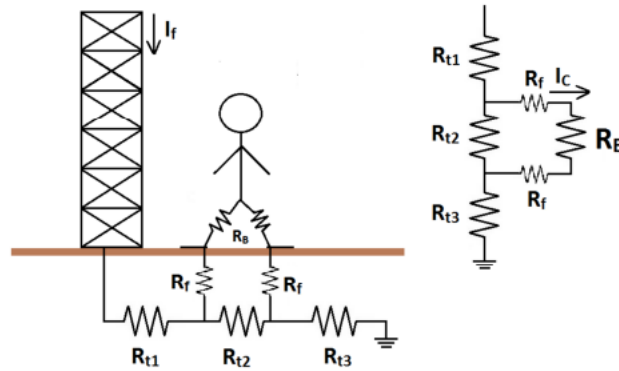


Figure 4.2 - Step Voltage Equivalent Circuit [5]

4.3 - Resistance

The resistance is an important factor to consider as a low impedance path allows the system to drain the excessive electric current in the system. For this matter, the IEEE-80 2013 standard recommends a resistance between 1 and 5 Ω , depending on the country where the earthing system will be built.

The foot of a human being can be modelled as a kind of plate that touches the ground. Its contact resistance can thus be approximately calculated by the following equation:

$$R = \frac{\rho}{4b} \quad (4.1)$$

Where ρ it's the resistivity of the ground and b the radius of the foot, modeled as a plate. Although a plate is not the same shape as a footprint, as long as the total area is similar, it will be an efficient method. To calculate the radius of the plate, the following formula is used:

$$b = \frac{A}{\pi} \quad (4.2)$$

In this equation, A is the area of the foot in contact with the ground. The average foot area of a human being is approximately 200 cm^2 . By using this value in the formula above, we arrive at a value of b equal to approximately 0.08m. Going back to the formula of the resistance of the plate:

$$R = \frac{\rho}{4 \times 0.08} = 3\rho \quad (4.3)$$

To calculate the total resistance of the grounding system, considering the soil resistivity, length of buried conductor, area occupied by the grounding grid and depth, the equation 57 of the IEEE-80 2013 standard is used.

$$R_g = \rho \left[\frac{1}{L_T} + \frac{1}{\sqrt{20A}} \times \left(1 + \frac{1}{1+h\sqrt{20/A}} \right) \right] \quad (4.4)$$

Where:

- R_g is the grid's resistance in ohms;
- L_T is the buried conductor length in meters;
- A is the area occupied by the mesh;
- h is the depth to which the conductor is buried.

This formula is only applied to uniform soils, so a formula will be needed for soils with several layers, which will also be studied in this thesis. In addition, this formula doesn't consider electrodes.

The formula 4.5 makes it possible to calculate the resistance of a ground mesh with electrodes in a soil with two layers with different resistivities.

$$R_g = 0.13 \times \frac{\rho_1}{\sqrt{A}} \times \left(1 - \frac{2}{3} \times \frac{l}{\sqrt{A}} \right) \times \log \left(\frac{2400 \times \sqrt{A}}{N} \right) \quad (4.5)$$

Where:

- ρ_1 is the electrical resistivity of the first soil layer in ohms per meter;
- l is the length of each electrode in meters;
- N is the number of electrodes in the mesh.

Due to the existence of a second layer, it is necessary to use the correction factor C^r .

$$C^r = \left(\frac{\rho_2}{\rho_1} \right)^x \quad (4.6)$$

Where:

- ρ_2 is the electrical resistivity of the second soil layer in ohms per meter;
- x is a constant.

The constant x depends on the ratio between the resistivities of the layers, one of the following equations being applied [18]:

$$x = 0.59 \times \log\left(\frac{15.5}{H}\right) + 0.016 \times \log(4.2 \times H) \times (\log(N \times \sqrt{A}))^2, \text{ se } \frac{\rho_2}{\rho_1} < 1 \quad (4.7)$$

$$x = 0.57 \times \log\left(\frac{8.5}{H}\right) + 0.06 \times \log(10 \times H) \times \log(N \times \sqrt{A}), \text{ se } \frac{\rho_2}{\rho_1} > 1 \quad (4.8)$$

Where:

- H is the depth of the first layer.

In order to determine the minimum dimensions of the conductor of the grounding system, the following equations is used, being S_{min} the minimum conductor section (mm^2).

$$S_{min} = \frac{I_f}{\sqrt{\frac{TCAP \times 10^{-4}}{t_f \times \alpha \times \rho_r} \times \ln\left(\frac{K_0 + T_m}{K_0 + T_a}\right)}} \quad (4.9)$$

Where:

- I_f , the total fault current (A);
- TCAP, is the heat capacity of the conductor per unit volume ($J/cm^3/^\circ C$);
- α , the coefficient of variation of resistivity at a temperature of $20^\circ C$;
- ρ_r , the conductor resistivity at a temperature of $20^\circ C$;
- K_0 , the result of $(1/\alpha) - 20$ ($^\circ C$);
- T_m , the conductor melting temperature ($^\circ C$);
- T_a , the room temperature ($^\circ C$).

The value of the minimum cross-section, as the name implies, only serves to limit the minimum cross-section that the cable can tolerate without being damaged. So, the cross-section chosen for the grounding system is not necessarily the standard section immediately above the calculated value.

The cross-section value used in PV plants and wind parks grounding systems varies depending on whether the cable passing through the trenches is for medium or low voltage. For medium voltage trenches, cables with a section of 50 or 70 mm^2 are normally used, and for low voltage 25, 35 or 50 mm^2 are used, depending on the radial distribution of the plant and the division of currents.

By using a higher cross-section, the contact between the grid and the ground increases, helping the system efficiently drain the fault current.

However, a minimum cross-section for grounding systems in PV plants and for wind farms is defined by the minimum cross-section of non-protected cables, which is 25 mm^2 , according to RTIEBT.

For substations, the minimum cross-section of the grounding system conductor is 50 mm^2 according to the RSSPT.

Regarding the material of the conductor in the meshes of grounding grids, it can be aluminium or copper. The decision between one material and another depends on factors such as resistivity, price, and safety. Although copper is five to eight times more expensive than aluminium, it's commonly used for earthing systems due to its better conductivity and endurance.

The voltage someone is exposed to if a short-circuit happens is also important in this study, mainly the voltage from a hand to the ground (touch voltage) and the voltage established between the person's feet (step voltage).

$$E_{touch} = \frac{(1000+1.5C_s \times p_s) \times k}{\sqrt{t_s}} \quad (4.11)$$

$$E_{step} = \frac{(1000+6C_s \times p_s) \times k}{\sqrt{t_s}} \quad (4.12)$$

In these equations, the t_s is the duration of the shock current, and k is a constant with a value of 0.155 or 0.116, for people with a body weight of 70 kg and 50 kg, respectively. The C_s is also a constant, and it is introduced when a thin layer of high resistivity material is spread on the earth's surface within the installation area, with the aim of increasing the resistance between people's feet and the ground, in order to reduce electric shock in case it happens.

A surface layer can be added to the soil with the goal of increasing the allowable touch and step voltage of the system. For this effect, gravel and bituminous asphalt can be used to increase the resistance in step voltage by providing a high resistance path for electrical current to flow through. This is done by laying a layer of the material over the surface of the ground. This helps to increase the resistance of the surface, not allowing electrical current to flow as easily, and reducing the potential of dangerous touch or step voltages to occur.

$$C_s = 1 - \frac{0.09 \times (1 - \frac{p}{p_s})}{2h_s + 0.09} \quad (4.13)$$

In this last equation, p (Ω) and p_s (Ω) are the resistance of the soil and of the material applied on the surface, respectively.

The estimates of touch and step voltages are made considering the maximum current that the human body can withstand without ventricular fibrillation, which in turn depend on the time a person is exposed to the current, their weight and as referred before, the value of the soil resistivity.

According to the IEEE Std 80-2013, the maximum current flowing through the earth grid, I_G , is obtained from the following equation:

$$I_G = D_f \times I_g \quad (4.14)$$

D_f is a depreciation factor that takes into account the dc offset of the asymmetrical short-circuit current, and it depends on the duration of the fault (t_f), and the X/R ratio indicates the dc offset decay, which is the ratio of inductive reactance to resistance of the system in the fault location.

$$D_f = \sqrt{1 + \frac{T_a}{t_f} \times (1 - e^{-\frac{2t_f}{T_a}})} \quad (4.15)$$

On the other hand, the symmetrical current flowing through the earth grid, I_g , is given by the following equation:

$$I_g = S_f \times I_f \quad (4.16)$$

S_f is the current split factor, and it represents the factor between the inverse of a ratio of the symmetrical fault current, and the current that flows between the ground grid and the surrounding earth. This factor can be calculated by the following equation.

$$S_f = \frac{I_g}{3I_o} \quad (4.17)$$

Where,

- I_g , is the rms symmetrical grid current (A);
- I_o , is the zero-sequence fault current (A).

Thus, the next step is to analyse the short-circuit current in order to know maximum current on the grid.

$$I_G = D_f \times S_f \times I_f \quad (4.18)$$

4.4 - Ground Potential Rise (GPR)

The GPR occurs when the fault current flows into the soil and creates a voltage drop between a certain location and the zone where the short circuit happened. The maximum value of the GPR corresponds to the maximum voltage drop that will occur in the installation. This potential is obtained by the product of the maximum current of the loop through the ground resistance [16].

$$GPR = I_G \times R_g \quad (4.19)$$

Then, it's needed to check if the following condition is verified:

$$\text{Ground Potential Rise (GPR)} < \text{Allowable Contact Voltage} \quad (4.20)$$

If the previous condition is verified, it will not be necessary to proceed with the touch and step voltage study, leaving that part of the grounding system validated. If it isn't, it will be necessary to resort to system optimization solutions to validate the contact and step voltages within the installations.

4.5 - Reach Distance

In large installations such as PV plants and wind farms, reach distance is used to limit the distance at which a person can touch a metal structure connected to the earthing system conductor, taking the potential in that conductor as a reference. Thus, if a person touches a metal structure that is far away from the short circuit location, only the voltage drop between the touched conductor and the person will be counted, instead of the voltage drop between the short circuit location and the person's position. In terms of simulation, SafeGrid doesn't have access to the metal structures above ground, and so it considers the earthing system as a touchable metal structure. The voltage drops more than 1.5 m away from the structure will automatically be set to zero.

Reach distance is an important approach to consider when there is certainty that some zones in the installation are further away than a person could touch. Usually, the considered reach

distance is 1.5 m, which is considered to be the maximum distance a standing person can touch. To be more conservative, higher distances can be used.

This effect helps to avoid oversizing grounding systems, by removing unrealistic voltage drops between the short circuit location and the person's location. In the practical part of this thesis, an example between the validation of PV plant with GPR and with reach distance will be made to understand their differences.

Chapter 5

Split Factor

When a new PV plant or wind farm is built, it is typically connected to other systems, such as substations, transmission lines and feeders. Thus, some of these systems have their own earthing system, and in the event of a short circuit in the installation in question, part of this current will be dispersed to the grounding system of another installation. For this reason, when designing an earthing system, the Split Factor effect must be taken into consideration, to assure that the system is safe, but not oversized. The split factor turns out to be nothing more than a current divider, in which part of the current is drained out of the new system's installations, and the other part remains in the new system.

5.1 - IEEE-80 2013 Norm Graphic Method

There are several ways to determine the split factor. The simplest way is to use graphics in the Annex C of the IEEE-80 2013 norm. These graphs show the percentage of current reaching the grounding system under consideration in relation to certain variables.

To use this method, it is necessary to know the following variables:

- The expected resistance of the earthing system in study (ranging from 0.1 Ω to 25 Ω);
- The remote and local fault current contribution;
- The number of transmission lines and feeders;
- The impedance to remote earth of each transmission ground electrode;
- The impedance to remote earth of each distribution ground electrode.

According to the IEEE 2013-80 norm, in practice the split factor changes during the fault duration due to decay of fault contributions and the sequence of interrupting device operations. However, for testing study purposes, the split factor is assumed to be constant during the entire duration of the short circuit.

5.2 - Substation Connected to a Transmission Line

Both wind farms and PV plants are connected to a substation responsible for ensuring a safe and efficient connection to the grid. Thus, substations are usually connected to the grid through overhead or underground transmission lines, responsible for distributing energy. All transmission lines have a shield wire that is grounded on each tower or pole, the short-circuit current is dispersed at each connection of the line to ground.

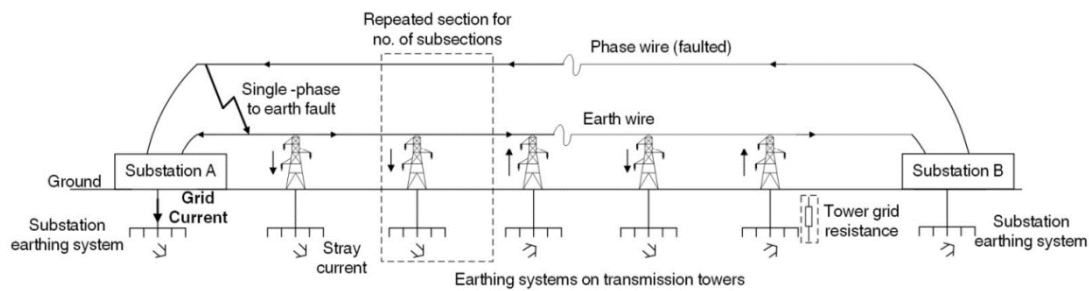


Figure 5.1 - Split factor on transmission lines [6]

In order to know the part of the current that is dispersed along the transmission line it is necessary to have the following information:

- Expected fault current;
- Line length;
- Number of poles;
- Phase conductor diameter;
- Phase conductor a.c. resistance;
- Earth conductor outer diameter;
- Earth conductor a.c. resistance;
- Cables positions;
- Individual earthing tower/pole resistance;
- Earth grid local resistance;
- Earth grid remote resistance.

Thus, if a fault occurs a portion of the current will flow along the transmission line, leaving less current for the substation and wind farm or PV plant grounding system to drain than the total fault current.

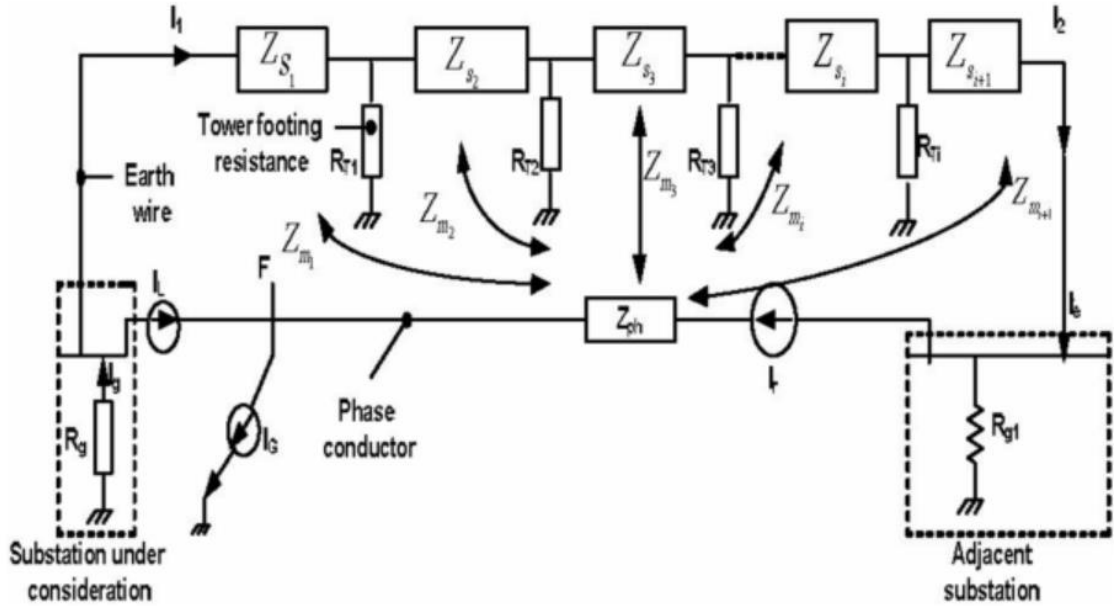


Figure 5.2 - Split factor on transmission lines connected to another substation [7]

Where:

- I_G , is the phase-to-phase short circuit current;
- I_g , is the current injected by the substation under consideration into the transmission line;
- I_1 , is the current injected by the substation under consideration into the transmission line through the earth wire;
- I_2 , is the current received by the adjacent substation through the earth wire of the transmission line;
- I_L , is the current injected by the substation under consideration into the transmission line through the phase conductor;
- I_r , is the current injected by the adjacent substation into the transmission line through the phase conductor;
- R_g , is the equivalent resistance of the substation and wind farm or PV plant connected to it;
- R_{g1} , is the adjacent substation's equivalent resistance;
- R_{Ti} , is the resistance of one pole of the transmission line;
- $Z_{s_{i+1}}$, is the impedance of the span between poles;
- Z_{ph} , is the impedance of the phase conductor;
- Z_{m1} , is the impedance of the path created in case of a phase-to-neutral short circuit.

The split factor is then given by the following equation, according to the IEEE-80 2013 standard:

$$S_f = \frac{Z_{eq}}{Z_{eq} + R_g} \quad (5.1)$$

Where:

- S_f is the split factor;
- Z_{eq} is the equivalent resistance of the network connected to the grounding system under study;
- R_g is the resistance of the grounding system under study.

While prioritizing safety is essential, taking this effect into consideration is important to ensure that the earthing system is not oversized, which translates into higher costs for the installation.

Chapter 6

Design

The design is a very important factor for the validation of the grounding system, as it can help achieve the desired resistance, which must be equal or under 1 Ω for substations and PV plants, and 10 Ω for wind farms, according to the IEC 61400-2019, and respect the contact and step voltages. However, the earthing system's resistance can vary from 1 Ω to 5 Ω , depending on the local standard, according to the NFPA-70 standard.

Designing the grounding system consists of defining the area to protect and choosing the tightness of the mesh. A tight mesh will increase the contact of the system with the soil and help drain the unwanted fault current to the ground. It is also necessary to take into account the cost of the system, and tightness of the mesh, as this could make it impossible to build it.

When designing the earth system, it is necessary to consider the boundaries of the land where the wind farm, solar park or substation will be implemented. This is because the unevenness of the terrain can influence the performance of the grounding system, making it more difficult to predict its operation. Other factors to be taken into account are the existence of bodies of water and trees on the terrain, which may not only complicate the construction of the mesh, but also cause future damage due to its activity on the ground.

6.1 - Design in Wind Farms

In the case of wind farms, the grounding system resistance of each turbine is typically provided by the wind turbine supplier. After making the connections, concrete is placed in order to optimize the dispersion of electric current in the soil and support the turbine during strong winds. The turbine's grounding system is also used as the foundation.

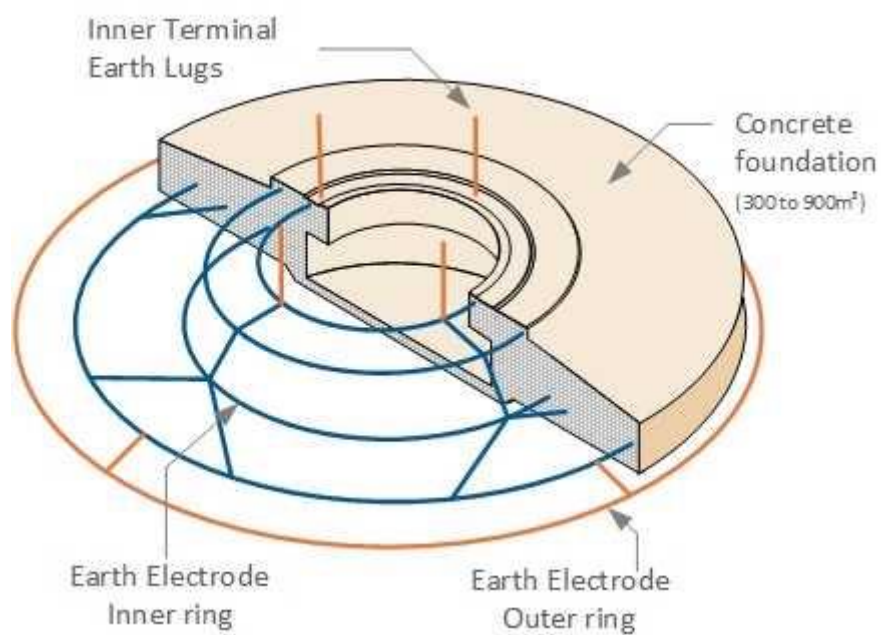
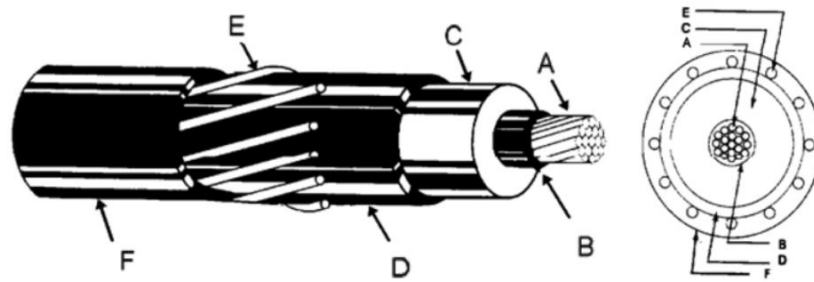


Figure 6.1 - Example of a grounding system bellow a wind turbine [4]

The collector cable system is the network of cables responsible for the transport of the electric energy produced by the wind turbines to the substation. In the event of a short circuit within the wind farm system's, it's crucial for the collector cable to be properly sized in order to handle the current flowing through it. This is crucial to protect the system and ensure an uninterrupted energy supply. This current will flow through the concentric neutral, providing a low impedance path for the fault current. Along the cable there are multiple points where the concentric neutral is connected to the ground, to help spreading the unwanted current.



- A: Conductor
- B: Conductor Shield
- C: Insulation
- D: Insulation Shield
- E: Concentric Neutral/Metallic Shield
- F: Jacket

“ © BICC Brand, General Cable Corporation, reprinted by permission” [13]

Figure 6.2 - Example of conductor for wind farms collector's system [8]

However, if additional protection needs to be added, or simple because it's cheaper than increasing the collector's cable size, an additional buried copper cable is added to dissipate the unwanted current.

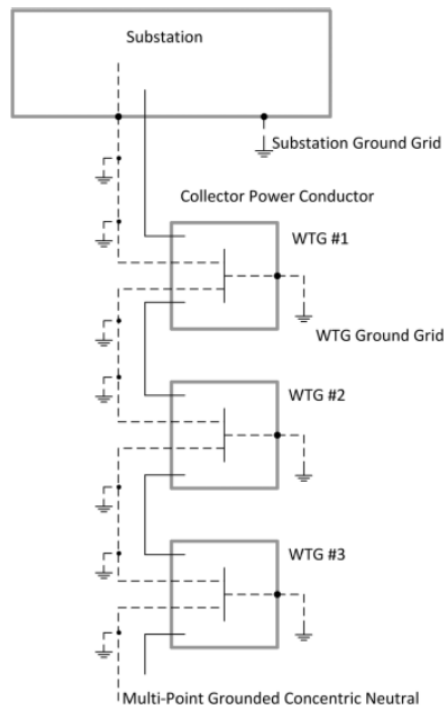


Figure 6.3 - Wind farm collector's system [8]

6.2 - Design in PV Plants

Since PV plants have a large dimension, it is necessary to consider ways to dimension the grounding system in the most efficient way possible. Creating a squared mesh as is done in substation grounding system is not the best solution since it would be necessary to dig trenches in areas of the park where it is not necessary to. Using medium and low voltage cable trenches is the solution normally used to design the structure of the grounding system in this type of project. The metallic structures holding the photovoltaic panels can be considered as an auxiliary part of the earthing system, representing electrodes, so that the system is not oversized.

Finally, it's done an assessment of the safety performance of the designed grounding system. In this part of the project, it's important to evaluate how fast the grounding system can clear the fault current depending also on the magnitude of the fault current.

In the work to be developed, a simulation software will be used in order to select which type of grounding is more beneficent to a photovoltaic park and a wind farm.

There are several ways to improve earthing systems in the future. By upgrading and modernizing existing grids, not only by replacing old infrastructures but also by installing new technology, replacing old earthing systems that have been operating for decades. The implementation of smart grids is something already being implemented.

For the proper functioning of the system in substations, the mesh is usually larger than the area of the substation, in order to increase the spread of current through the ground and reduce dangerous touch and step voltages in that area. However, since part of the mesh is outside the installations, it can be a target to criminals due to the value of copper.

6.3 - Electrodes

The goal of grounding electrodes is to protect people and equipment from electrical hazards, such as electric shock, electrical fires, and equipment damage due to voltage surges. Grounding electrodes work by establishing a low-resistance path to the earth, which allows excess electrical energy to be safely dispersed into the ground. This is achieved by connecting a conductor, such as a copper wire, to the grounding electrode and then connecting that conductor to the electrical system's neutral or ground bus. Since the electrodes are installed in a vertical position, they allow the system to drain the current into deeper soil.

There are several characteristics that can influence their performance, such as the material that they are made of, length, cross-section, etc.,. Typically, ground electrodes are made of copper, galvanized steel, or other conductive material that is effective for its purpose. The advantage of using copper is that it has a very high conductivity and is resistant to corrosion. However, it is a more expensive material than galvanized metal, which on the other hand is not as conductive. Another factor it's the size of the electrodes. It's diameter and length are dependent on the current that the grounding grid will have to flush.

Ground electrodes can have many designs and sizes, some of which:

- Smooth: type of welding electrode that has a smooth surface finish.
- Threaded: type of electrode used in welding and other metalworking applications that has threads on one or both ends.

The bottom part of the electrode can vary, and it can be flat or pointed. Pointed electrodes are easier to drive, however, they are potentially less stable when comparing with the flat end electrodes. The distance at which the ground electrode is buried is also important due to variations in ground resistance in cold and hot seasons.

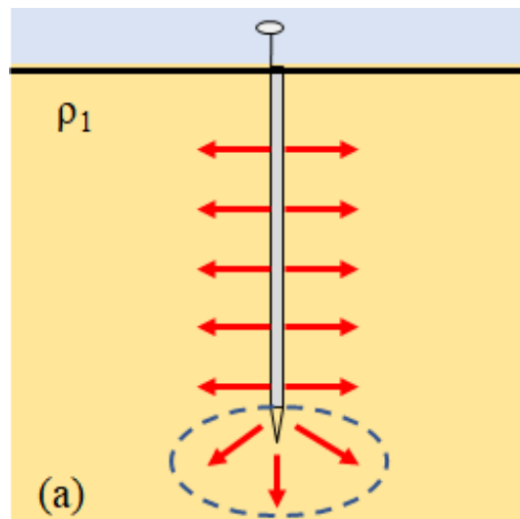


Figure 6.4 - Fault current flow direction with pointed ground electrode [4]

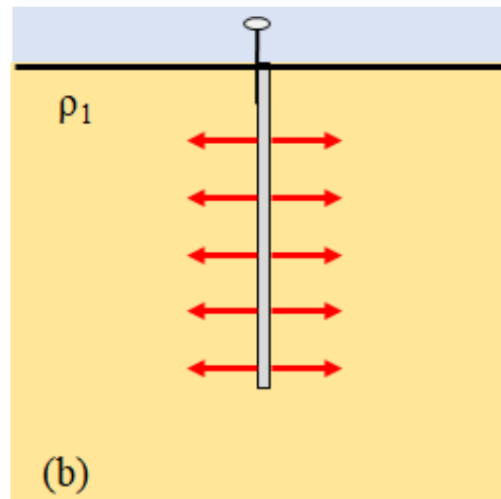


Figure 6.5 - Fault current flow direction with flat ground electrode [4]

In addition to the classic shape of the ground electrode, in cases where the soil resistivity is very high and other methods of reducing earth resistance have not worked, one can choose to use a ground electrode in the form of a plate or a twisted plate. This electrode shape allows for a larger connection area between the electrode and the ground, helping the fault current to drain more efficiently.

The current directions drained by the earthing systems for each spoken physical type of electrode are shown in the figures presented below.

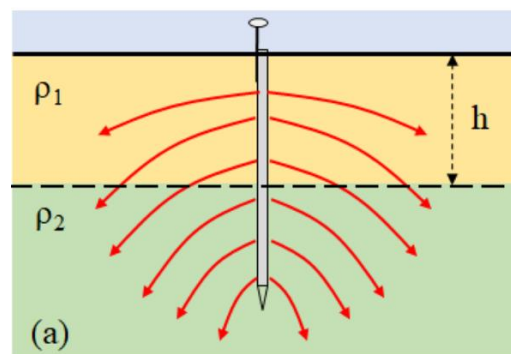


Figure 6.6 - Fault current flow direction with pointed ground electrode and two soils with different resistivity [4]

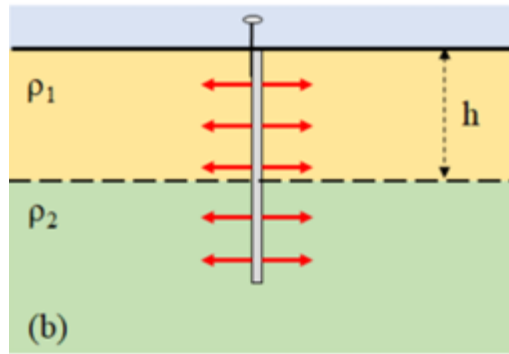


Figure 6.7 - Fault current flow direction with flat ground electrode and two soils with different resistivity [4]

Chapter 7

Earth Connection Diagrams

Many appliances of our daily life have a wire responsible for the earth connection. This connection aims to protect the device and establish an electrical potential reference point. Ground connections are more common in our daily higher power appliances, such as washing machines. Devices with low power such as telephones and laptops do not need this connection.

In PV plants and wind farms, all exposed metal structures must be connected to the general grounding system to allow the fault current to flow through a low impedance path to the ground, protecting someone who touches the structure in case of a short circuit.

In order to build a safe yet cost-efficient grounding system in a PV plant, the metallic structure that supports the panels is considered to be an electrode due to the part of the structure buried in the ground. Although the section of this structure is typically larger than the earth conductor, it has a lower capacity to conducting the fault current to the ground. In this way, metallic structures are used as components of the grounding system, which allows the system to not be oversized.

There are several possible connections of the systems to the ground. In these schemes, in the first letter, the letter T represents a direct connection from neutral to earth. The letter I can also be in this position, which is relative to the isolation of all active parts in relation to the earth.

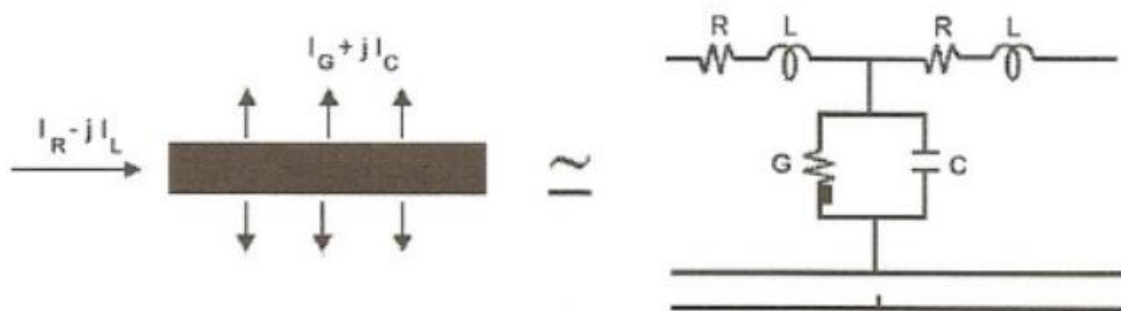


Figure 7.1 - Ground current distribution and equivalent circuit [10]

Regarding the second letter, there can be a T or an N. The T represents the masses connected directly to the ground, and the N represents the masses connected to the grounded supply point.

7.1.1 - TT scheme

This scheme is characterized by having the neutral of the system connected to the service ground, and the masses connected to the protective earth, protecting someone who touches a metal part of the equipment from electric shocks. The TT scheme is the simplest solution to install.

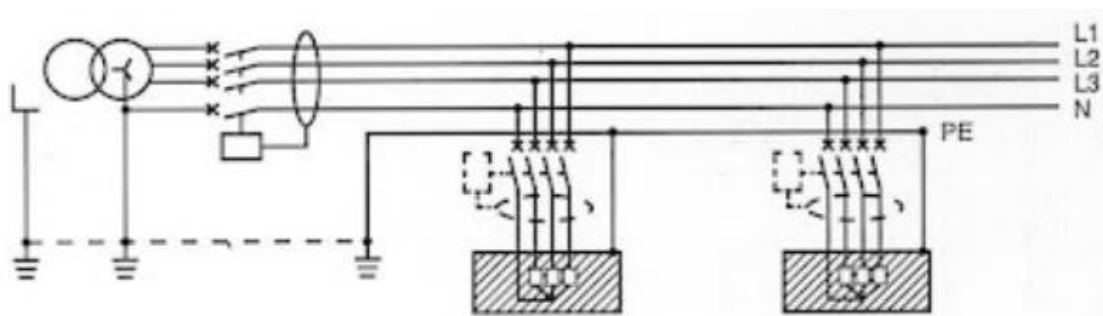


Figure 7.2 - TT grounding system [10]

7.1.2 - TN scheme

The TN scheme is characterized by having a point connected directly to earth, and the masses are connected to that point. Depending on the neutral position, there are three types of TN schemes: TN-S, TN-C and TN-C-S.

Regarding S, this represents the neutral conductor and the protective conductor in different conductors, which results in the N conductor and the PE conductor.

In this nomenclature, the C represents the neutral and the protective conductor in a single conductor that has both functions. This conductor is called a PEN conductor.

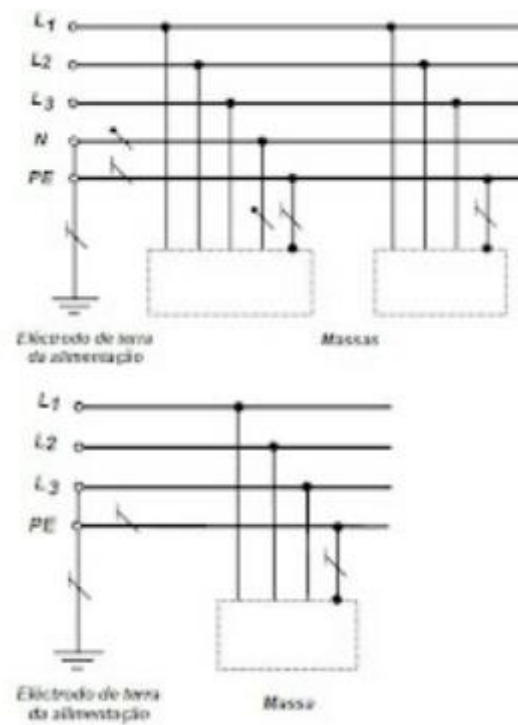


Figure 7.3 - TN-S grounding system [10]

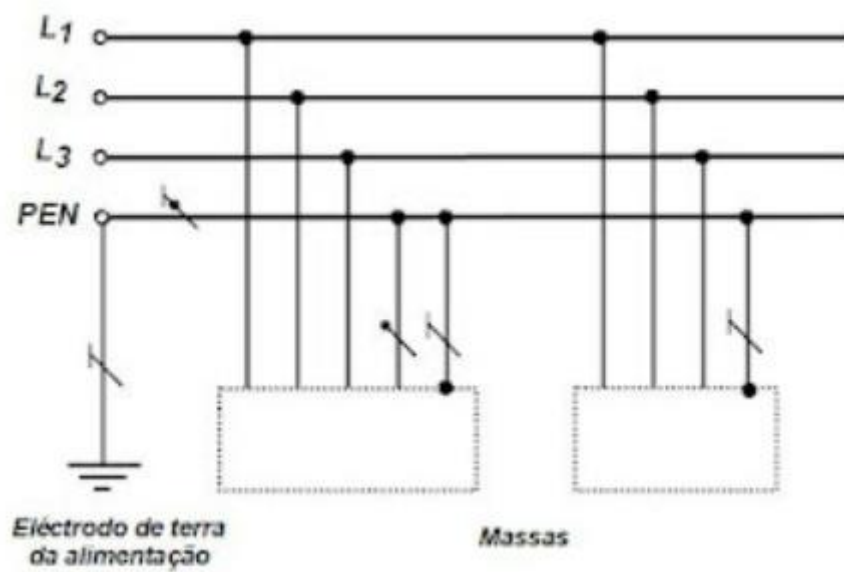


Figure 7.4 - TN-C grounding system [10]

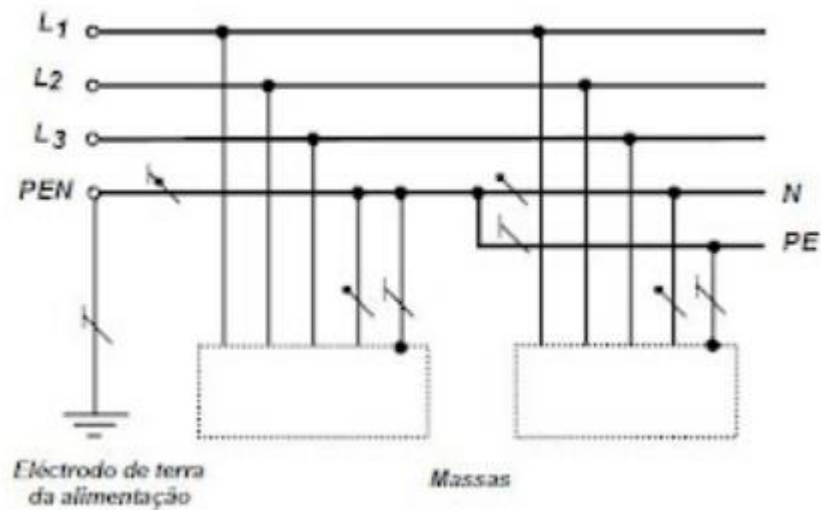


Figure 7.5 - TN-C-S grounding system [10]

7.1.3 - IT scheme

In this type of scheme, the neutral is connected to earth through an impedance in order to protect equipment and people from the hazards of electrical shocks and to help ensure the proper functioning of electrical and electronic systems.

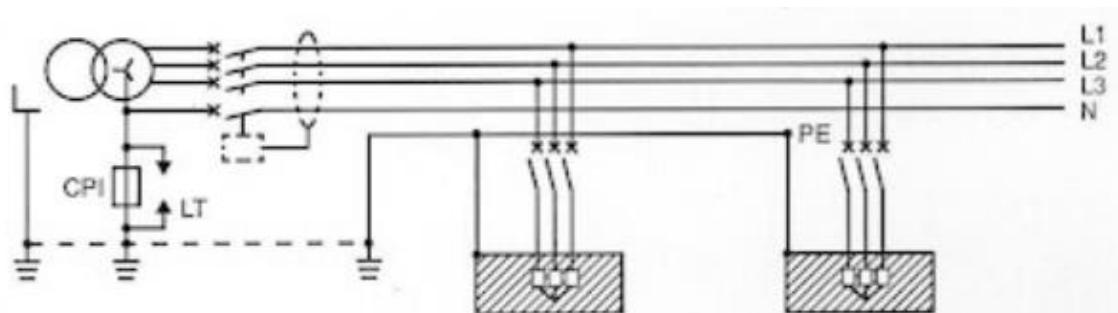


Figure 7.6 - IT grounding system [10]

Chapter 8

Ground Enhancement Material (GEM)

Ground Enhancement Material (GEM) is a conductive material used to lower the resistivity of the soil where the grounding system is going to be built. Reducing the grounding system's resistance helps the system to dissipate the fault current allowing it to work safely if a short circuit occurs [17].

In situations where the soil around the grounding system has a high resistivity, such as soils with high levels of salt or rocky soils, achieving the desired earth resistance may be difficult or even impossible without the use of Ground Enhancement Material. It may also be used for reducing the size of the grounding system in areas where space is limited or reduce the effects of corrosion, extending the system's life expectancy.

GEM is a product consisting in a mix of conductive materials, usually graphite or carbon-based, and a binding agent, and it's designed to be mixed with the soil around the conductive parts of the grounding system.

8.1.1 - Application Modes

The application of GEM on a rod is done after installing it in a hole with a predefined diameter that is made according to the thickness of GEM desired to be around the rod. After this step, the powdered mixture of GEM is mixed with water forming a pasty mixture that is poured into the hole up to a previously established height. For mesh application the process is very similar.

When the mixture solidifies, tests are carried out to measure its resistance to ensure that it will perform as intended.



Figure 8.1 - Application of GEM in an electrode [9]



Figure 8.2 - Application of GEM on the mesh [9]

8.1.2 - Maintenance

The maintenance of the soil improvement product will depend on the type that will be used in the installation. All information in this document relates to the nVent ERICO brand, whose product is maintenance-free as it does not require water to maintain its electrical conductivity.

The resistivity of this product varies between 2 $\Omega\cdot\text{m}$, if it is powdered, and 20 $\Omega\cdot\text{m}$ if it is mixed with other materials that turn the material into a paste. The brand claims that this product complies with the IEC 61400-24-2019 standard.

Chapter 9

Validation and Optimization Algorithm

Optimization algorithms play a significant role in designing safe and efficient earthing systems. These algorithms help finding optimal solutions by evaluating which variables have the most effect on each output of the system. In this chapter, optimization solutions will be presented for each step of the grounding system's validation process.

The validation process of an earthing system, according to the IEEE-80 2013 standard, includes the following steps:

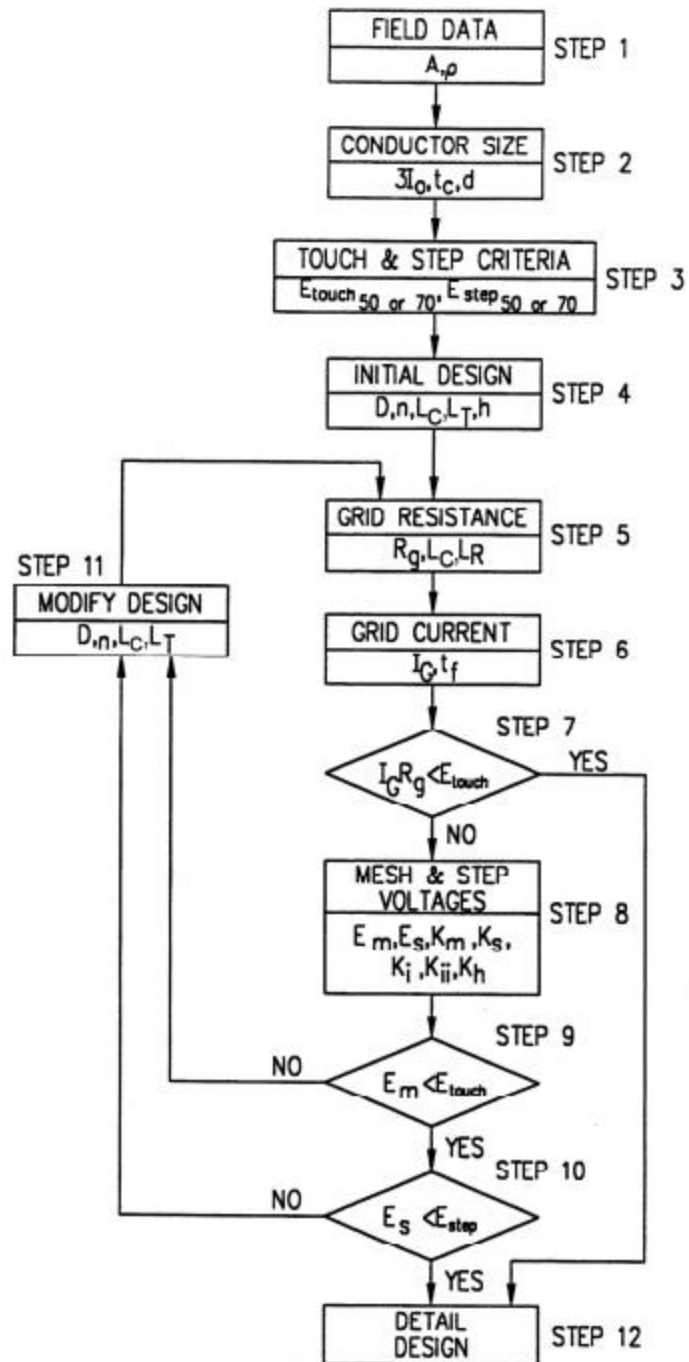


Figure 9.1 - Validation steps of an earthing system [19]

9.1.1 - Installation Data (Step 1)

First of all, it is necessary to know the value of the fault current that may occur in the installation, which is obtained through a short circuit study. This study usually doesn't only show the phase-to-earth, phase-to-phase-to-earth and phase-to-phase-to-phase-to-earth fault

currents, but also the expected values of currents after a certain number of years, and the X/R ratios. It is up to the engineer and the customer to decide which value to use considering a possible grid expansion, and that three-phase faults are the least likely to occur but causes the most damage.

Following, it is necessary to have the geotechnical study to determinate the soil model, search for the connections of the installation to the main grid, and if there is information about these connections, fault clearing time, and the space available to design the grounding system.

9.1.2 - Grounding System Conductor Sizing (Step 2)

The calculation equation for the minimum section of the grounding system conductor is given by the IEEE 80-2013 standard (equation 4.4). Since the variables on which the minimum section depends cannot be easily changed, it is difficult to adjust this value. The variables that could eventually be changed are the fault clearing time and the melting temperature of the conductor by changing the operating time of the system's protection devices, and the way the connections are made in the earthing mesh, correspondingly.

The fault clearing time can be changed by changing the response time of protection devices, more powerful fault detection sensors, more efficient communication and control systems, and reducing the impedance of the system for a faster fault clearing time, while ensuring that the system operates safely and efficiently. Thus, by reducing the fault clearing time, the minimum section of the conductor will also decrease. However, this option isn't very reliable because major changes to the system are required.

When it comes to the maximum allowable temperature, the higher the maximum temperature admissible for the material, the smaller the minimum section required.

The most common cases to consider are the following:

- Copper melting temperature - 1085 °C;
- Aluminothermic welding - 660 °C (aluminium melting point);
- Copper type C connectors - 250 °C.

By changing from the copper's melting temperature to compression connectors or aluminothermic welding, which are the most used techniques to join the connection points in the mesh, the minimum section required is increased which can cause an increase in the cross-section of the conductor that will be used, increasing the grounding system's building cost.

On the other hand, if the overall resistance of the grounding system needs to be decreased, one of the ways to do so is by creating more contact between the conductor and the soil. So, choosing a section bigger than the minimum section needed may be an option. This topic will be explored in more detail in the step 5.

9.1.3 - Touch and Step Voltage Criteria (Step 3)

As described in Chapter 4, touch and step voltages present risks of electric shock that can lead to severe injuries or fatalities. Therefore, it is crucial to optimize and minimize these voltages to ensure the safety of everyone inside the installation. Although touch and step voltages refer to humans, by reducing its value in the event of a short circuit, the exposed equipment will also be more protected, which could increase the lifetime of the installation.

In order to optimize or even validate the touch and step voltages there are several options to take into account and understand which ones have the most impact in the grid's resistance and the touch voltages in the installations.

Thus, touch voltage and step voltage can be reduced by:

- Adding electrodes;
- Increasing the size and/or cross-section of the electrodes;
- Increasing cable length on the mesh;
- Increasing cross-section of the cable on the mesh;
- Changing cable installation depth;
- Adding a layer of surface material;
- Increasing the height of the surface material;
- Considering mandatory use of protective boots;
- Increasing the minimum body weight from 50kg to 70kg;
- Removing the existing soil and put vegetable soil;
- Placing soil improvement product around the electrodes and/or directly on the mesh cable.

In Chapter 10 several simulations will be made to validate a fictitious grounding system in order to understand in which situations each one should be used.

9.1.4 - Earthing System Design (Step 4)

The grounding system will be designed depending on the type of installation it will protect, whether it's a photovoltaic solar park, a wind farm, or a substation.

In the case of a substation, the design starts with, a mesh with a larger spacing, and as necessary, it will be tightened to reach the validation of the system.

In the case of a photovoltaic solar plant, the initial design of the grounding system will follow the trenches through which the medium and low voltage cables pass, ensuring that the grounding system will be extended through the park. If it is necessary to consider the supporting structures of the solar panels, to reduce the system's resistance, touch voltages and step voltages, the buried parts will be considered as electrodes and the remaining structure as a conductive line that will allow the connection to the main grounding system of the park. This measure is sometimes difficult to implement due to its complexity and computational effort, so it will not be considered in the first phase. Since it is common for photovoltaic solar parks to be surrounded with metallic fence, this also must be considered. If considering an insulating fence, it must be ensured that the touch voltage in the area of the fence is lower than the voltage that the fence allows to protect.

For wind farms, the support structure of each wind turbine is not only for supporting the turbine in harsh conditions but also to drain the excessive current flowing through the grid. The design of wind turbine grounding system can start as simple as just a squared mesh at the base of the turbine to the total support structure. Typical grounding systems resistance values recommended by manufacturers are between 5 and 10 Ω for each turbine. The wind turbines in the installation are connected to the collector system, as mentioned in chapter 6.

9.1.5 - Ground Resistance Calculation (Step 5)

As previously mentioned, the maximum resistance that the grounding system can have is 1 Ω for substations, according to the IEEE 80-2013 standard, for PV plants and wind farms, and 10 Ω for each wind turbine, according to IEC 62305-3. In order to reduce the resistance, there needs to be more contact between the conductor and the soil, according to equation 4.3, or reduce the soil resistivity. Thus, there are several procedures to be taken into account to reach this value if the preliminary system fails to reach it. Some of these steps are also used to lower touch and step voltage as seen in step 3.

- Add electrodes;
- Increase the size and/or cross-section of the electrodes;

- Increase cable length on the mesh;
- Increase cross-section of the cable on the mesh;
- Remove the existing soil and put vegetable soil;
- Place soil improvement product around the electrodes and/or directly on the mesh cable.

The performance of these variables will be tested in a practical example in Chapter 10 using the software SafeGrid.

9.1.6 - Calculation of the Maximum Grounding System Current (Step 6)

As already mentioned in chapter 4, the maximum current that reaches the grounding system is given by:

$$I_G = D_f \times S_f \times I_f \quad (9.1)$$

Therefore, it is necessary to calculate the value of the split factor and the decay factor.

9.1.7 - Ground Potential Rise (GPR) < Allowable Touch Voltage - Verification (Step 7)

According to IEEE-80 2013 standard, if the ground potential rise (GPR) is lower than the allowable touch voltage, the grid is automatically validated since the touch and step voltages will always be below the safety limit.

If this condition isn't verified, the system isn't automatically validated, and the touch and step voltages need to be checked with more detail, to see if there are dangerous voltages in the installations, or even reduce these voltages by applying the previously discussed methods.

9.1.8 - Touch Voltage Values Verification (Step 8)

In this step, it will be checked whether the maximum touch voltage inside the installations is lower than the limit touch voltage. The touch voltage will be validated when this condition is satisfied.

9.1.9 - Step Voltage Values Verification (Step 9)

Similar to what was done in the previous step, the step voltage will be validated if the maximum value inside the installation is below the allowable step voltage limit.

Chapter 10

PV Plant Earthing System Validation

One of the main objectives of this thesis is to show the solutions for the validation of grounding systems. In this chapter, a real practical example of the validation of a PV plant will be done to illustrate the validation procedure. For this earthing system, the client requested that the switching station was validated separate from the substation and the PV plant, in order to safely operate without it, in case the PV plant is not renewed when the lifetime of the panels ends. As for the substation, it only makes sense to exist if the PV plant is in operation, so its validation will be made considering a connection to the PV plant.

ELEK SafeGrid Grounding System, from now on referred to as SafeGrid, is a software used to accurately validate earthing systems, allowing a deeper and faster study. SafeGrid complies with the IEEE-80 2013 standard. However, in the real world there are other considerations to take into account, namely prices and feasibility of installing the proposed solutions.

The three earthing systems were validated as follows:

Switching Station:

- Earthing system of the Switching Station;
- Fault in the Switching Station of 16.2 kA.

Substation

- Earthing system of the Switching Station connected to the earthing system of the substation and PV plant;
- Fault in the Switching Station of 16.2 kA.

PV Plant

- Earthing system of the Switching Station connected to the earthing system of the substation and PV plant;
 - Fault in the Switching Station of 16.2 kA, and fault of 1.2 kA in each of the two transformation stations.

As the study of the switching station and the substation was only done to complement the whole earthing system, the detailed step by step validation process will only be made in the PV plant validation.

10.1 - Installation Data (Step 1)

The installation will consist of a photovoltaic solar park connected to a substation connected to a Switching Station, which in turn is connected to a medium voltage line. The park also includes two transformation stations.

A short circuit study of the transmission line was made, in which was obtained a value of 13.50 kA. To this value, a margin of 20% was added in case of future system expansion, resulting in a total fault current of 16.2 kA. For this grounding system, it was considered that the short circuit occurs at the line gantry of the substation, as this is the place where the probability of a fault occurring is greater.

The remaining considerations are presented below:

- X/R ratio: 6.135;
- Fault clearing time: 0.5 seconds;
- Frequency: 50 Hz;
- Ambient temperature: 20 °C;
- Conductor material for the mesh: commercial hard-drawn (97% conductivity) copper;
- Conductor material for the rods: copper-clad steel (20% conductivity);
- Conductor material for the PV panel's structure: Aluminium-clad steel wire (20.3% conductivity).

10.1.1 - Medium Voltage Line Parameters

As previously mentioned in this document, medium voltage lines have metallic shields that connect to the ground on each passing pole, causing part of the fault current to be dispersed along the line. Thus, the line will be important to calculate the split factor, helping to ensure that the system is not oversized.

Line Parameters from Ferro Substation

- Total fault current: 16.2 kA;

- Total length: 3231.3 m.
- Number of poles: 11;
- Soil electrical resistivity: 277 $\Omega\cdot\text{m}$;
- Earth grid (local) resistance: 1 Ω ;
- Earth grid (remote) resistance: 1 Ω .

Line Parameters to SE Várzea

- Total fault current: 0 kA;
- Total length: 3342.5 m.
- Number of poles: 18;
- Soil electrical resistivity: 277 $\Omega\cdot\text{m}$;
- Earth grid (local) resistance: 1 Ω ;
- Earth grid (remote) resistance: 1 Ω .

It was only considered the potential short circuit from the Ferro Substation line.

Cable Parameters

The conductor cable chosen for the transmission line was the ACSR BEAR AA325, and the guard cable chosen was the OPQW AL/AA/St 34/170.

- Cond. A position, Z: 39 m
- Cond. A position, Y: 4.5 m
- Earth A position, Z: 41.8 m
- Earth A position, Y: 0 m
- Phase conductor diameter: 326.1 mm;
- Phase conductor a.c. resistance: 0.109 Ω/km ;
- Earth outer diameter: 204 mm;
- Earth a.c. resistance: 0.184 Ω/km ;
- Tower resistance: 20 Ω .

10.1.2 - Switching Station Measures

Since the PV plant has much bigger dimensions than the switching station, new measures for the switching station area were taken.

Table 10.1 - Switching Station soil measures

Spacing [m]	Resistivity [Ω .m]
1.33	100.0
1.77	373.0
2.12	246.5
2.21	681.5
2.37	389.5
2.64	526.5
2.65	1002.5
2.89	646.5
3.68	805.5
3.97	1402.0
4.45	1235.0
5.24	1428.5
6.01	1528.0
6.80	1497.5
7.57	1395.5
9.13	976.0
10.69	728.5
12.25	544.0

All measures were introduced into SafeGrid's Soil Model and the soil model was calculated. In this first attempt, as in the modelling of the Switching Station soil model, a two-layer soil model was tested:

Soil Model Results - Dataset 1	
No. of layers	3
Error (RMSE) of model	94.9 %
Model Parameters	
Layer 1 resistivity	20 Ohm.m
Thickness	2.22 m
Layer 2 resistivity	1217105.22 Ohm.m
Thickness	6.28 m
Layer 3 resistivity	5388.07 Ohm.m
Thickness	Inf m

Figure 10.1 - First Soil Model obtained in SafeGrid

Then, a three-layer soil model was tested with the same conditions:

Soil Model Results - Dataset 1	
No. of layers	2
Error (RMSE) of model	94.96 %
Model Parameters	
Layer 1 resistivity	20 Ohm.m
Thickness	2.23 m
Layer 2 resistivity	5440 Ohm.m
Thickness	Inf m

Figure 10.2 - Second Soil Model obtained in SafeGrid

Since the two-layer soil model has a layer with an unrealistic resistivity, the two-layer model was chosen.

Observing the field measures, those with the higher deviation from the average were eliminated with the objective of decreasing the RMSE. These measures were the ones with 681.5 Ω .m and 1002.5 Ω .m.

No. of layers	2
Error (RMSE) of model	39.25 %
Model Parameters	
Layer 1 resistivity	132.39 Ohm.m
Thickness	0.81 m
Layer 2 resistivity	1270.6 Ohm.m
Thickness	Inf m

Figure 10.3 - Final Soil Model obtained in SafeGrid

10.2 - Switching Station Validation

The earthing system was then simulated, starting with simple solutions to more effective options until the system was validated.

10.2.1 - Depth

The depth of the earthing system will directly influence its performance. So, the system will be tested for the depths of 0.6 m, 0.8 m and 1.0 m, which were the depths allowed by the customer.

Depth: 0.6 m

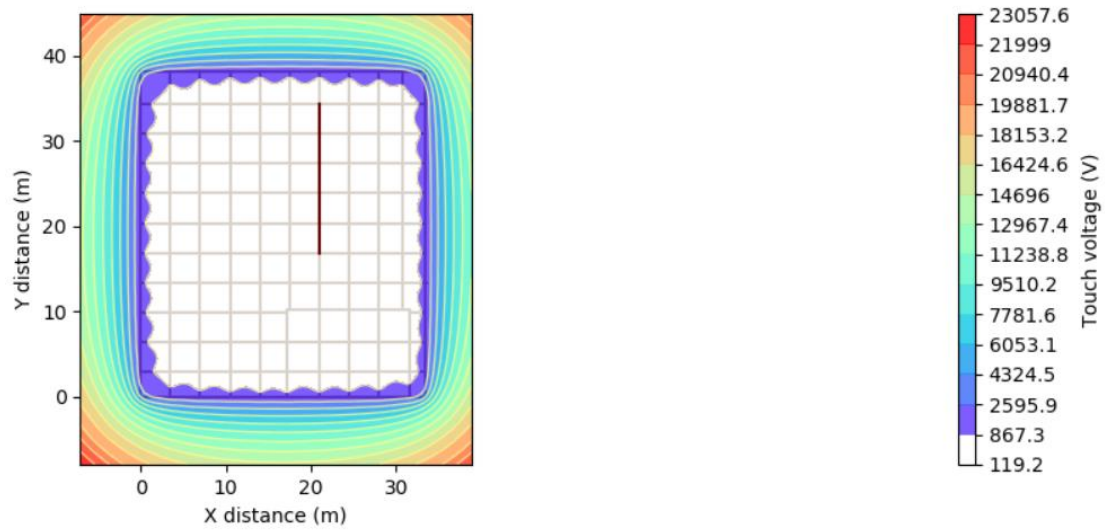


Figure 10.4 - Touch Volatge values on the earthing system of the Switching Station at a depth of 0.6 m

Depth: 0.8 m

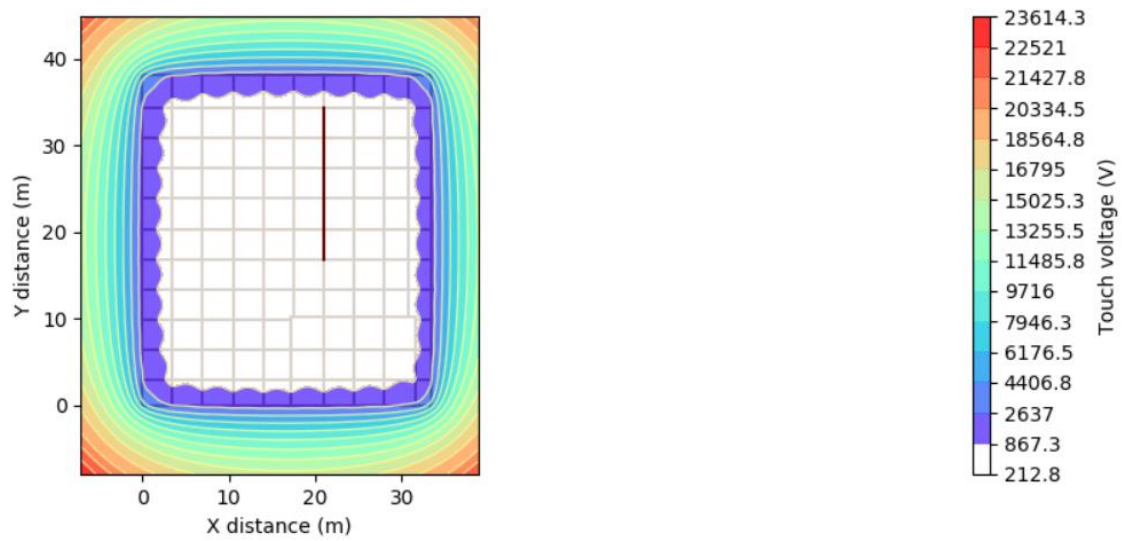


Figure 10.5 - Touch Volatge values on the earthing system of the Switching Station at a depth of 0.8 m

Depth: 1.0 m

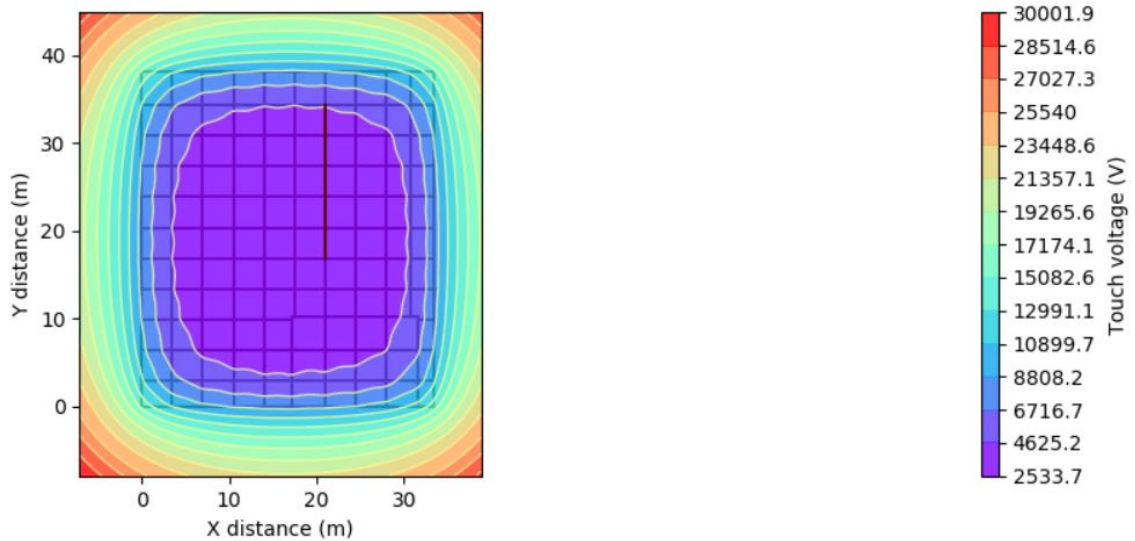


Figure 10.6 - Touch Voltage values on the earthing system of the Switching Station at a depth of 1.0 m

The earthing system shows a better performance at a depth of 0.6m, so this is the one considered to the rest of the study.

With the optimum depth of the switching station earthing system decided, an optimization study will be made in order to validate the touch and step voltages in installations.

Tested variables:

- A squared 3.5x3.5 m mesh;
- Conductor with a cross-section of 95 mm²;
- Minimum weight to enter the installation of 50 kg;
- A 10 cm superficial layer of limestone gravel (3000 Ω.m).

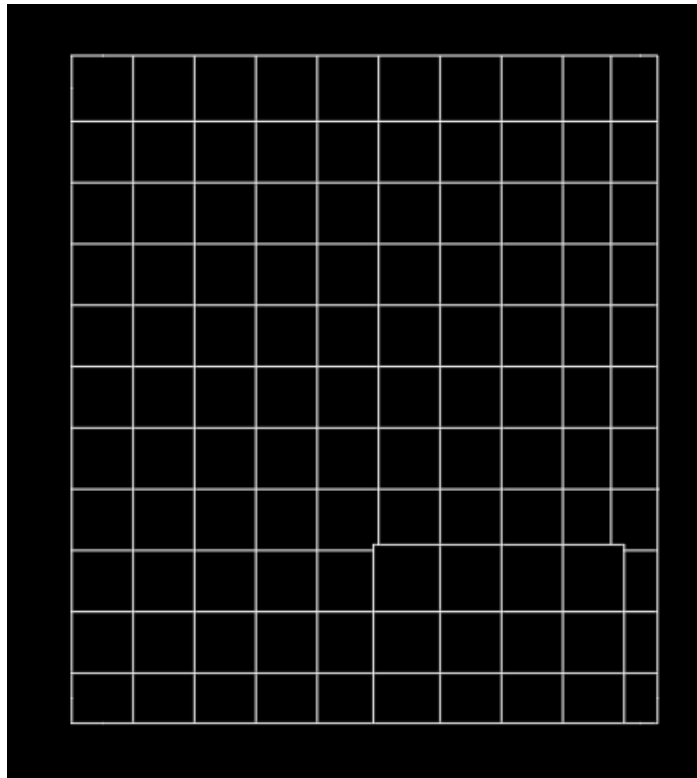


Figure 10.7 - Squared 3.5x3.5m mesh - First mesh

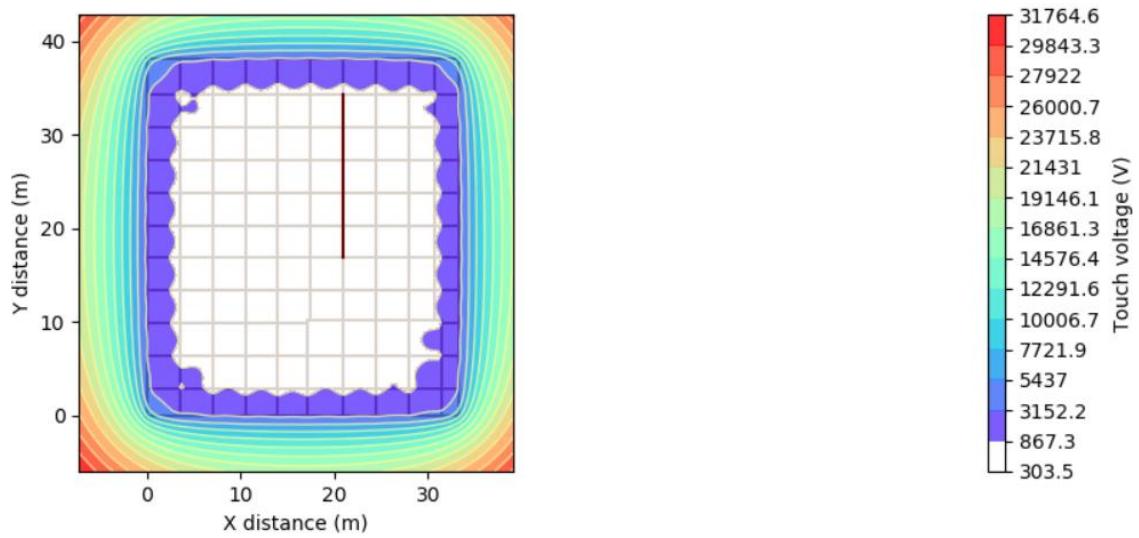


Figure 10.8 - Touch Voltage values on the Switching Station considering the first mesh

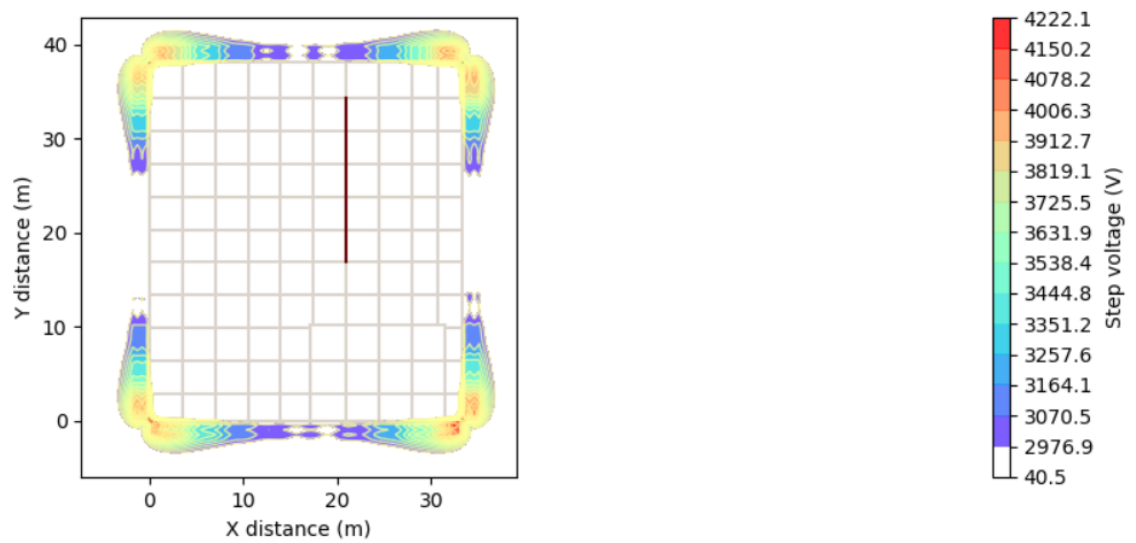


Figure 10.9 - Step Voltage values on the Switching Station considering the first mesh

Tested variables:

- Second mesh;
- The same cross-section of the conductor;
- The same minimum weight to enter the installation;
- The same superficial layer.

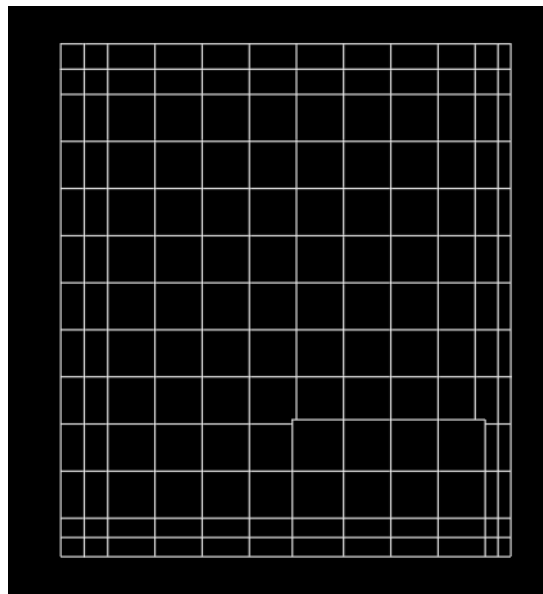


Figure 10.10 - Mesh updated with additional cable in the outer squares of the mesh - Second mesh

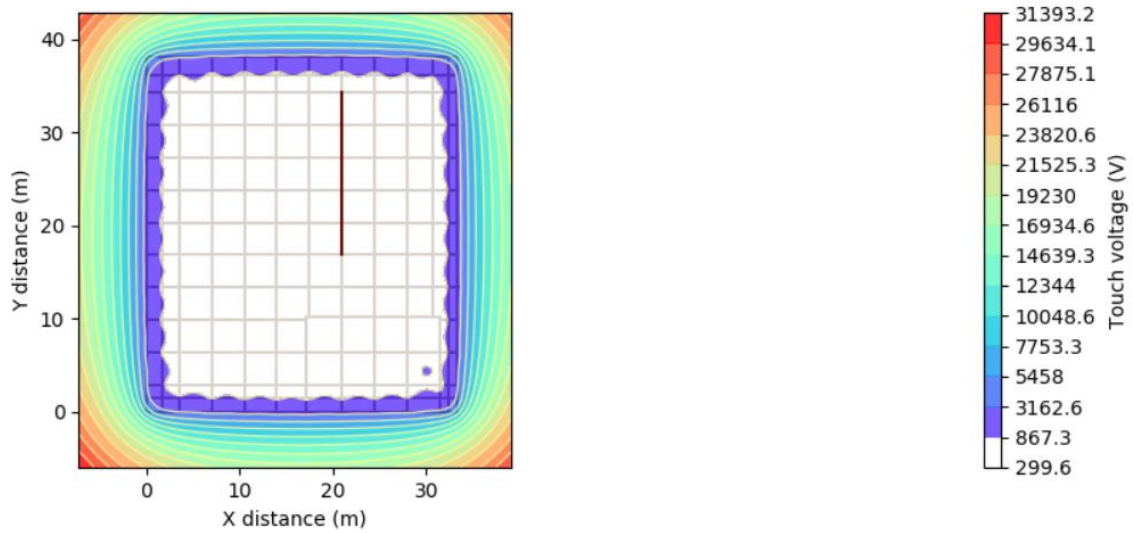


Figure 10.11 - Touch Voltage values on the Switching Station considering the second mesh

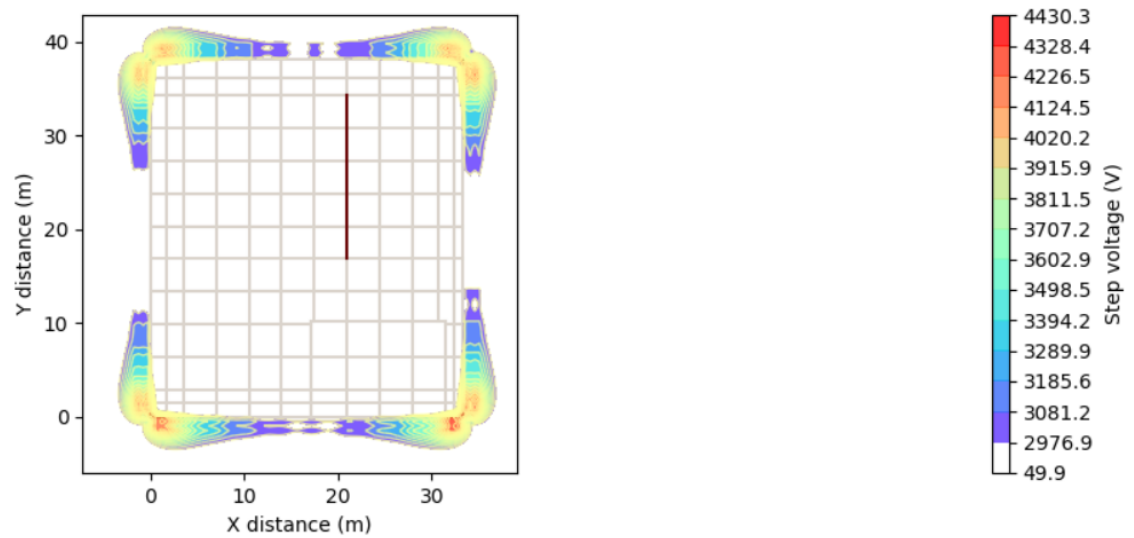


Figure 10.12 - Step Voltage values on the Switching Station considering the second mesh

Tested variables:

- Second mesh;
- The same cross-section of the conductor;
- The same minimum weight to enter the installation;
- Change in the superficial material to 15 cm of granite gravel ($5000 \Omega.m$).

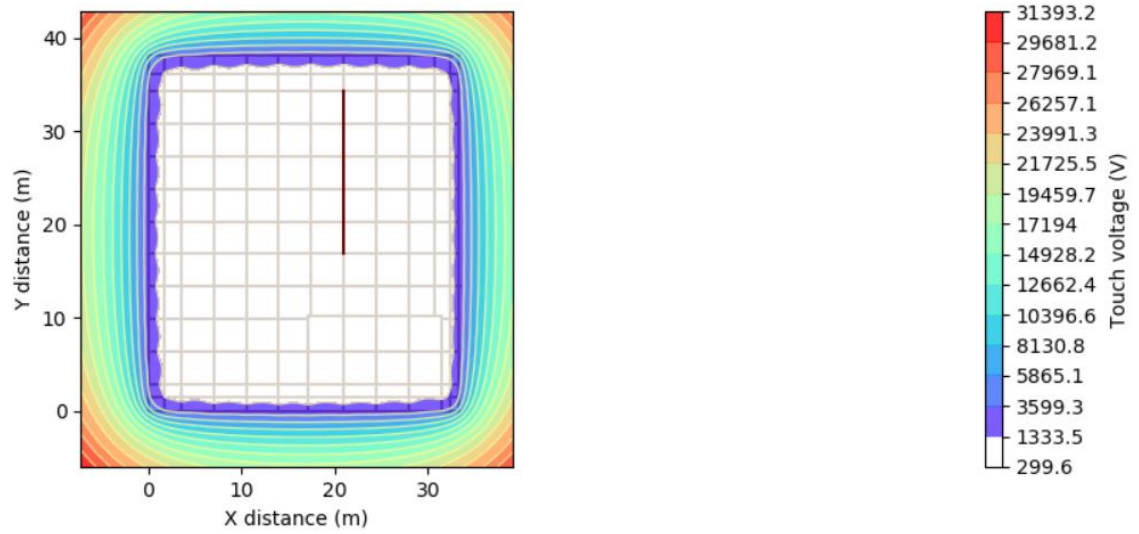


Figure 10.13 - Touch Voltage values on the Switching Station considering the second mesh

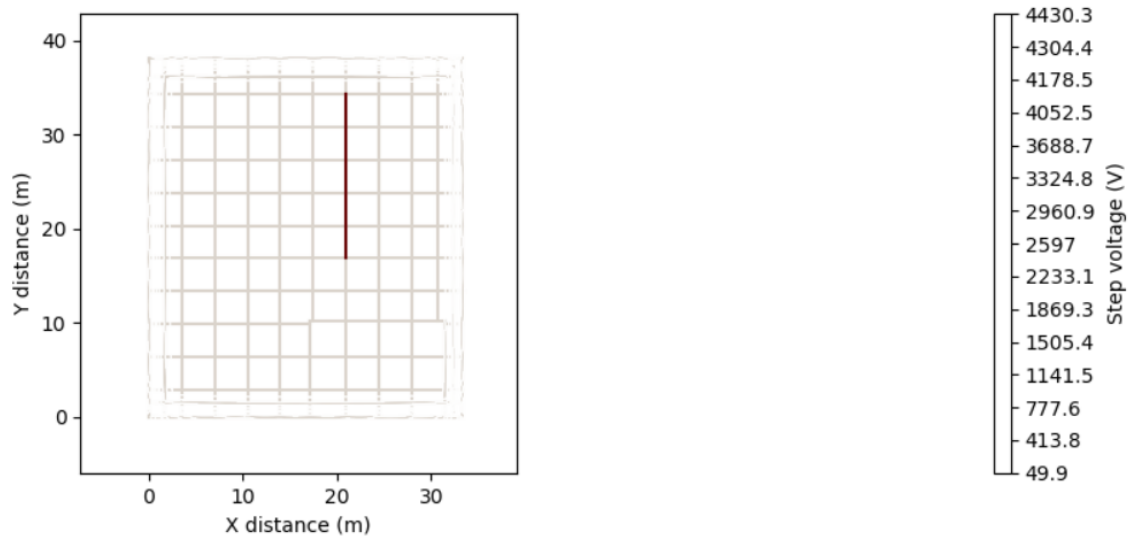


Figure 10.14 - Step Voltage values on the Switching Station considering the second mesh

Tested variables:

- Third mesh;
- One 25m electrode in each corner of the mesh;
- The same cross-section of the conductor;
- The same minimum weight to enter the installation;
- The same superficial material.

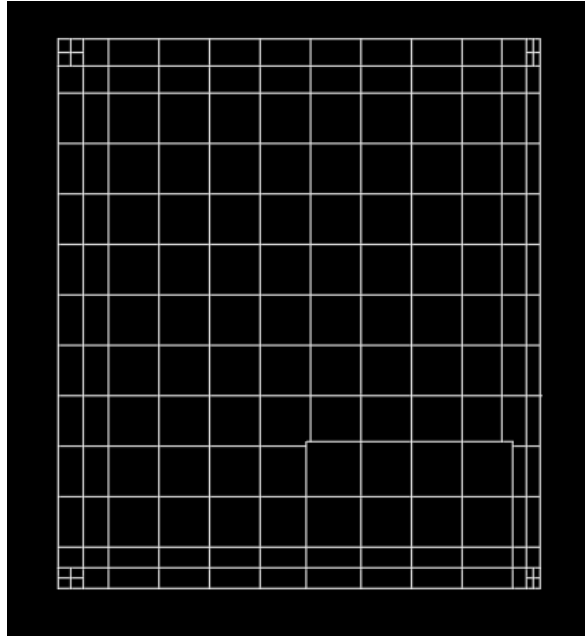


Figure 10.15 - Mesh updated with additional cable in each corner - Third mesh

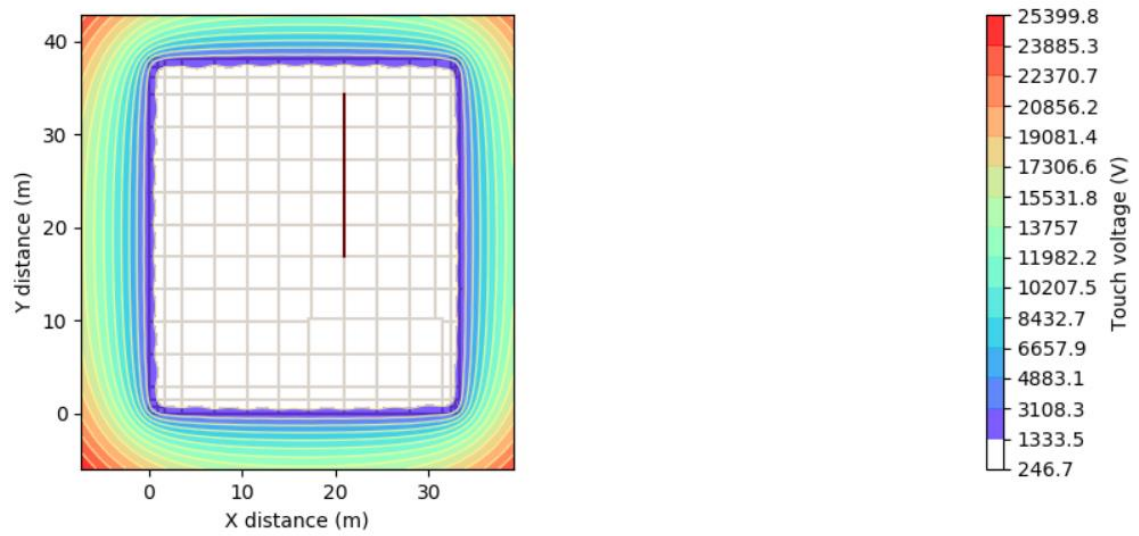


Figure 10.16 - Touch Voltage values on the Switching Station considering the third mesh

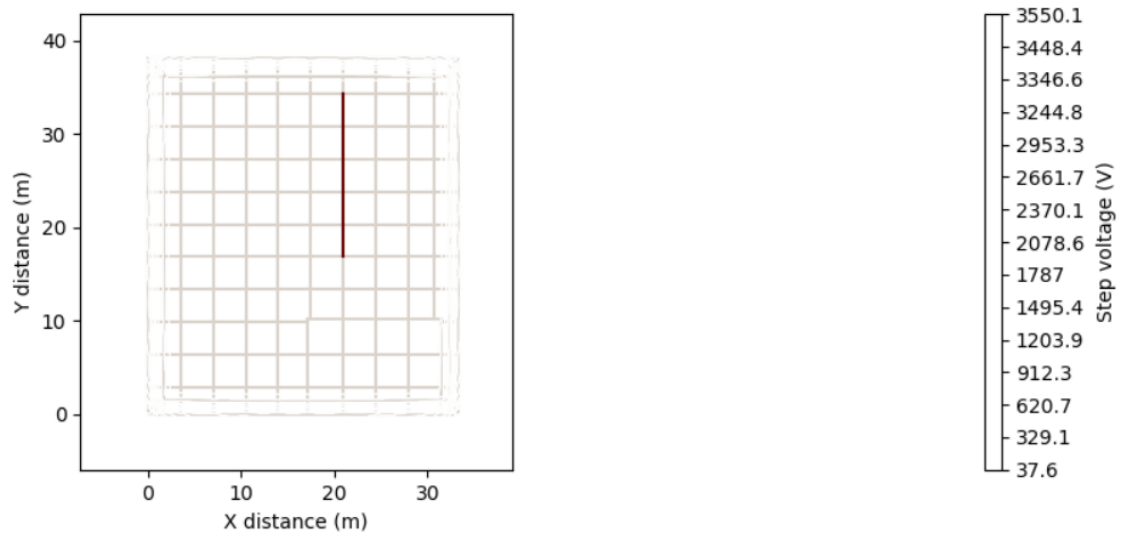


Figure 10.17 - Step Voltage values on the Switching Station considering the third mesh

- Third mesh;
- The same electrodes;
- The same cross-section of the conductor;
- An increase to 70kg as the minimum weight to enter the installation;
- The same superficial material.

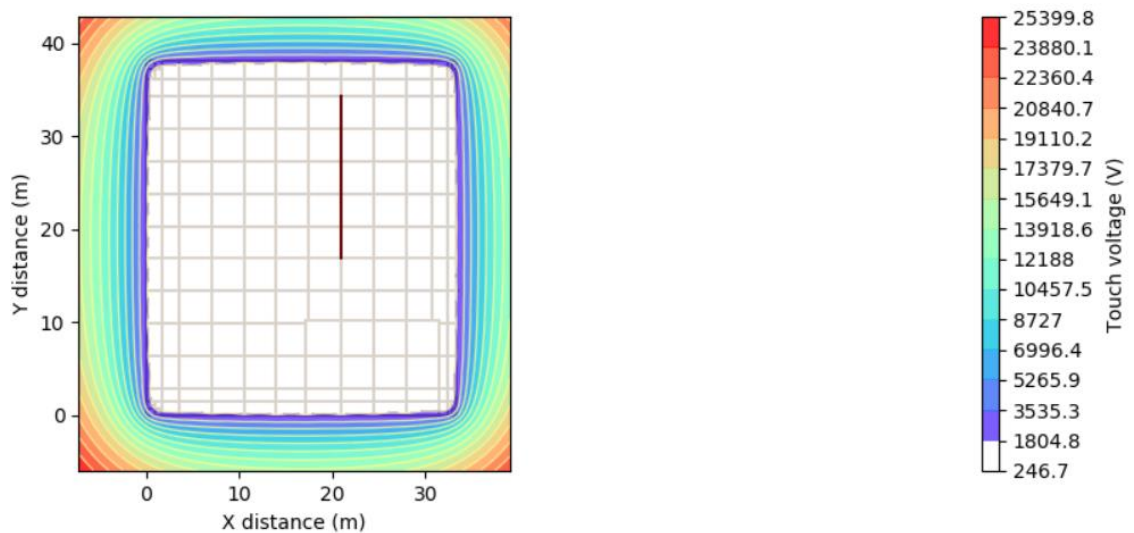


Figure 10.18 - Touch Voltage values on the Switching Station considering the third mesh

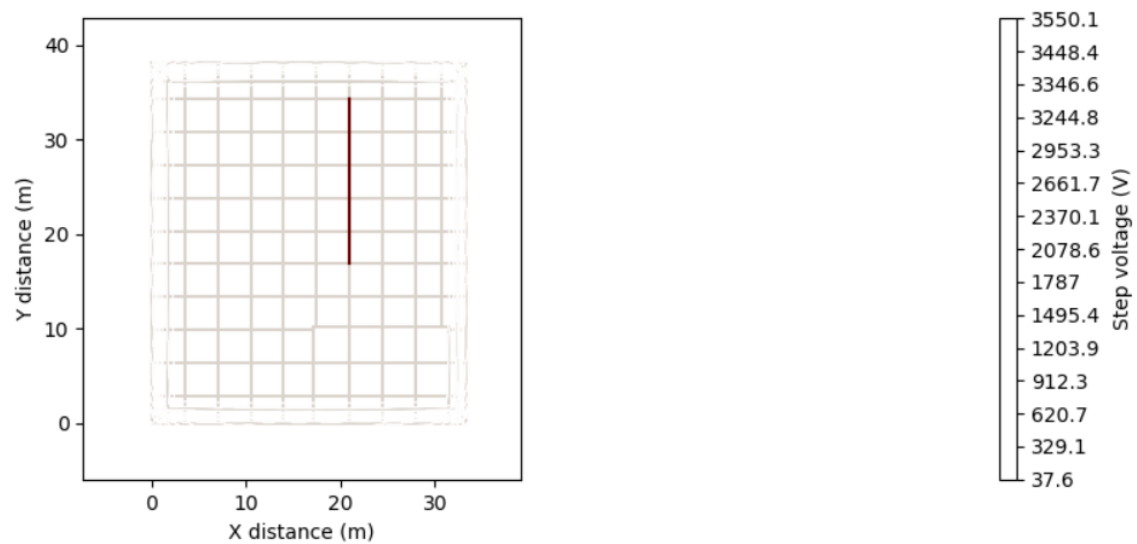


Figure 10.19 - Step Voltage values on the Switching Station considering the third mesh

- Third mesh;
- The same electrodes;
- The same cross-section of the conductor;
- The same minimum weight to enter the installation;
- A change of the superficial material to 15cm of bituminous asphalt ($10000 \Omega \cdot m$).

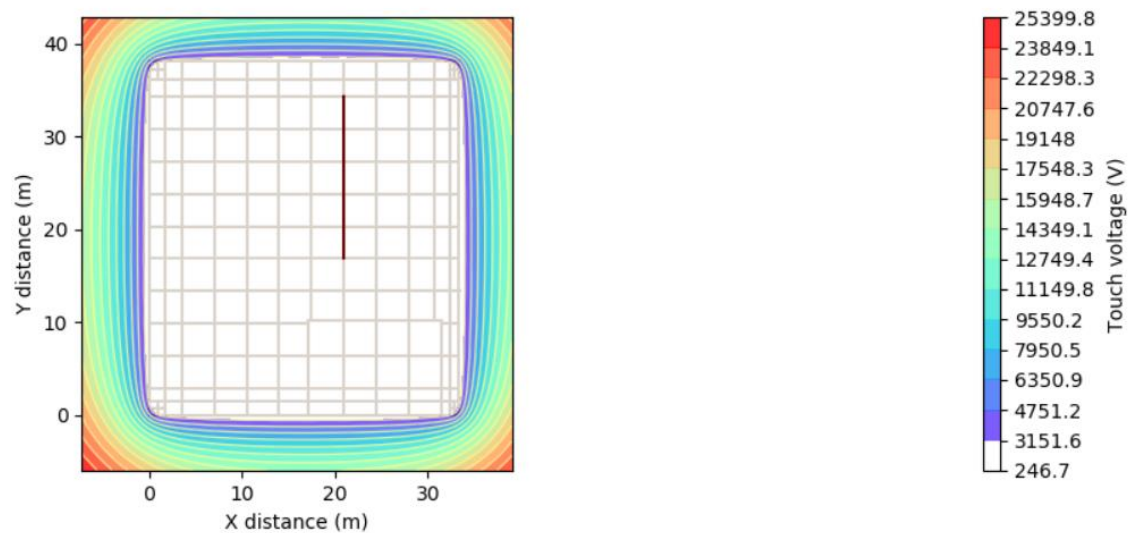


Figure 10.20 - Touch Voltage values on the Switching Station considering the third mesh

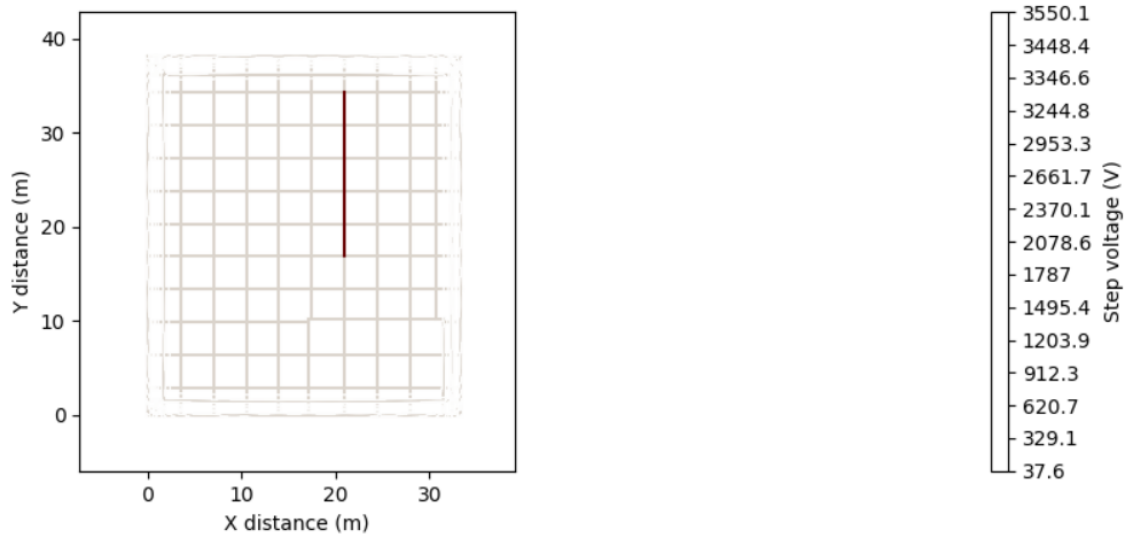


Figure 10.21 - Step Voltage values on the Switching Station considering the third mesh

Since the earthing system wasn't only validated in the corners of the installation, it is only necessary to place bituminous in the corners, and the rest would be left with granite gravel, which is a lot cheaper.

As the dangerous touch voltage area doesn't contain any conductive structures, there can't be any touch voltage in those specific areas, and so the touch and step voltages of the system are validated.

10.2.2 - Resistance Optimization

Despite the touch and step voltages being below the maximum tolerable limit, the resistance obtained was 9.581Ω , which is above the 1Ω limit value. Since the ground is very resistive, putting more cable in the mesh will not do much good and it will increase the cost of the system. Thus, the use of ground enhancement material (GEM) will be implemented.

The great disadvantage of using GEM is its cost. Some considerations were made in order to simulate the price increase when adding GEM to an electrode.

- Soil resistivity (First Layer): $132.39 \Omega \cdot \text{m}$;
- Target resistance: 1Ω ;
- Single ground rod;
- Rod diameter: 16.0 mm^2 ;
- Length of the rod with GEM: 3.0 m ;
- Diameter of the hole: 20 cm ;

- Conductor material: Copper.

By introducing these parameters into the calculation tool on the Erico website (a company dedicated to the production of GEM), the following results are obtained:

- Resistance without GEM: 44.01 Ω ;
- Resistance with GEM: 26.41 Ω ;
- Bags of GEM needed per electrode: 9.

By consulting Erico's website, the cost of a single GEM bag is 35€. So, the total cost for a single rod with GEM is expected to be 315€. However, in most situations several rods are needed to reach the desired resistance.

The equivalent resistance of the earth mesh and electrode system is calculated from the following equation:

$$R_{eq} = \frac{R_{mesh} \times R_{eq,rods}}{R_{mesh} + R_{eq,rods}} \quad (10.3)$$

Where:

- R_{eq} , is the equivalent resistance of the grounding system;
- R_{mesh} , is the resistance of the mesh;
- $R_{eq,rods}$, is the equivalent resistance of all the rods in the system, assuming they all have GEM.

To get as close as possible to 1 Ω the number of rods needed is determined by trial and error. Using the following formula it's possible to calculate the equivalent resistance of all the rods in parallel.

$$R_{eq} = \frac{1}{\frac{N_{rods}}{R_{rods}}} \quad (10.4)$$

Where:

- N_{rods} , is the number of rods;
- R_{rods} , is the resistance of a single rod.

The equivalent resistance of 40 rods is calculated by:

$$R_{eq} = \frac{1}{\frac{40}{44.01}} = 1.100 \, \Omega \quad (10.5)$$

Finally, the equivalent resistance of the grounding system is calculated.

$$R_{eq} = \frac{9.581 \times 1.100}{9.581 + 1.100} = 0.987 \, \Omega \quad (10.6)$$

Since 0.987 is lower than 1, the target resistance has been achieved. The total cost for this is calculated by the number of electrodes with GEM times the number of GEM bags by electrode.

$$N_{total \, bags} = N_{rods} \times N_{bags,rod} = 40 * 9 = 360 \quad (10.7)$$

Where:

- $N_{total \, bags}$, is the number of total bags needed;
- $N_{bags,rod}$, is the number of bags needed by rod.

As previously said, the cost a single bag of GEM is 35€. So the total cost of using GEM for the grounding system considered is:

$$Total \, cost = N_{total \, bags} \times Bag \, cost = 360 * 35 = 12600 \, \text{€} \quad (10.8)$$

Despite the additional cost of 12600€, the grid resistance, touch voltages and step voltages are now below their limit, and the PV plant's grounding system is finally validated.

10.3 - Substation Validation

10.3.1 - Substation Measures

The measures obtained for the soil resistivity of the PV plant area will be the same for the substation, as the substation will be simulated connected to the PV plant. SafeGrid doesn't yet allow the division of two different soils models for two different zones in the same simulation. Thus, the soil model will be the one obtained for the PV plant.

No. of layers	3
Error (RMSE) of model	4.63 %
Model Parameters	
Layer 1 resistivity	1750.02 Ohm.m
Thickness	0.69 m
Layer 2 resistivity	434.15 Ohm.m
Thickness	0.25 m
Layer 3 resistivity	1129.31 Ohm.m
Thickness	Inf m

Figure 10.22 - Soil Model obtained in SafeGrid

The earthing system of the substation is in greater detail in Figure 10.23.



Figure 10.23 - Detailed substation earthing system

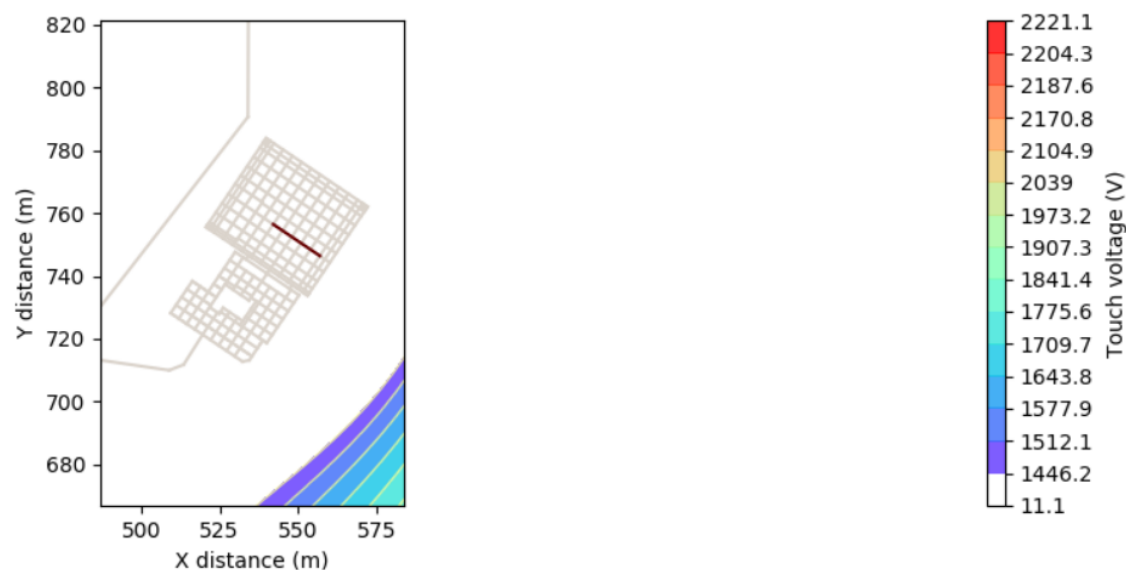


Figure 10.24 - Touch Voltage values on the Substation considering a ground mesh of 3x3m

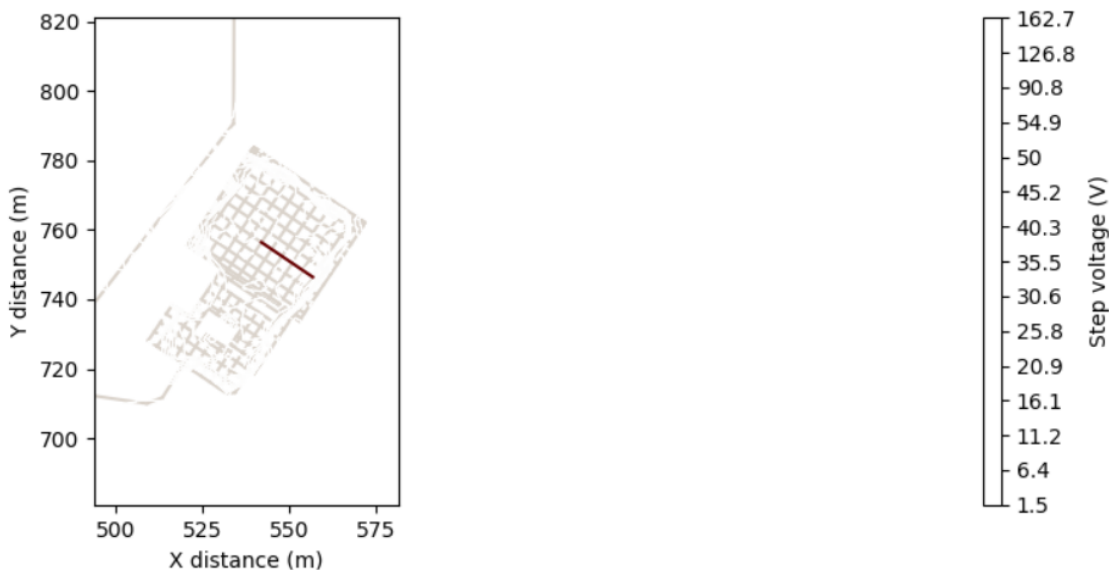


Figure 10.25 - Step Voltage values on the Substation considering a ground mesh of 3x3m

Since the substation’s earthing system is connected to the PV plant’s earthing system, the drainage of electrical current into the ground is more efficient, meaning that the system is validated even with just 10 cm of limestone gravel (3000 Ω .m).

10.4 - PV Plant Validation

This subchapter will be dedicated to the validation of a PV plant, taking into account the considerations of step one in the previous subchapters. Its objective is to show a practical example of the validation of the grounding system of PV plant from the receipt of initial variables, such as soil measures, to the validation of the grounding system.

To validate the grounding system, the 1.5 m reach distance method will be used, since the PV plant has large dimensions.

10.4.1 - PV Plant Soil Measures

Soil resistivity measures were carried out by a company specialized in this process. The values obtained for are shown in Table 10.2.

Table 10.2 - PV Plant soil measures

Spacing [m]	Resistivity [Ω .m]
0.40	1457.5
0.80	1522.4
0.87	1568.7
1.07	1523.5
1.31	1445.9
1.33	1113.6
1.60	1582.2
2.33	1086.0
2.67	1094.1
3.20	1104.5
3.87	1113.9
4.00	1100.1
4.67	1120.5
5.33	1133.7
6.13	1115.3
7.07	1109.1
7.73	1099.7
9.33	1078.2
10.67	951.4

All measures were introduced into SafeGrid's Soil Model and the soil model was calculated. In this first attempt, a two-layer soil model was tested:

Soil Model Results - Dataset 1	
No. of layers	2
Error (RMSE) of model	22.07 %
Model Parameters	
Layer 1 resistivity	1703.25 Ohm.m
Thickness	0.35 m
Layer 2 resistivity	1086.21 Ohm.m
Thickness	Inf m

Figure 10.26 - First Soil Model obtained in SafeGrid

Then, a three-layer soil model was tested with the same conditions:

Soil Model Results - Dataset 1	
No. of layers	3
Error (RMSE) of model	22.01 %
Model Parameters	
Layer 1 resistivity	1626.74 Ohm.m
Thickness	0.52 m
Layer 2 resistivity	962.54 Ohm.m
Thickness	1.15 m
Layer 3 resistivity	1132.44 Ohm.m
Thickness	Inf m

Figure 10.27 - Second Soil Model obtained in SafeGrid

Since the three-layer soil model is slightly better than the two-layer soil model, this is the one chosen from now on.

Observing the field measures, there is an abrupt decrease in soil resistivity in a short space, changing from 1445.9 Ω .m to 1113.6 Ω .m, which may just be an error in the system due to the measuring device having found a punctual concentration of stones. Thus, this measure and some other were removed from the calculation to decrease the RMSE. The new soil model shown in Figure 10.27 was obtained:

Soil Model Results - Dataset 1	
No. of layers	3
Error (RMSE) of model	4.63 %
Model Parameters	
Layer 1 resistivity	1750.02 Ohm.m
Thickness	0.69 m
Layer 2 resistivity	434.15 Ohm.m
Thickness	0.25 m
Layer 3 resistivity	1129.31 Ohm.m
Thickness	Inf m

Figure 10.28 - Final Soil Model obtained in SafeGrid

In this practical example it can be concluded that for the soil model it is not enough to look at the soil resistivity, it is also necessary to consider the depth or spacing of the measures.

10.4.2 - Grounding System Conductor Sizing (Step 2)

Before designing the initial earthing system, it is necessary to know the cable that can be used, and it is necessary to dimension it. For this purpose, the calculation equation for the minimum conductor cross-section of a grounding system, given by the IEEE-80 2013 standard, will be used.

$$S_{min} = \frac{I_f}{\sqrt{\frac{TCAP \times 10^{-4}}{t_f \times \alpha \times \rho_r} \times \ln \left(\frac{K_0 + T_m}{K_0 + T_a} \right)}} = 42.53 \text{ mm}^2 \quad (10.1)$$

Since the minimum value that can be used is 42.53 mm^2 , the cable used will have a 50 mm^2 cross-section.

10.4.3 - Touch and Step Voltage Criteria (Step 3)

The maximum admissible value for touch and step voltage was calculated through SafeGrid which, again, considers the IEEE-80 standard. For this calculation it was considered that:

- The fault clearing time has a value of 0.5 seconds;
- The minimum allowed body weight is 50 kg;

- The body resistance for the touch voltage was $2000\ \Omega$ and for the step voltage $5000\ \Omega$, meaning that anyone entering the premisses must wear appropriate boots;
- No surface layer material was considered.

Given these variables, the maximum admissible touch and step voltages are:

- $U_{touch} = 776.67\ V$;
- $U_{step} = 3560.84\ V$.

10.4.4 - Earthing System Design (Step 4)

The first design of the PV plant's grounding system was designed in the software AutoCAD. This choice was driven by the compatibility of SafeGrid with DXF files, and the greater ease of designing in AutoCAD as opposed to directly in SafeGrid.

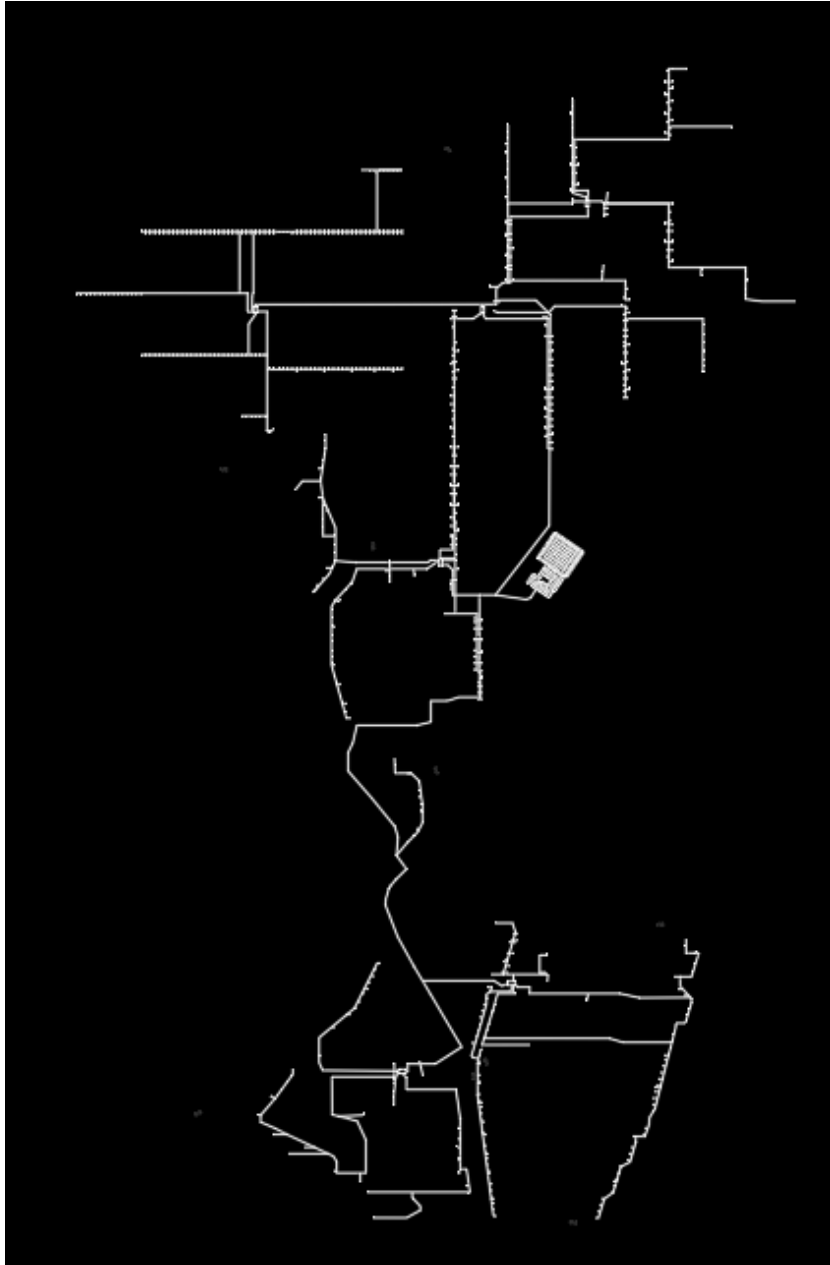


Figure 10.29 - PV Plant's grounding system with connection to the substation's and switching station's grounding system designed in AutoCAD

The total cable on the PV plant grounding system is 11193 m.

For the design of the PV plant, the trenches responsible to carry the MV and LV cables in the plant were considered to also carry the earthing system, saving money on opening new trenches to install the cable.

According to the company that built SafeGrid, by considering the metallic structures of PV panels the earthing system will have less dangerous voltages, and so the system can be

validated without them, making it more conservative. The same doesn't apply to the metallic fence, and so, it will be considered for this study.

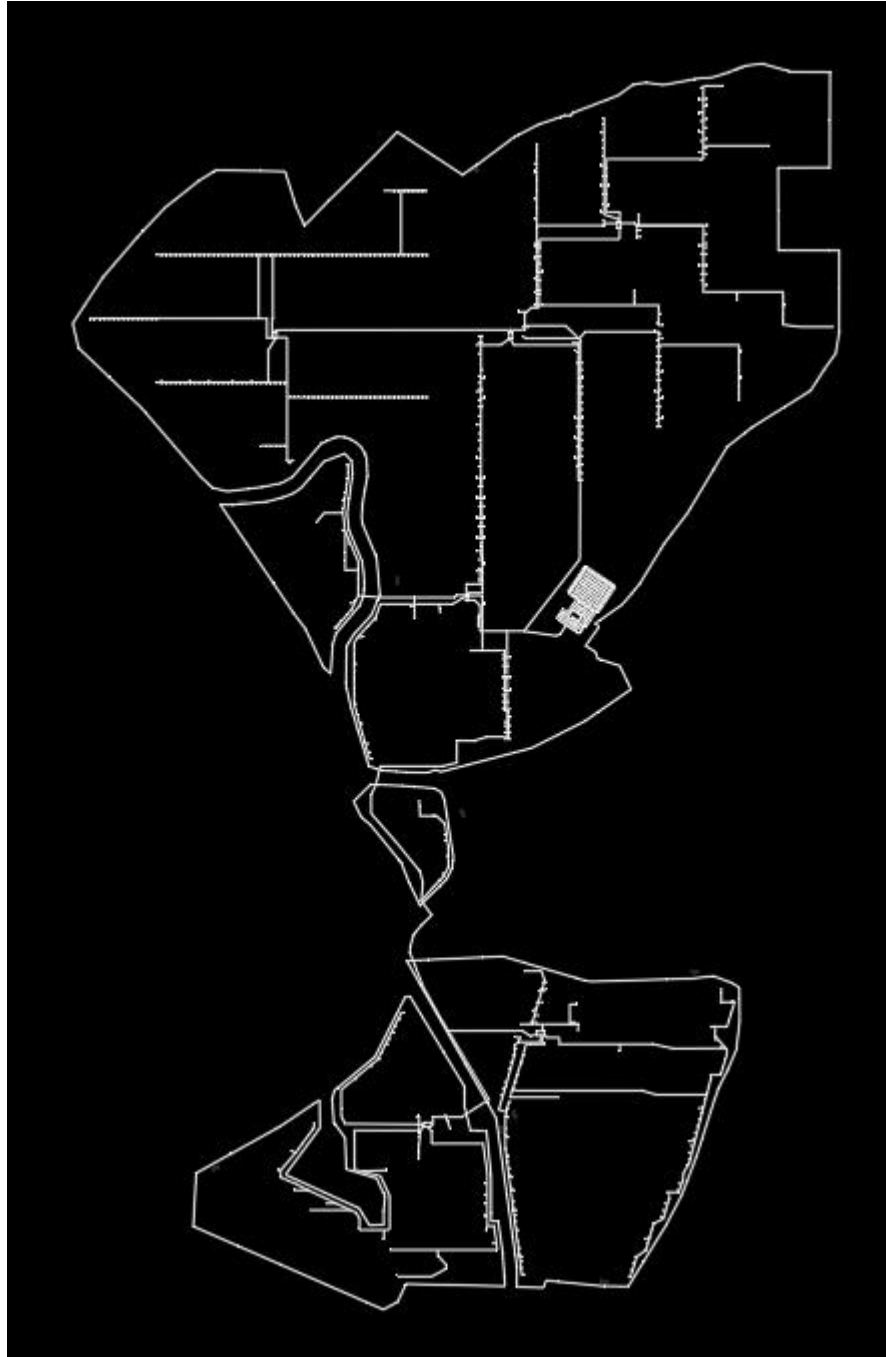


Figure 10.30 - PV Plant's grounding system with connection to the substation's and switching station's grounding system designed in AutoCAD, and considering metallic fence

Although the drawing is in 2D, when introduced into SafeGrid, a 3D model is made and the fence will be considered to be 2.5m above ground level, with a few points connected to the ground to represent the fence support structure.

10.4.5 - Ground Resistance Calculation (Step 5, Step 8 and Step 9)

For the first design, the resistance of the grounding system was calculated through a simulation carried out in SafeGrid, where the value of the grid's mesh resistance depends on the amount of cable in the system and where it's located.

The grid's resistance will be validated once its value is equal or below 1 Ω . The touch and step voltages will be validated if their maximum value on the installation is below the maximum values defined in step 3.

10.4.6 - Calculation of the Maximum Grounding System Current (Step 6)

All these values mentioned in the previous subchapter were necessary to use the Fault Current mode on SafeGrid, which allows to calculate the split factor in relation to a transmission line. The value of the split was 33%, rounded to the units, which results in a short-circuit current of 5.355 kA.

$$\begin{aligned} I_G &= I_f * S_f * D_f \Leftrightarrow & (10.2) \\ \Leftrightarrow I_G &= 16200 * 0,33 * 1.019 \Leftrightarrow \\ \Leftrightarrow I_G &\simeq 5.355 \text{ kA} \end{aligned}$$

10.4.7 - Ground Potential Rise (GPR) < Allowable Touch Voltage - Verification (Step 7)

For the initial design, the GPR given by SafeGrid is 3854 V. Since the GPR is higher than the allowable touch voltage, this condition is not validated, and an optimization of the system will have to be made.

In this first test, the Grid Potential Rise (GPR) was used to shows the difference between considering this method and reach distance in an big dimensions installation.

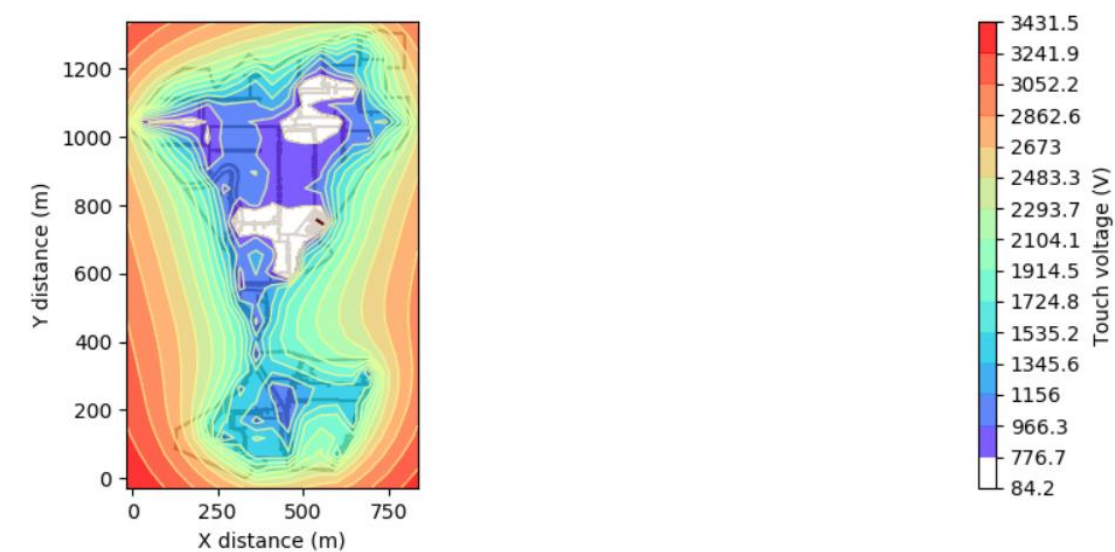


Figure 10.31 - PV plant's touch voltages obtained from SafeGrid (Ground Potential Rise method)

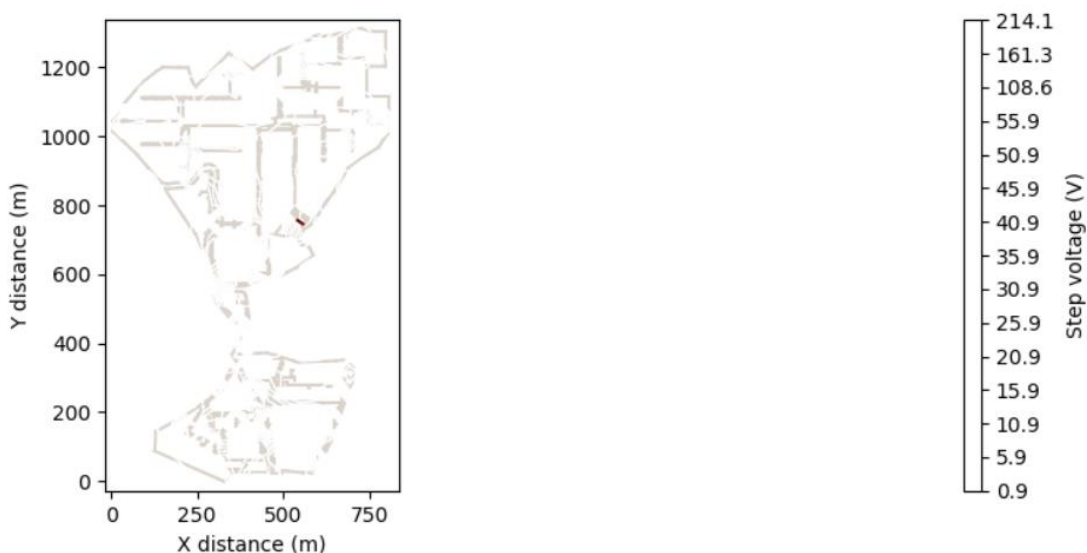


Figure 10.32 - PV plant's step voltages obtained from SafeGrid (Ground Potential Rise method)

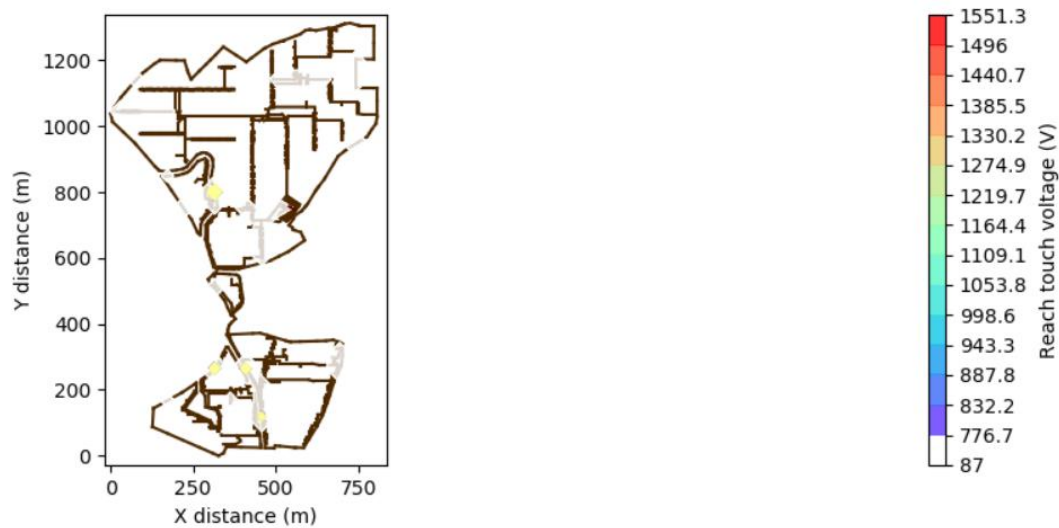


Figure 10.33 - PV plant's touch voltages obtained from SafeGrid (Reach distance method)

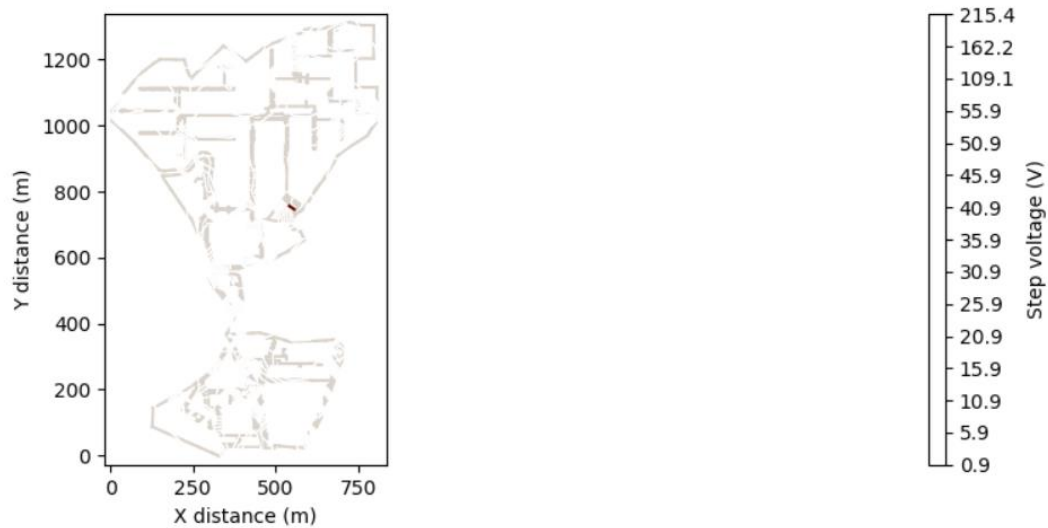


Figure 10.34 - PV plant's step voltages obtained from SafeGrid (Reach distance method)

It can be concluded that to validate the earthing system using would a lot more difficult using the GPR method instead of the reach distance method, as the maximum touch voltage in the installation is more than double. So, by using the reach distance method, the system won't be as oversized as it would with the GRP method.

10.4.8 - Depth

The depth of the PV plant earthing system was defined by the client at 0.8m. However, due to the difference of depths of the PV plant, the substation, and the switching station, the cable connecting the PV plant and the substation will start at 0.8 m (in the PV plant) and finish at 0.6 m (in the substation).

10.4.9 - Connecting the Fence to the Earthing System



Figure 10.35 - Validation of the PV plant's touch voltages

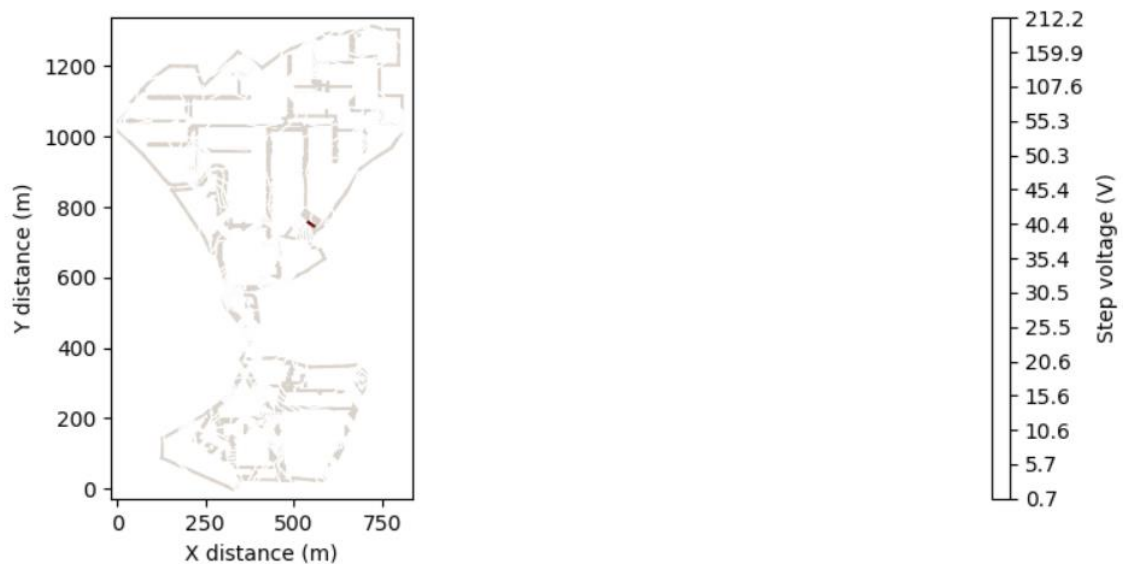


Figure 10.36 - Validation of the PV plant's step voltages

10.4.10 - Adding Extra Cable

Due to the size of the installation and tough soil, adding electrodes wouldn't have much effect and it would be a very hard solution to implement. So, it was chosen to add cable at 0.8 m deep in parallel with the fence on the problematic areas. It was requested by the client to

validate the middle-left problematic zone with the smallest depth possible due to especially rocky soil. It was possible to validate the system with cable on the middle-left zone at just 0.4m depth.



Figure 10.37 - Validation of the PV plant's touch voltages

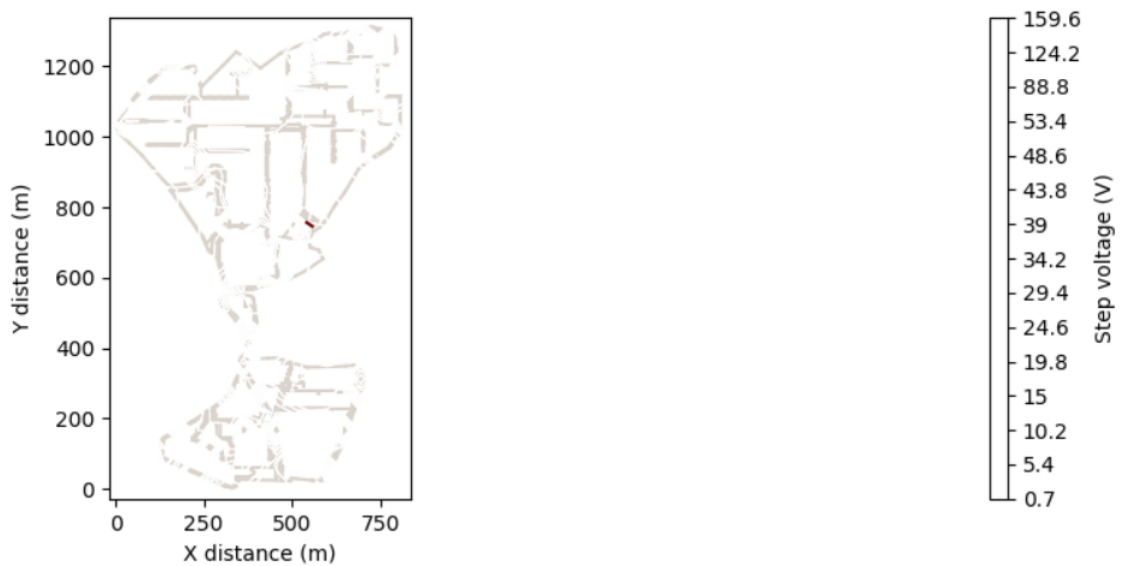


Figure 10.38 - Validation of the PV plant's step voltages

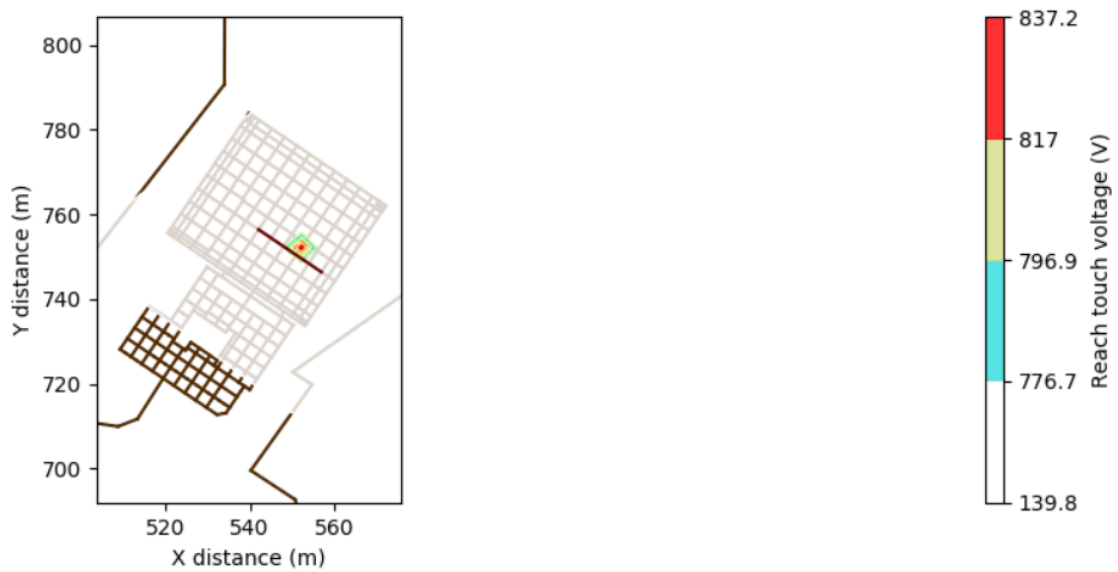


Figure 10.39 - Close up on the validation of the PV plant's touch voltages

Although the substation has a problematic zone, this value doesn't need to be considered, as a deeper study of the substation was already done and validated using GPR. IEEE-80 2013 classifies GPR as a more conservative study than reach distance due to the fact that GPR considers the voltage drop from the fault zone to every point in the installation.

Table 10.3 - Change in resistance and touch voltage

Allowable Touch Voltage (V)	Touch Voltage in the PV plant (V)	Allowable Step Voltage (V)	Step Voltage in the PV plant (V)
776.7	765.1	3560.8	149.5

As both touch and step voltages are below the allowable limit and the resistance is below 1 Ω , the earthing system is now validated.

10.4.11 - Fault at the northern Transformation Station

As previously mentioned, a 1.2kA fault will be simulated in each existing transformation station in the solar park. Although the probability of this effect is lower, as well as its severity, a study should be carried out to ensure that there are no complications in the system.

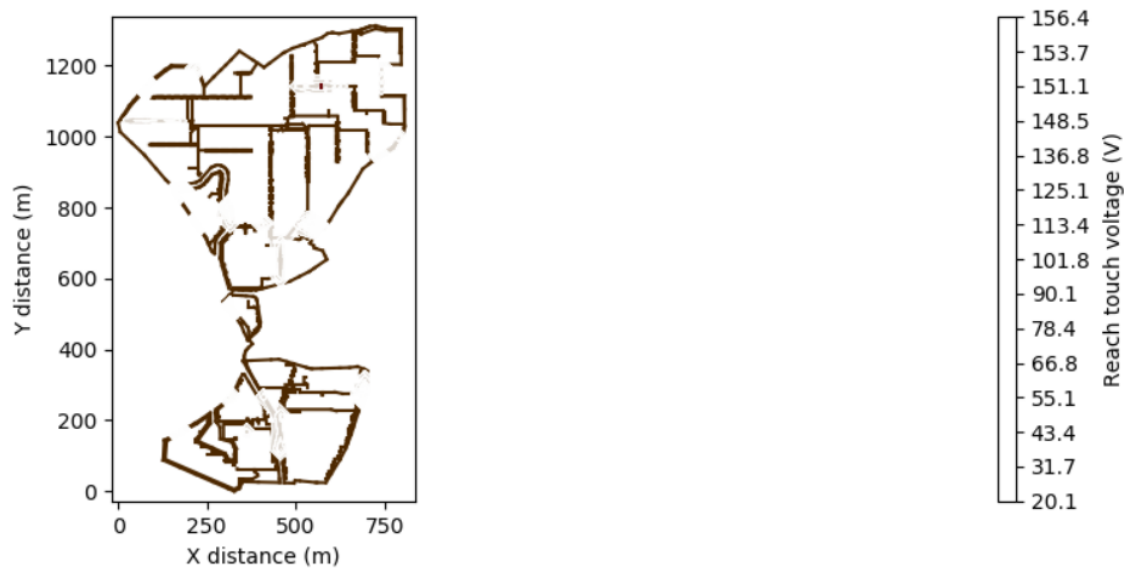


Figure 10.40 - Touch Voltage considering the fault current at the northern transformation station

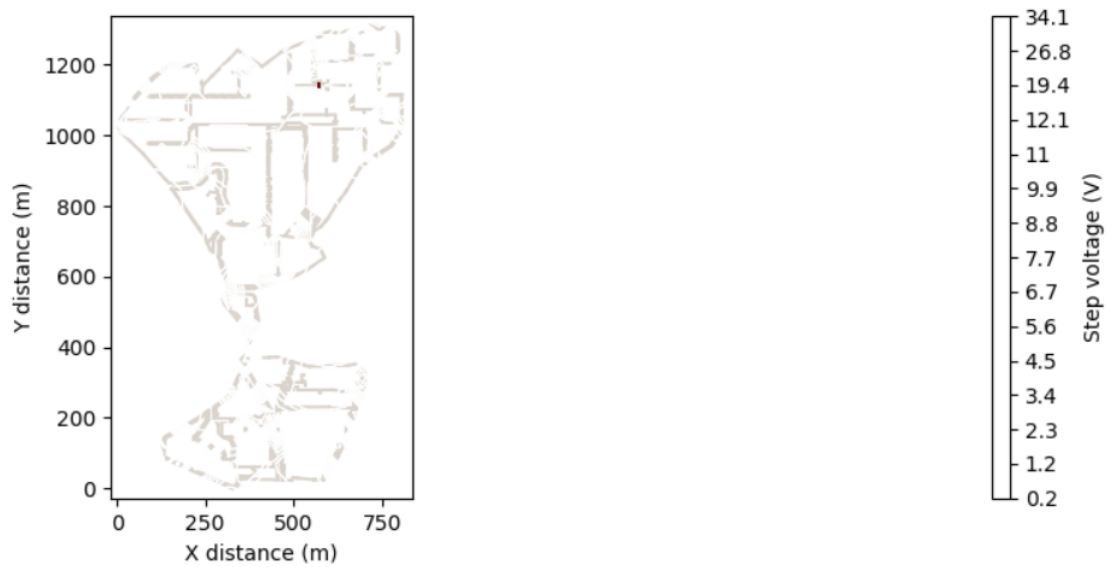


Figure 10.41 - Step Voltage values considering the fault current at the northern transformation station

Table 10.4 - Change in resistance and touch voltage

New Resistance [Ω]	New Touch Voltage [V]
0.723	156.4

10.4.12 - Fault at the middle Transformation Station

The same was done for the transformation station in the south of the solar park.



Figure 10.42 - Touch Voltage considering the fault current at the middle transformation station

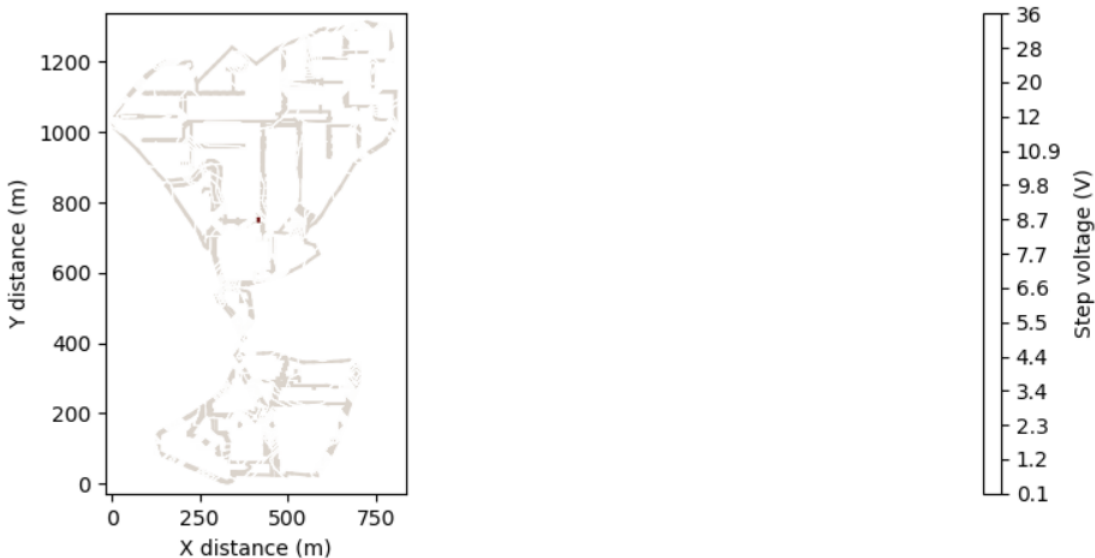


Figure 10.43 - Step Voltage values considering the fault current at the middle transformation station

Table 10.5 - Change in resistance and touch voltage

New Resistance [Ω]	New Touch Voltage [V]
0.684	176.5

It is verified that the solar park grounding system is capable of withstanding a short circuit of 1.2 kA in any of the transformer stations.

10.4.13 - Fault at the southern Transformation Station

The same was done for the transformation station in the south of the solar park.

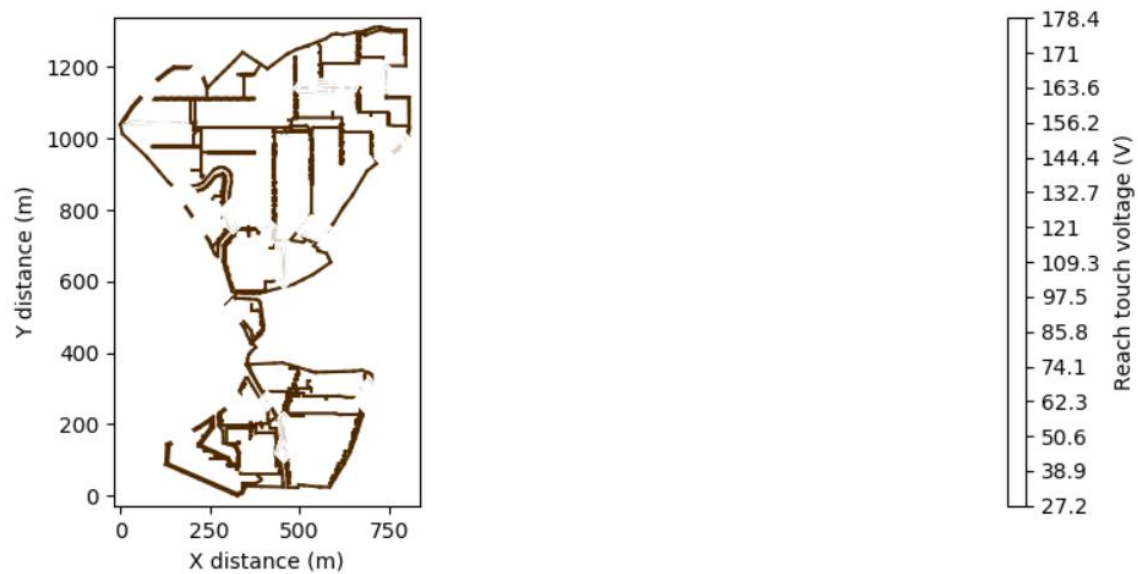


Figure 10.44 - Touch Voltage values considering the fault current at the southern transformation station

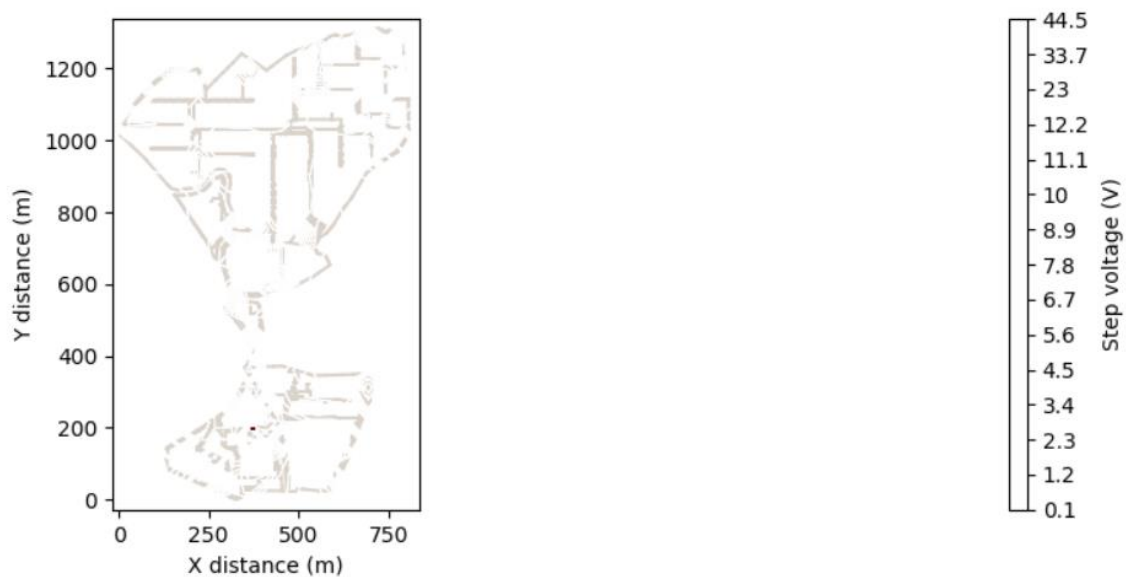


Figure 10.45 - Step Voltage values considering the fault current at the southern transformation station

Table 10.6 - Change in resistance and touch voltage

New Resistance [Ω]	New Touch Voltage [V]
0.786	178.4

It is verified that the solar park grounding system is capable of withstanding a short circuit of 1.2 kA in any of the transformer stations.

10.4.14 - Conclusion

It is concluded that the validation of the solar park's grounding system was successfully completed, both in terms of touch and step voltages and grid resistance.

If it were possible to introduce heavier files into the SafeGrid software, there would be a closer approximation to a real scenario through the introduction of all existing metal support structures in the park, which would allow progress with grid optimization.

The table presented below shows the values of resistance and touch voltage of the initial non-optimized and of the optimized grounding system.

Table 10.7 - Change in resistance and touch voltage

Non-Optimized Resistance [Ω]	Optimized Resistance [Ω]	Non-Optimized Touch Voltage [V]	Optimized Touch Voltage [V]
0.789	0.786	3431.5	178.4

Chapter 11

Wind Farm Earthing System Validation

Similar to what was done in the previous chapter, a series of simulations will be performed using the SafeGrid software. The main objective of this study is to better understand the efficiency of individual components within specific scenarios. It is expected that with these results it will be possible to determine the most efficient validation methods for several wind farm grounding system scenarios.

11.1.1 - Grounding System Conductor Sizing (Step 2)

Before designing the initial earthing system, it is necessary to know the cable that can be used, and it is necessary to dimension it. For this purpose, the calculation equation for the minimum conductor section of a grounding system, given by the IEEE-80 2013 standard, will be used.

$$S_{min} = \frac{I_f}{\sqrt{\frac{TCAP \times 10^{-4}}{t_f \times \alpha \times \rho_T} \times \ln\left(\frac{K_0 + T_m}{K_0 + T_a}\right)}} = 31.51 \text{ mm}^2 \quad (10.9)$$

Since the minimum value that can be used is 31.51 mm^2 , the cable used will have an 50 mm^2 section.

11.1.2 - Touch and Step Voltage Criteria (Step 3)

The maximum admissible value for touch and step voltage was calculated through SafeGrid which, again, considers the IEEE-80 standard. For this calculation it was considered that:

- The fault clearing time has a value of 0.5 seconds;
- The minimum allowed body weight is 50 kg;
- The body resistance for the touch voltage was 2000Ω and for the step voltage 5000Ω , meaning that anyone entering the premisses must wear appropriate boots.
- A surface layer with a thickness of 10 cm of bitumen ($10000 \Omega.m$) was considered.

For the validation of each turbine, it was used the ground potential rise (GPR) method which is more conservative than reach distance.

Given these variables, the maximum admissible touch and step voltages for the validation of each turbine are:

- $U_{touch} = 2161.38 \text{ V};$
- $U_{step} = 8153.39 \text{ V}.$

For the validation of the whole wind farm, it was used the 1.5m distance reach distance, due to the large dimensions of the wind farm. The same considerations were made, without taking into account the application of the surface layer, the maximum admissible touch and step voltages for the validation of each turbine are:

- $U_{touch} = 526.45 \text{ V};$
- $U_{step} = 1613.64 \text{ V}.$

11.1.3 - Earthing System Design (Step 4)

For the design of the land network of the wind farm, a network was designed with a substation with a 5x5m mesh and three wind turbines.

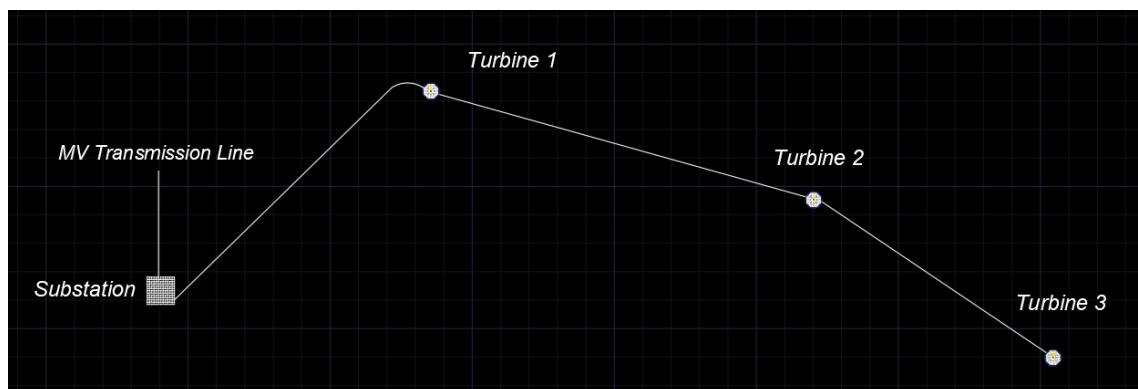


Figure 11.1 - Wind farm's grounding system with connection substation's grounding system designed in AutoCAD

The total cable on the grounding system (substation, wind plant interconnections and turbine foundations) is 7952.11 m.

The outside circular cable is 36m in diameter, the stairs are 2m high from the ground and 8m long horizontally, and the mesh is around 3x3m.

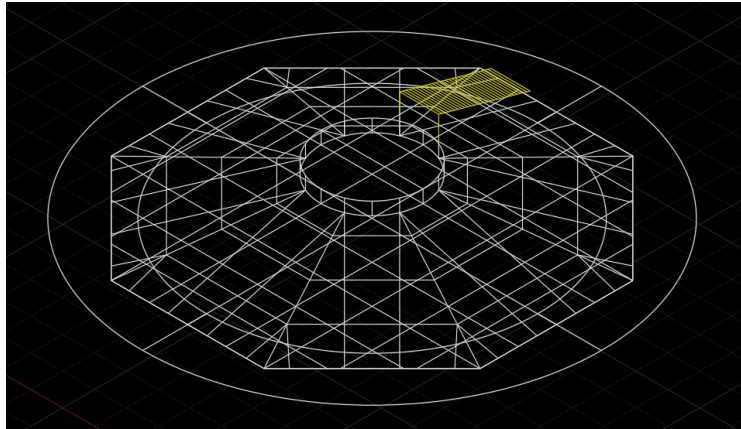


Figure 11.2 - Grounding system at the base of each wind turbine (in white) and access stairs (in yellow), designed in AutoCAD

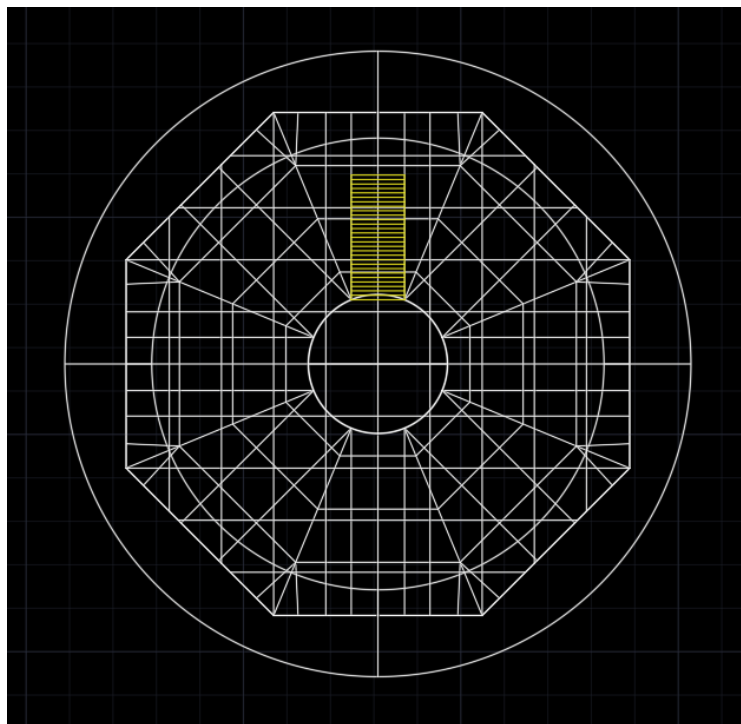


Figure 11.3 - Top view of the grounding system at the base of each wind turbine (in white) and access stairs (in yellow), designed in AutoCAD

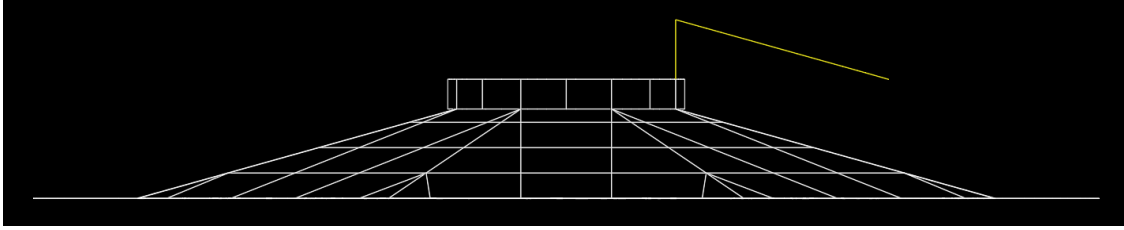


Figure 11.4 - Side view of the grounding system at the base of each wind turbine (in white) and access stairs (in yellow), designed in AutoCAD

It was considered that the entire structure below the level of the stairs is buried.

11.1.4 - Ground Resistance Calculation (Step 5, Step 8, and Step 9)

For the first design, the resistance of the grounding system was calculated through a simulation carried out in SafeGrid, where the value of the grid's mesh resistance depends on the amount of cable in the system and where it's located. So, resistance optimization will be done simultaneously with the optimization of touch and contact voltages.

The grid's resistance will be validated once its value is equal or below 10Ω , which is the maximum value according to the IEC 61499-24-2019 standard. The touch and step voltages will be validated if their maximum value on the installation is below the maximum values defined in step 3.

11.1.5 - Calculation of the Maximum Grounding System Current (Step 6)

All these values mentioned in the previous subchapter were necessary to use the Fault Current mode on SafeGrid, which allows to calculate the split factor in relation to a transmission line. The value of the split was 31%, rounded to the units, which results in a short-circuit current of 3.686 kA.

$$\begin{aligned} I_G &= I_f * S_f * D_f \Leftrightarrow \\ \Leftrightarrow I_G &= 12000 * 0,31 * 1.062 \Leftrightarrow \\ \Leftrightarrow I_G &\simeq 3.686 \text{ kA} \end{aligned} \tag{10.10}$$

11.1.6 - Ground Potential Rise (GPR) < Allowable Touch Voltage - Verification (Step 7)

For the initial design, the GPR given by SafeGrid is 6875 V. Since the GPR is higher than the allowable touch voltage, this condition is not validated, and an optimization of the system will have to be made.

11.1.7 - Conductor Depth

In this section, the effects of depth on the resistance and voltage of the wind farm's grounding system will be studied for three cases: 0.5m, 1.0m and 1.5m.

Depth: 0.5 m

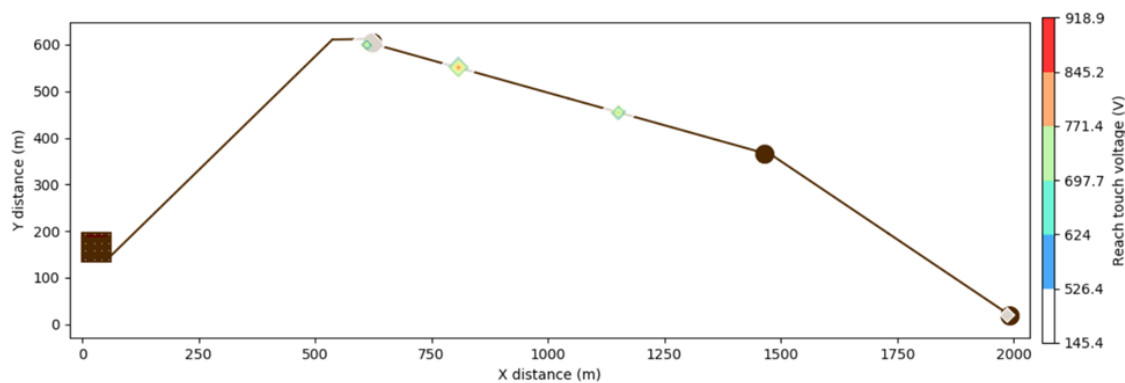


Figure 11.5 - Touch Voltage values on the PV Plant considering the grounding system at a depth of 0.5m

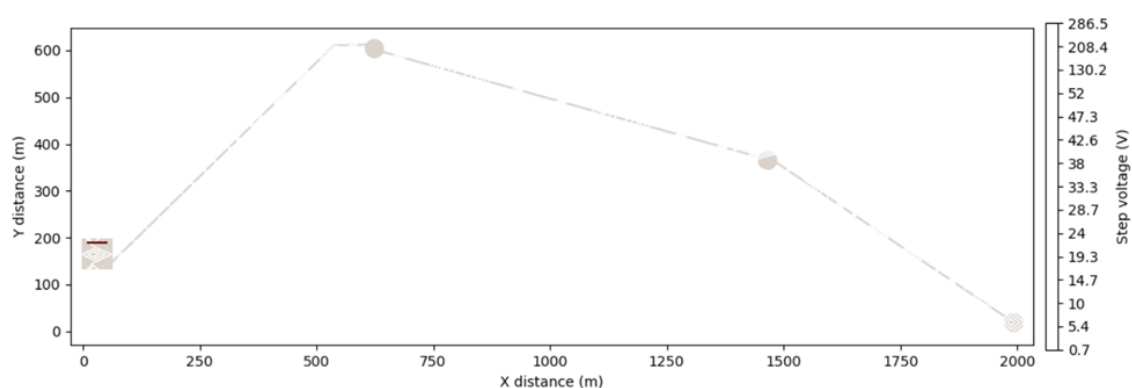


Figure 11.6 - Step Voltage values on the PV Plant considering the grounding system at a depth of 0.5m

The grid resistance obtained for the wind farm's grounding system at 0.5 m was 1.759 Ω .

Depth: 1.0 m

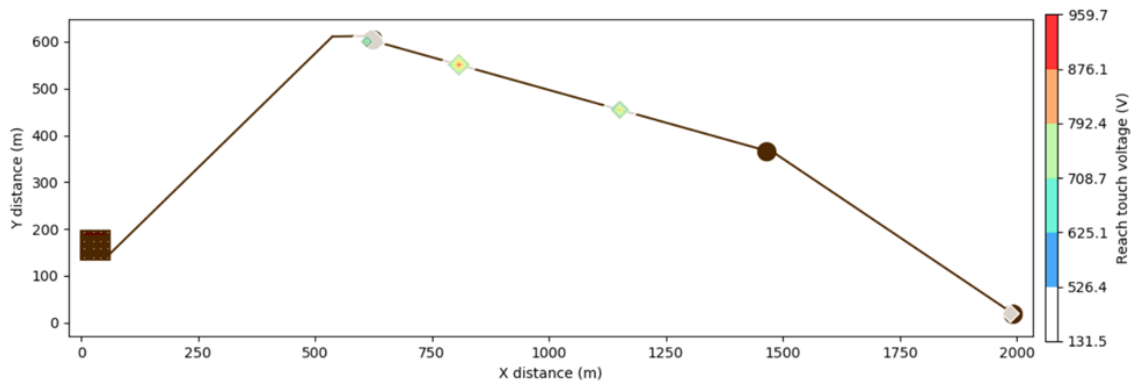


Figure 11.7 - Touch Voltage values on the PV Plant considering the grounding system at a depth of 1.0m

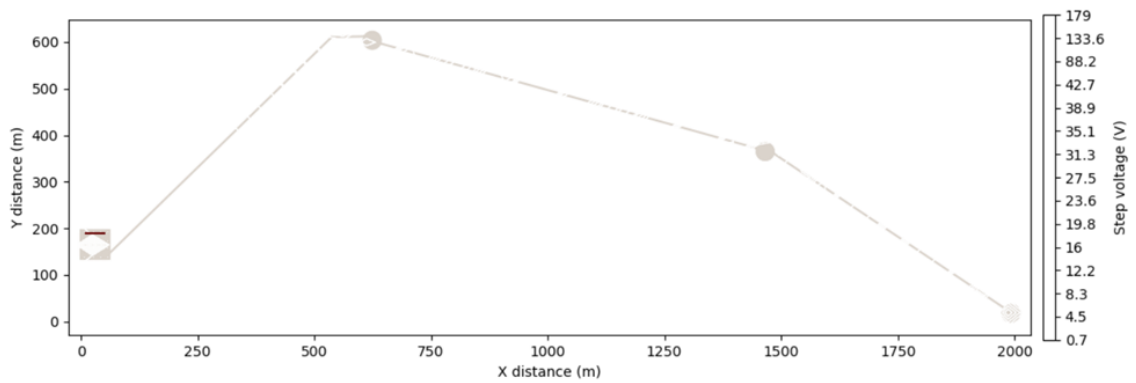


Figure 11.8 - Step Voltage values on the PV Plant considering the grounding system at a depth of 1.0m

The grid resistance obtained for the wind farm's grounding system at 1.0 m was 1.740 Ω .

Depth: 1.5 m

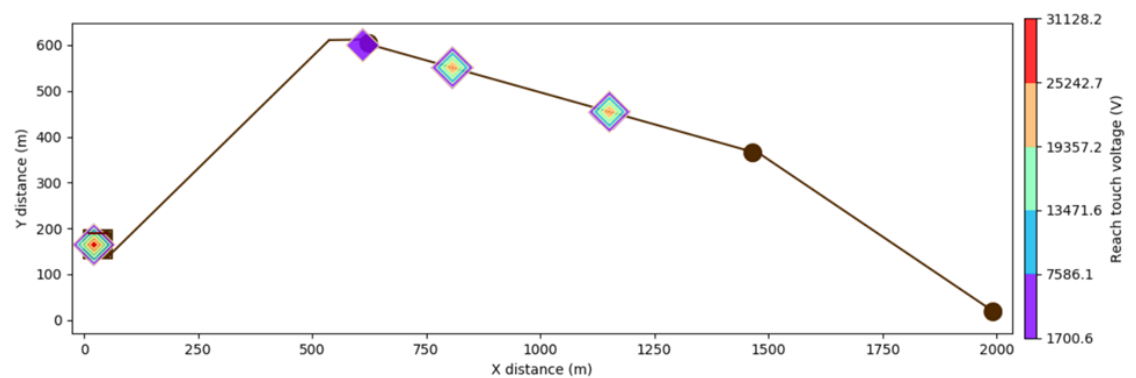


Figure 11.9 - Touch Voltage values on the PV Plant considering the grounding system at a depth of 1.5m

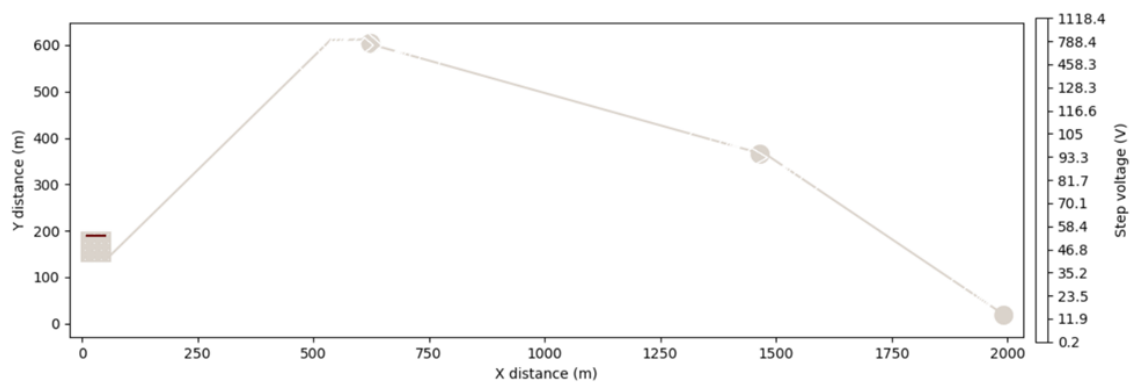


Figure 11.10 - Step Voltage values on the PV Plant considering the grounding system at a depth of 1.5m

The grid resistance obtained for the wind farm's grounding system at 1.5 m was 8.048 Ω .

A summary of the results obtained can be found in the following tables.

Table 11.1 - Resistance, Touch Voltage and Step Voltage results for the grounding system at a depth of 0.5 m

Grid Resistance [Ω]	Touch Voltage [V]	Step Voltage [V]
1.759	918.9	286.5

Table 11.2 - Resistance, Touch Voltage and Step Voltage results for the grounding system at a depth of 1.0 m

Grid Resistance [Ω]	Touch Voltage [V]	Step Voltage [V]
1.740	959.7	179.0

Table 11.3 - Resistance, Touch Voltage and Step Voltage results for the grounding system at a depth of 1.5 m

Grid Resistance [Ω]	Touch Voltage [V]	Step Voltage [V]
8.048	31128.2	1118.4

From the results obtained, it can be concluded that the most efficient depth is 0.5m, since the contact voltage has the lowest values of the three scenarios. Thus, this will be the depth of the grid considered in the remaining study.

11.1.8 - Fault in Wind Turbine One -

Similar to what was done at the transformer stations at the solar plant, a simulation of the defect in each of the park's turbines will also be carried out, also with 1.2 kA.

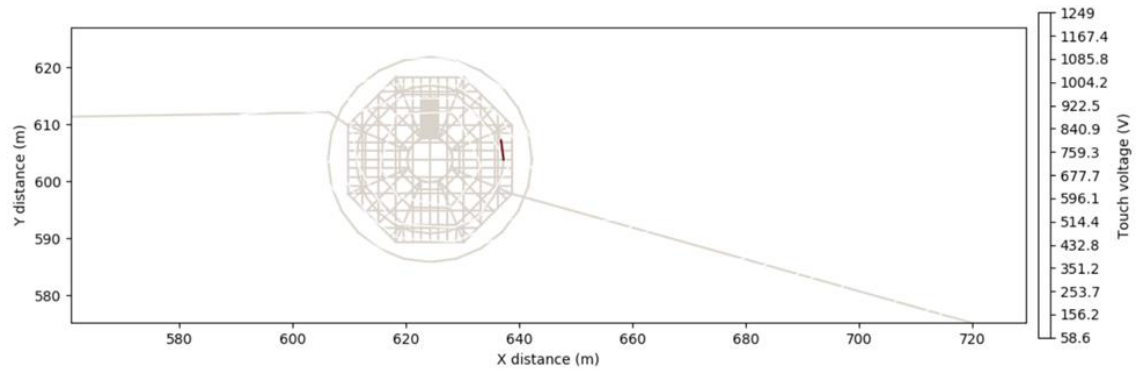


Figure 11.11 - Touch Voltage values on the wind turbine one, considering the grounding system at a depth of 1.5m

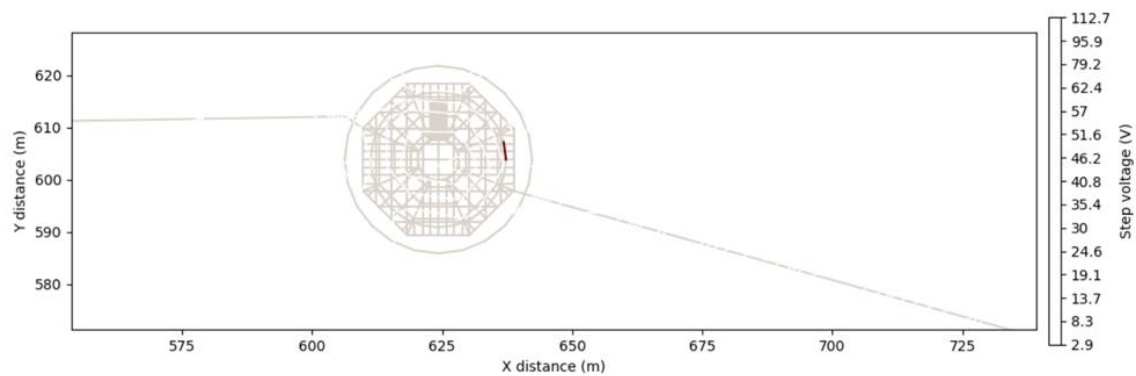


Figure 11.12 - Step Voltage values on the wind turbine one, considering the grounding system at a depth of 1.5m

It is verified that the touch and step voltage levels obtained are well below the maximum admissible limits.

11.1.9 - Fault in Wind Turbine Two -

The same procedure was made for turbine two.

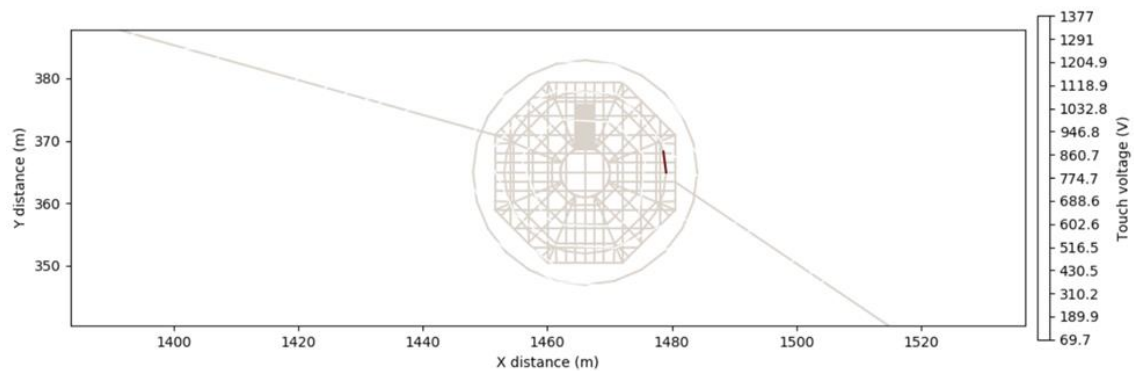


Figure 11.13 - Touch Voltage values on the wind turbine two, considering the grounding system at a depth of 1.5m

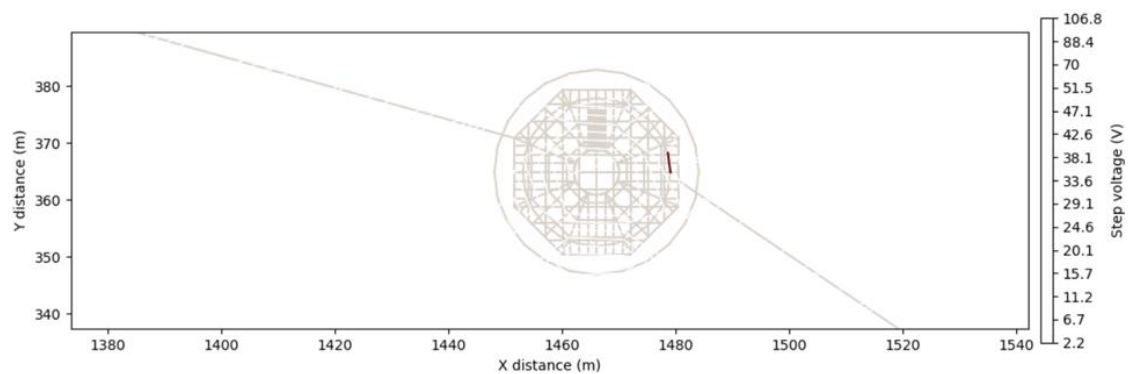


Figure 11.14 - Step Voltage values on the wind turbine two, considering the grounding system at a depth of 1.5m

Again, it's verified that the touch and step voltage levels obtained are well below the maximum admissible limits.

11.1.10 - Fault in Wind Turbine Three -

The same procedure was made for turbine three.

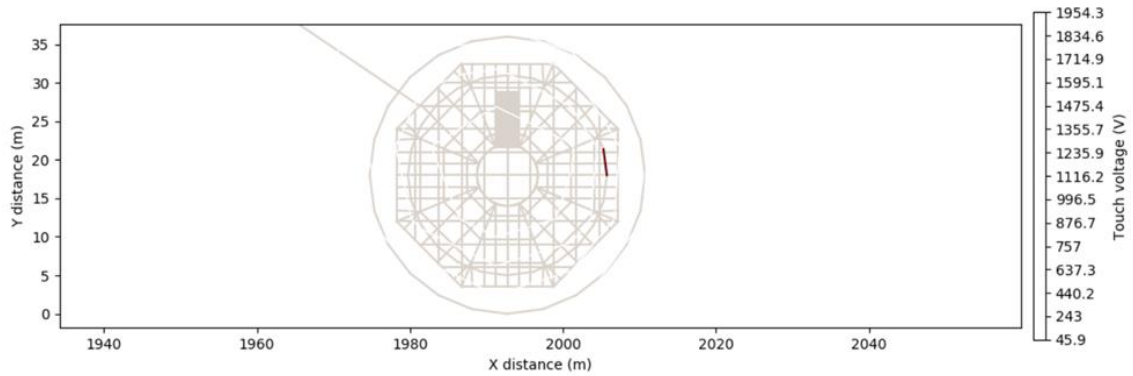


Figure 11.15 - Touch Voltage values on the wind turbine three, considering the grounding system at a depth of 1.5m

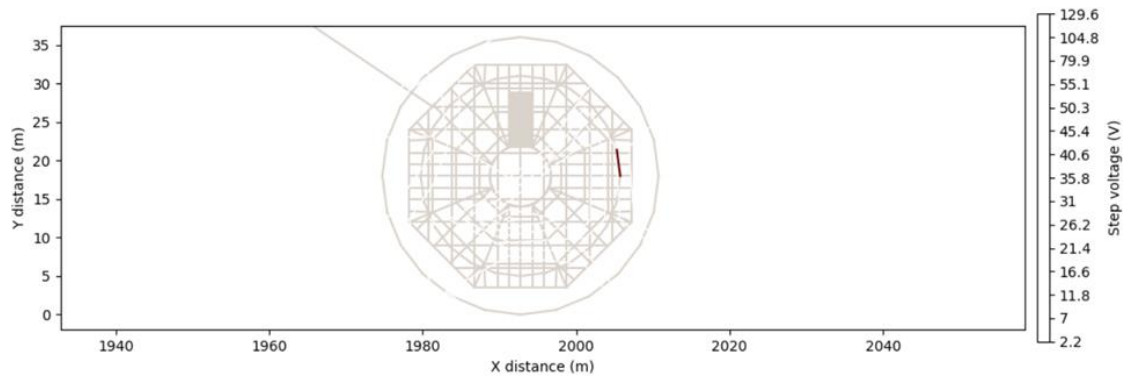


Figure 11.16 - Step Voltage values on the wind turbine three, considering the grounding system at a depth of 1.5m

Since the maximum touch voltage is lower than the touch voltage limit, and the grid's resistance is lower than 1Ω , in the event of a short circuit in the substation or in one of the transformer stations, the wind farm's grounding system is validated.

Chapter 12

Optimization Study

In this chapter, a series of simulations will be performed using the SafeGrid software. The main objective of this study is to better understand the efficiency of individual components within specific scenarios. It is expected that with these results it will be possible to determine the most efficient validation methods for several grounding system scenarios.

However, in the real world there are other considerations to take into account, namely prices and feasibility of installing the proposed solutions.

12.1 - Conductor Depth

In this section, the effects of depth on the resistance and voltage of the grounding system will be studied for three cases:

- Case 1: Two layers (the second layer more resistive than the first);
- Case 2: Two layers (the second layer less resistive than the first);
- Case 3: One layer.

For each case, checkered grids will be simulated at depths of 0.5m, 0.7m, 0.9m, 1.1m, 1.3m and 1.5m and the results will be presented in graphs to better understand the behaviour of the system at each depth.

By inputting these values into SafeGrid's Soil Model mode, the three previously mentioned soil models were created. An attempt was made to reduce the RMSE by eliminating layers with values with the greatest deviation, ensuring that the soil model does not differ too much from the measures taken.

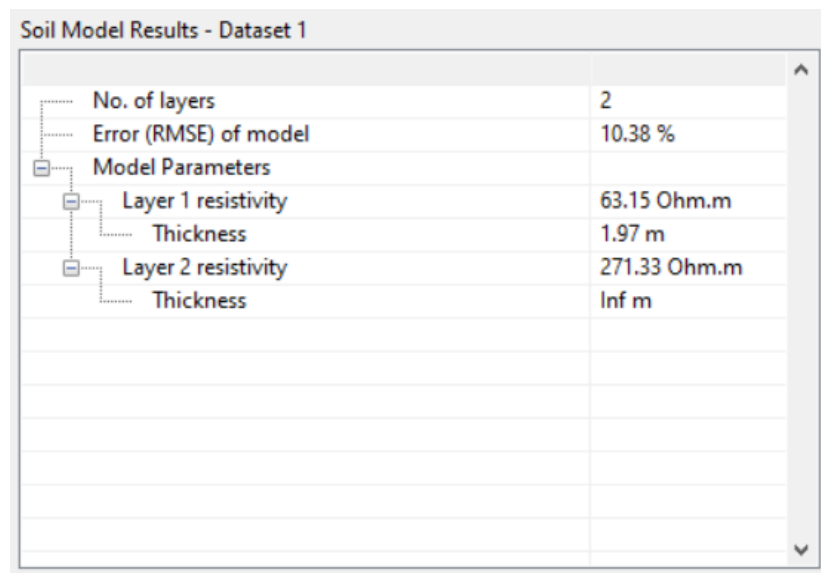
12.1.1 - Case 1 - Two Layers (the Second Layer More Resistive than the First)

Random values were assigned to soil resistivity, in order to approximate as much as possible to field measures in the real world, within the desired conditions. These values are displayed in Table 12.1.

Table 12.1 - Soil measures

	Depth [m]	Spacing [m]	Measure 1 [Ω .m]	Measure 2 [Ω .m]	Measure 3 [Ω .m]	Measure 4 [Ω .m]	Average [Ω .m]
First Layer	0.20	0.29	84.64	96.35	90.32	92.34	90.91
	0.50	0.71	64.52	82.46	75.12	78.94	75.26
Second Layer	0.90	1.29	136.42	105.23	108.65	187.22	134.38
	1.50	2.14	154.59	186.57	181.17	179.43	175.44
	2.00	2.86	176.94	194.28	167.14	184.74	180.78

In the first case it was not necessary to remove measures since the RMSE is only 10.38%, which is considered a low value. The soil model obtained is shown in Figure 12.1.



No. of layers	2
Error (RMSE) of model	10.38 %
Model Parameters	
Layer 1 resistivity	63.15 Ohm.m
Thickness	1.97 m
Layer 2 resistivity	271.33 Ohm.m
Thickness	Inf m

Figure 12.1 - Soil Model obtained in SafeGrid

Table 12.2 - Touch voltage and resistance as function of conductor depth

Conductor Depth [m]	Touch Voltage [V]	Resistance [Ω]
0.5	3983.8	1.756
0.7	3946.2	1.749
0.9	3920.3	1.745
1.1	3903.5	1.742
1.3	3895.2	1.740
1.5	3896.8	1.740

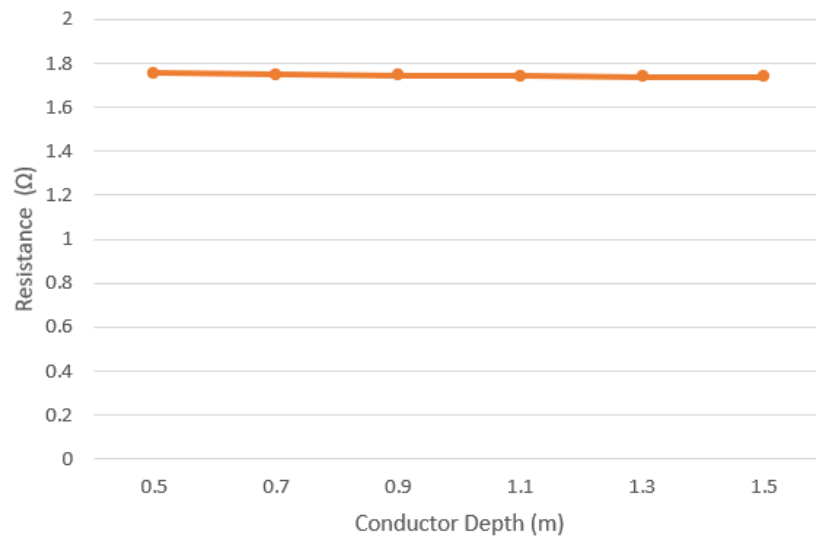


Figure 12.2 - Resistance of the grounding system as a function of conductor depth

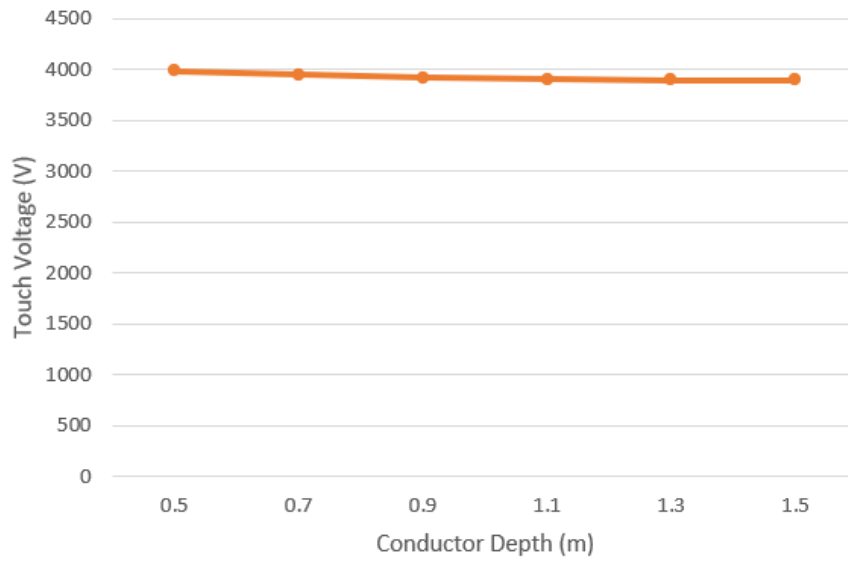


Figure 12.3 - Touch voltage of the grounding system as a function of conductor depth

With these results it can be concluded that when the bottom layer is more resistive than the top layer the difference that the depth has in the grounding system is very low. However, there is a slight decrease in both resistance and tension so in terms of efficiency this is the most efficient depth. In a real scenario this small change may not be enough for the costs associated with a deeper excavation.

12.1.2 - Case 2 - Two Layers (the Second Layer Less Resistive than the First)

The same procedure was done for the second scenario.

Table 12.3 - Soil measures

	Depth [m]	Spacing [m]	Measure 1 [Ω .m]	Measure 2 [Ω .m]	Measure 3 [Ω .m]	Measure 4 [Ω .m]	Average [Ω .m]
First Layer	0.20	0.29	84.64	96.35	90.32	92.34	90.91
	0.50	0.71	64.52	82.46	75.12	78.94	75.26
Second Layer	0.90	1.29	16.42	25.23	28.65	17.22	21.88
	1.50	2.14	24.59	29.57	31.17	26.43	27.94
	2.00	2.86	36.94	34.28	37.14	34.74	35.78

Again, it was not necessary to remove any value since the RMSE is only 10.38%. The soil model obtained is shown in Figure 12.4.

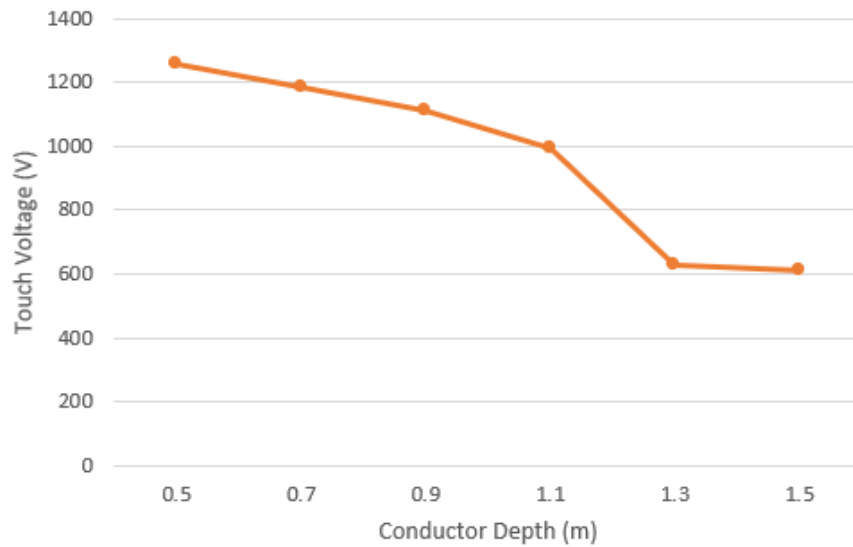


Figure 12.5 - Resistance of the grounding system as a function of conductor depth

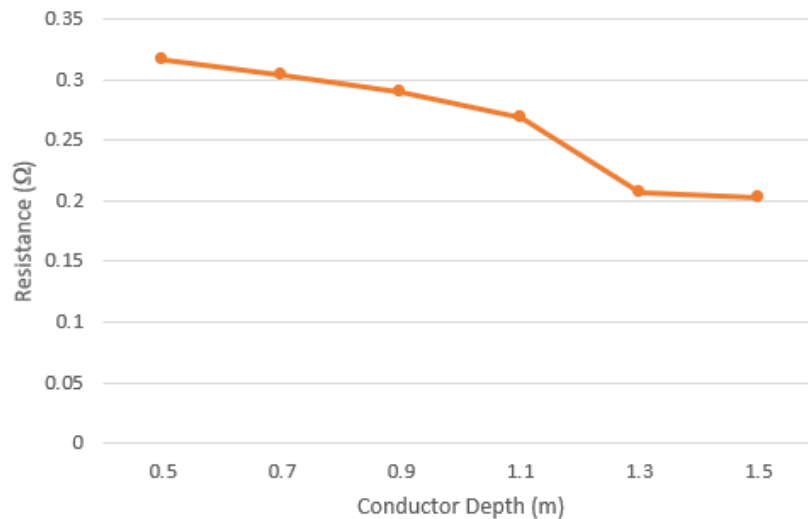


Figure 12.6 - Touch voltage of the grounding system as a function of conductor depth

It can be seen from the results obtained that the closer the mesh is to the layer with less resistivity, the lower the resistance and contact voltages in the grounding system. Although the best result is at 1.5m, since the difference between 1.3m and 1.5m is not very significant, and the difference between 1.1m and 1.3m is quite significant, this would be the best option for a real case.

12.1.3 - Case 3 - One Layer

Table 12.5 - Soil measures

	Depth [m]	Spacing [m]	Measure 1 [Ω .m]	Measure 2 [Ω .m]	Measure 3 [Ω .m]	Measure 4 [Ω .m]	Average [Ω .m]
First	0.20	0.29	84.64	96.35	90.32	92.34	90.91
Layer	0.50	0.71	64.52	82.46	75.12	78.94	75.26
	0.90	1.29	80.25	82.37	78.56	83.49	81.17
Second	1.50	2.14	74.53	78.61	71.68	75.94	75.19
Layer	2.00	2.86	70.14	71.59	68.72	72.06	70.63

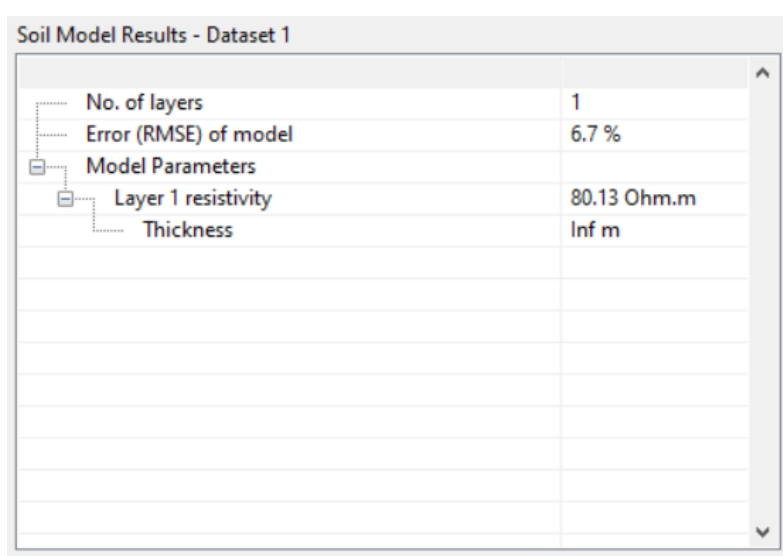


Figure 12.7 - Soil Model obtained in SafeGrid

Table 12.6 - Touch voltage and resistance as a function of conductor depth

Conductor Depth [m]	Touch Voltage [V]	Resistance [Ω]
0.5	2177.9	0.711
0.7	2135.7	0.704
0.9	2100.8	0.698
1.1	2070.2	0.693
1.3	2042.6	0.688
1.5	2017.2	0.683

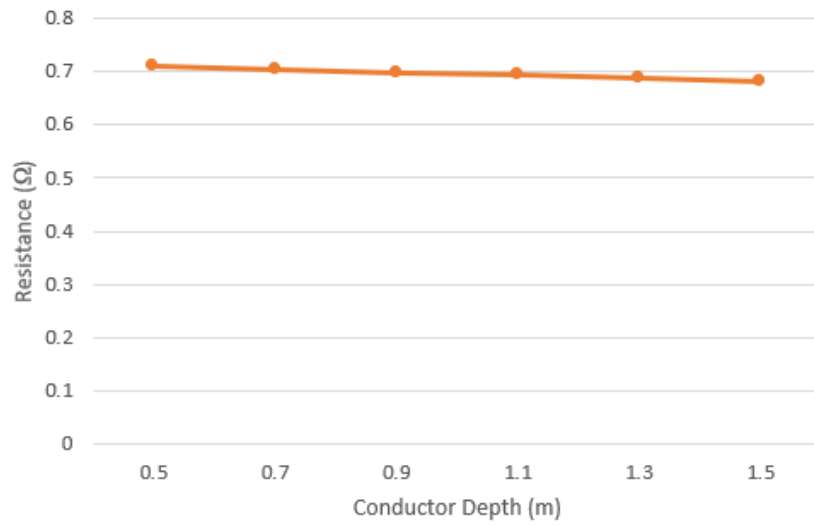


Figure 12.8 - Resistance of the grounding system as a function of conductor depth

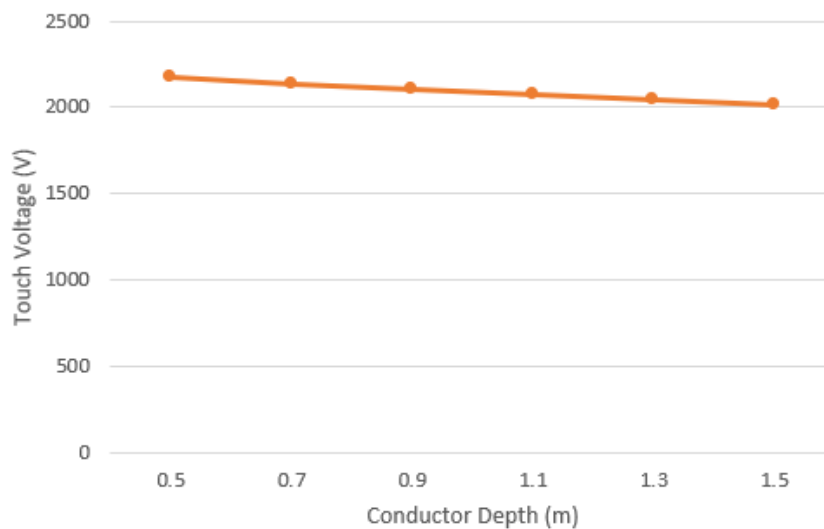


Figure 12.9 - Touch voltage of the grounding system as a function of conductor depth

Since the soil model has only one layer, the performance obtained is the expected result, with a practically proportional decrease of the touch voltage and resistance as the depth at which the grid is buried increases.

It follows from the study in this chapter that the grounding system should be as close as possible to the layer with the lowest resistivity and as far as possible from the layer with the lowest resistivity, as would be expected. If the soil model used is only one layer, which is not common, a proportional performance is obtained.

12.2 - Electrodes

Electrodes are an almost always indispensable component when it comes to validating a grounding system. In this subchapter, a study will be carried out to understand the influence that the number and length of electrodes have on the resistance and touch voltage of the grounding system.

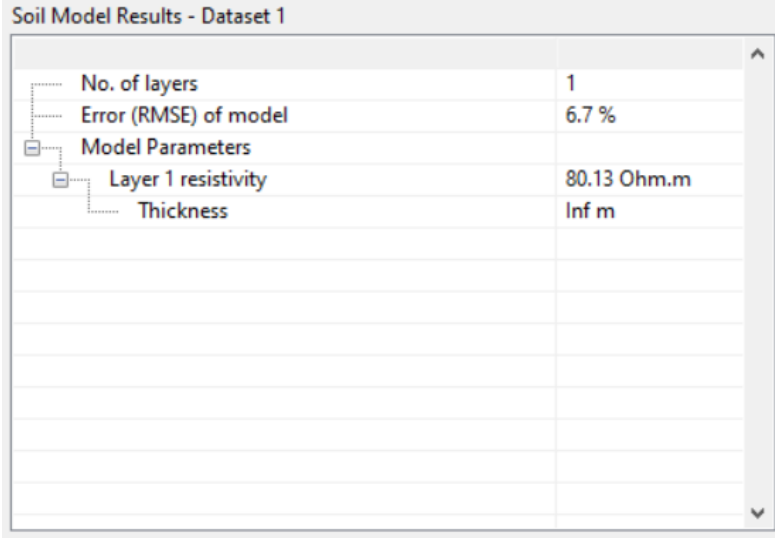
For this study, the number of electrodes will change between 0 and 320, and the length of each electrode will change between 2m and 100m.

Since the electrodes reach great depths, a soil model with deeper measures was considered so as not to be so easily for the fault current to reach the last layer. So, two soil models were made, with the upper layer the same for both, but with the lower layer more resistive for one and less resistive for the other.

12.2.1 - Case 1 - Two Layers (the Second Layer More Resistive than the First

Table 12.7 - Soil measures (more resistive second layer)

	Depth [m]	Spacing [m]	Measure 1 [$\Omega \cdot m$]	Measure 2 [$\Omega \cdot m$]	Measure 3 [$\Omega \cdot m$]	Measure 4 [$\Omega \cdot m$]	Average [$\Omega \cdot m$]
First Layer	0.5	0.7	184.64	196.35	190.32	192.34	190.91
	1.5	2.1	264.52	282.46	275.12	278.94	275.26
	3.0	4.3	296.42	305.23	308.65	287.22	299.38
	5.0	7.1	324.59	316.57	311.17	329.43	320.44
	10.0	14.3	376.94	394.28	367.14	384.74	380.78
Second Layer	15.0	21.4	423.61	401.16	413.58	409.73	412.02
	20.0	28.6	574.70	559.34	591.26	569.18	573.62
	30.0	42.9	621.82	603.27	631.29	641.42	624.45
	40.0	57.1	710.31	697.64	724.93	719.54	713.11
	50.0	71.4	862.94	826.97	837.64	879.68	851.81
	60.0	85.7	1136.25	1087.64	1193.57	1235.61	1163.27
	70.0	100.0	1354.89	1397.28	1284.61	1276.39	1328.29
	80.0	114.3	1812.36	1743.92	1872.48	1912.74	1835.38
	90.0	128.6	2168.67	2269.67	2098.17	2206.58	2185.77
	100.0	142.9	3016.21	2913.53	3109.84	3145.76	3046.34



The screenshot shows a software interface titled "Soil Model Results - Dataset 1". It displays a tree view on the left with expandable folders: "No. of layers", "Error (RMSE) of model", "Model Parameters", "Layer 1 resistivity", and "Thickness". The right pane shows the values for these parameters: "No. of layers" is 1, "Error (RMSE) of model" is 6.7 %, "Layer 1 resistivity" is 80.13 Ohm.m, and "Thickness" is Inf m. The interface has a scroll bar on the right.

Parameter	Value
No. of layers	1
Error (RMSE) of model	6.7 %
Model Parameters	
Layer 1 resistivity	80.13 Ohm.m
Thickness	Inf m

Figure 12.10 - Soil Model obtained in SafeGrid

12.2.1.1 - Influence of 2m Electrodes

Table 12.8 - Touch voltage and resistance as a function of number of 2m electrodes

Number of 2m electrodes [m]	Touch Voltage [V]	Resistance [Ω]
0	8951.9	6.025
20	8636.2	5.980
40	8443.4	5.948
80	8376.6	5.935
160	8005.0	5.875
320	7841.8	5.844

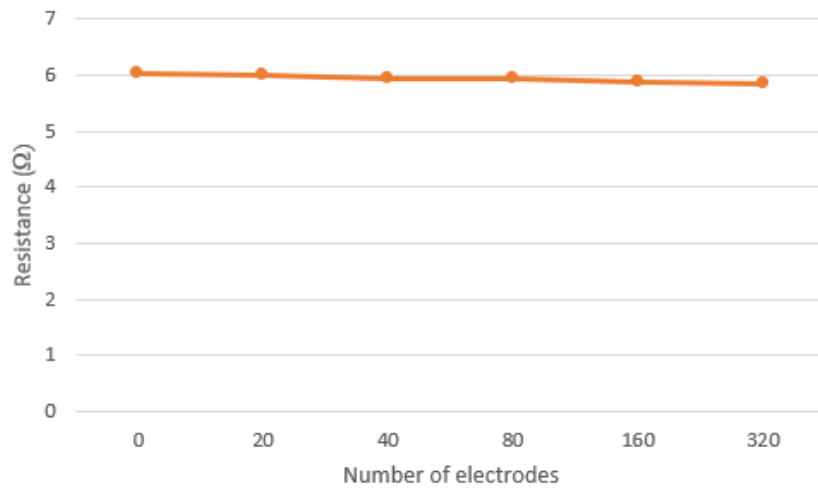


Figure 12.11 - Resistance of the grounding system as a function of number of 2m electrodes

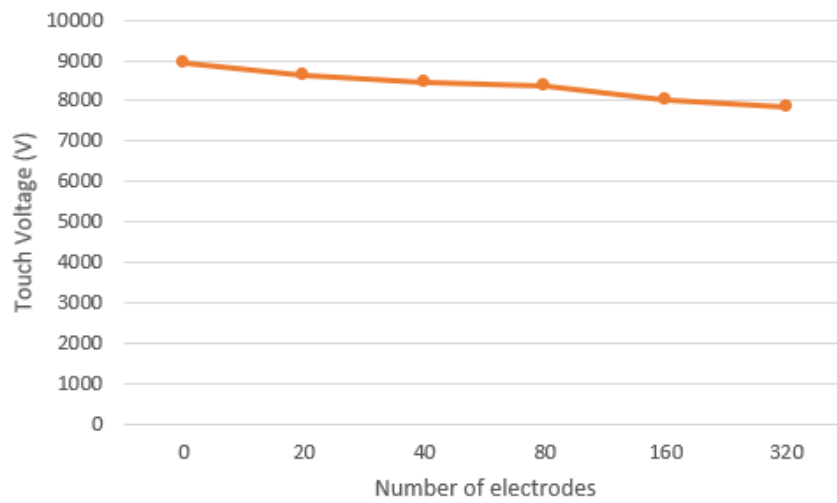


Figure 12.12 - Touch voltage of the grounding system as a function of number of 2m electrodes

12.2.1.2 - Influence of 10m Electrodes

Table 12.9 - Touch voltage and resistance as a function of number of 10m electrodes

Number of 10m electrodes [m]	Touch Voltage [V]	Resistance [Ω]
0	8951.9	6.025
20	6917.8	5.685
40	6123.7	5.541
80	5861.0	5.487
160	5251.8	5.381
320	5145.7	5.359

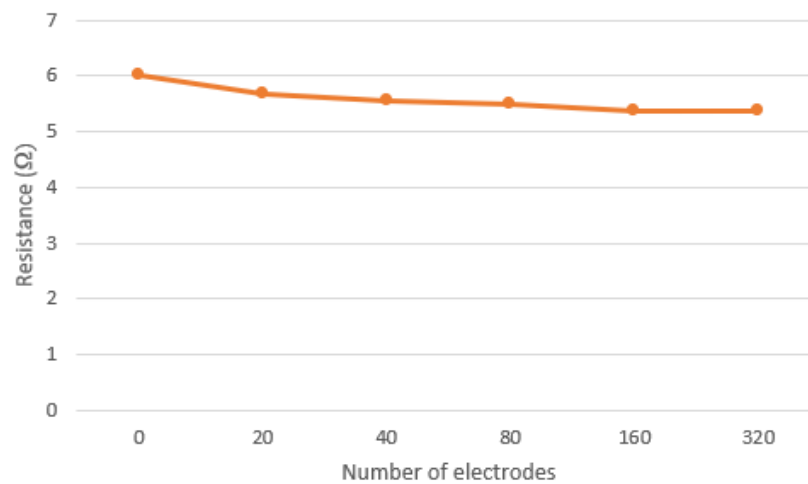


Figure 12.13 - Resistance of the grounding system as a function of number of 10m electrodes

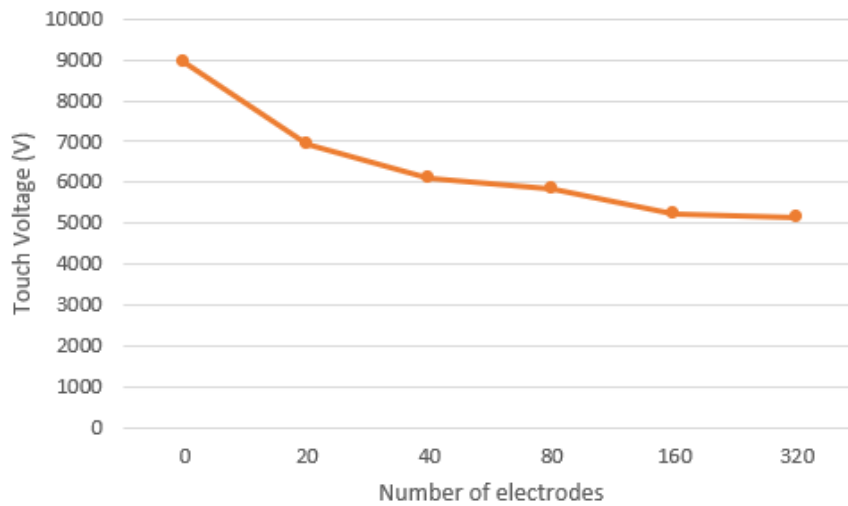


Figure 12.14 - Touch voltage of the grounding system as a function of number of 10m electrodes

12.2.1.3 - Influence of 50m Electrodes

Table 12.10 - Touch voltage and resistance as a function of number of 50m electrodes

Number of 50m electrodes [m]	Touch Voltage [V]	Resistance [Ω]
0	8951.9	6.025
20	5206.4	5.241
40	4454.2	5.075
80	4292.6	5.024
160	3885.5	4.939
320	3844.8	4.926

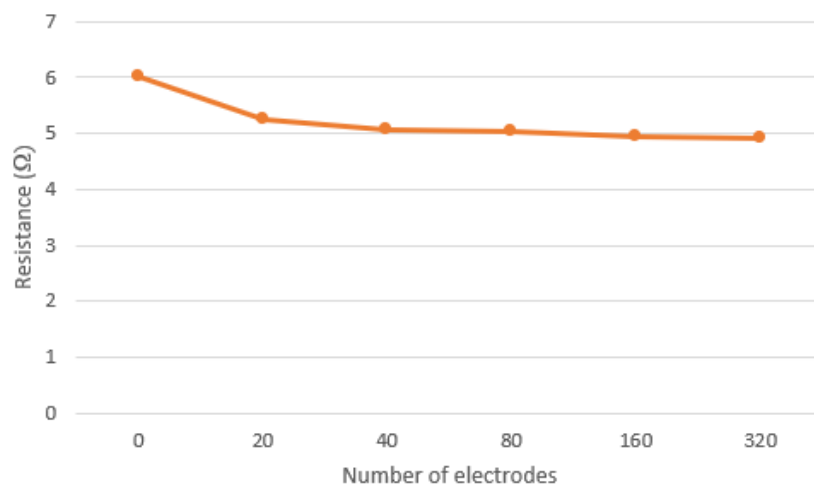


Figure 12.15 - Resistance of the grounding system as a function of number of 50m electrodes

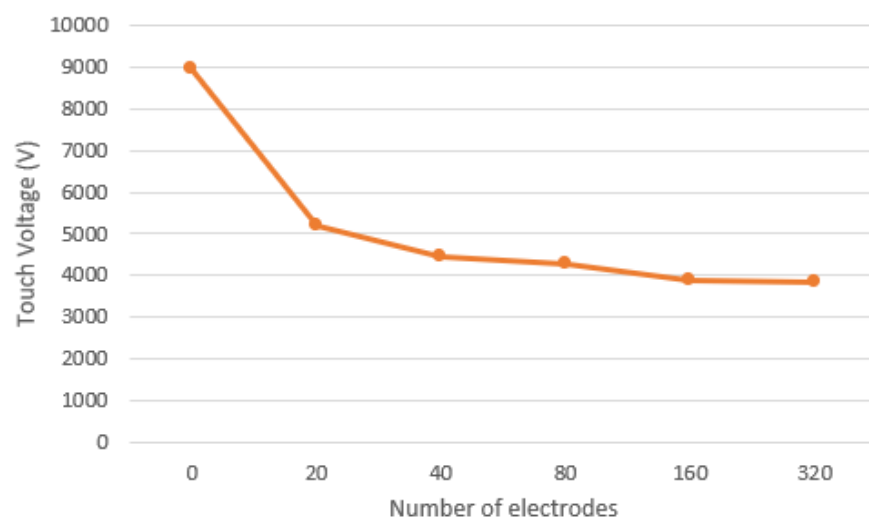


Figure 12.16 - Touch voltage of the grounding system as a function of number of 50m electrodes

12.2.1.4 - Influence of 100m Electrodes

Table 12.11 - Touch voltage and resistance as a function of number of 100m electrodes

Number of 100m electrodes [m]	Touch Voltage [V]	Resistance [Ω]
0	8951.9	6.025
20	4366.7	4.770
40	3715.9	4.601
80	3583.2	4.550
160	3246.4	4.475
320	- ¹	- ¹

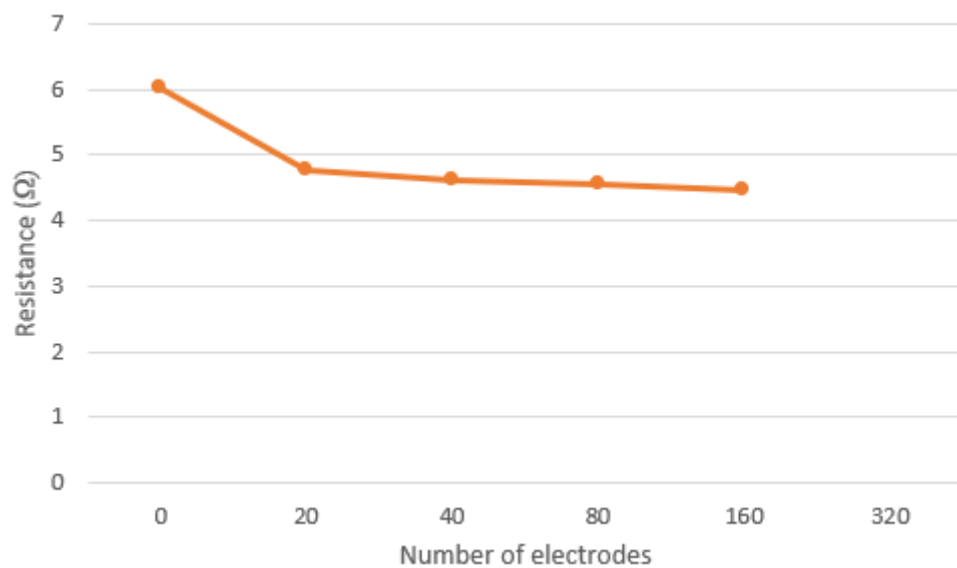


Figure 12.17 - Resistance of the grounding system as a function of number of 100m electrodes

¹ It wasn't possible to obtain this value due to the high computational weight.

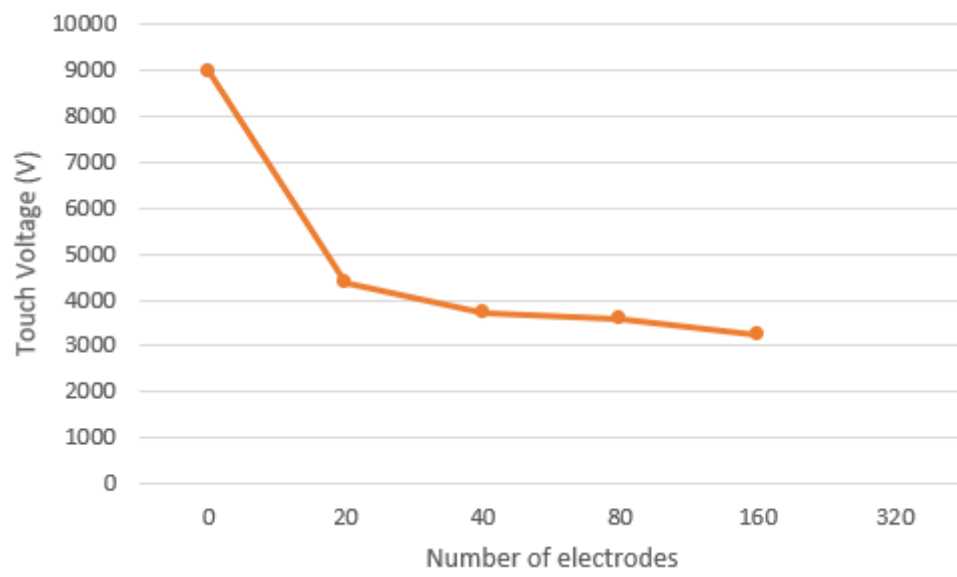


Figure 12.18 - Touch voltage of the grounding system as a function of number of 100m electrodes

12.2.2 - Case 2 - Two Layers (the Second Layer Less Resistive than the First)

Table 12.12 - Soil measures (less resistive second layer)

	Depth [m]	Spacing [m]	Measure 1 [$\Omega \cdot m$]	Measure 2 [$\Omega \cdot m$]	Measure 3 [$\Omega \cdot m$]	Measure 4 [$\Omega \cdot m$]	Average [$\Omega \cdot m$]
First Layer	0.5	0.7	184.64	196.35	190.32	192.34	190.91
	1.5	2.1	264.52	282.46	275.12	278.94	275.26
	3.0	4.3	296.42	305.23	308.65	287.22	299.38
	5.0	7.1	324.59	316.57	311.17	329.43	320.44
	10.0	14.3	376.94	394.28	367.14	384.74	380.78
Second Layer	15.0	21.4	65.21	69.24	67.81	61.52	65.95
	20.0	28.6	59.65	56.31	58.96	52.47	56.85
	30.0	42.9	55.71	58.49	61.64	51.67	56.88
	40.0	57.1	69.57	70.24	62.85	64.53	66.80
	50.0	71.4	74.68	72.43	71.61	68.15	71.72
	60.0	85.7	80.59	69.51	76.34	72.56	74.75
	70.0	100.0	82.67	80.32	87.34	84.53	83.72
	80.0	114.3	93.84	90.35	96.15	92.05	93.10
	90.0	128.6	99.25	102.67	103.75	98.64	101.08
	100.0	142.9	117.95	134.59	121.96	119.84	123.59

12.2.2.1 - Influence of 2m Electrodes

Table 12.13 - Touch voltage and resistance as a function of number of 2m electrodes

Number of 2m electrodes [m]	Touch Voltage [V]	Resistance [Ω]
0	4885.0	1.152
20	4708.1	1.127
40	4590.9	1.108
80	4510.2	1.092
160	4235.8	1.046
320	4014.6	1.004

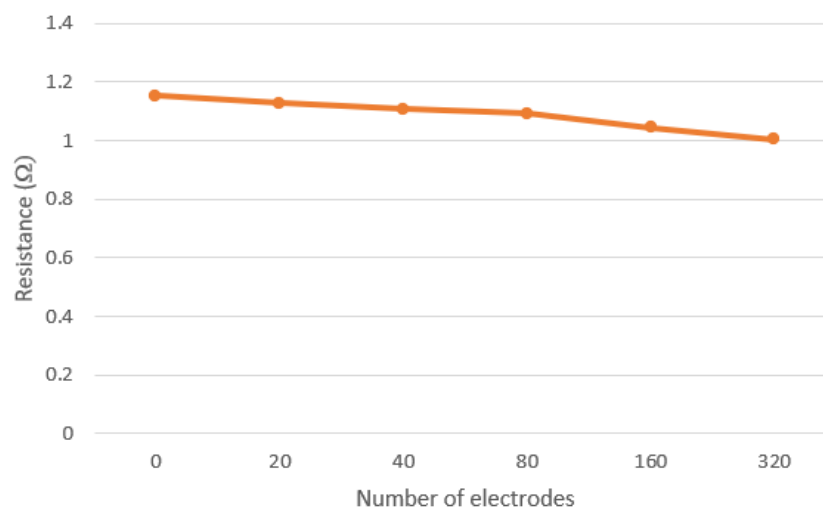


Figure 12.19 - Resistance of the grounding system as a function of number of 2m electrodes

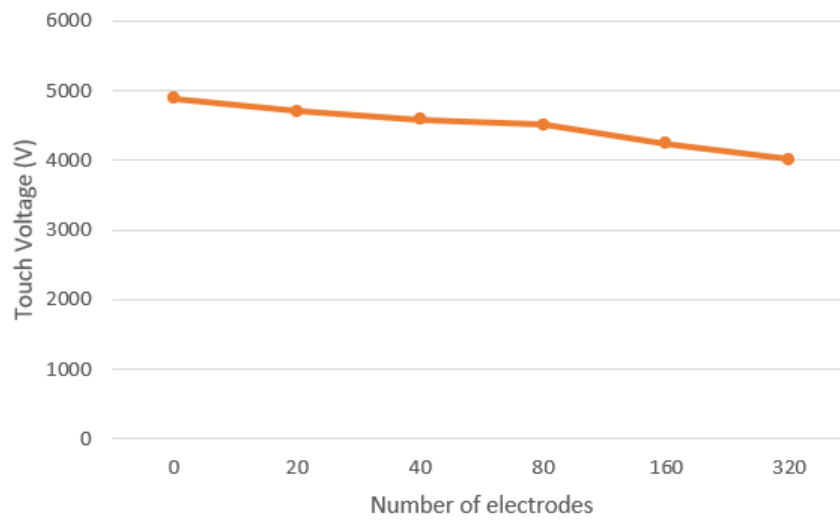


Figure 12.20 - Touch voltage of the grounding system as a function of number of 2m electrodes

12.2.2.2 - Influence of 10m Electrodes

Table 12.14 - Touch voltage and resistance as a function of number of 10m electrodes

Number of 10m electrodes [m]	Touch Voltage [V]	Resistance [Ω]
0	4885.0	1.152
20	2469.4	0.718
40	1829.2	0.598
80	1452.6	0.518
160	1126.3	0.456
320	1038.3	0.436

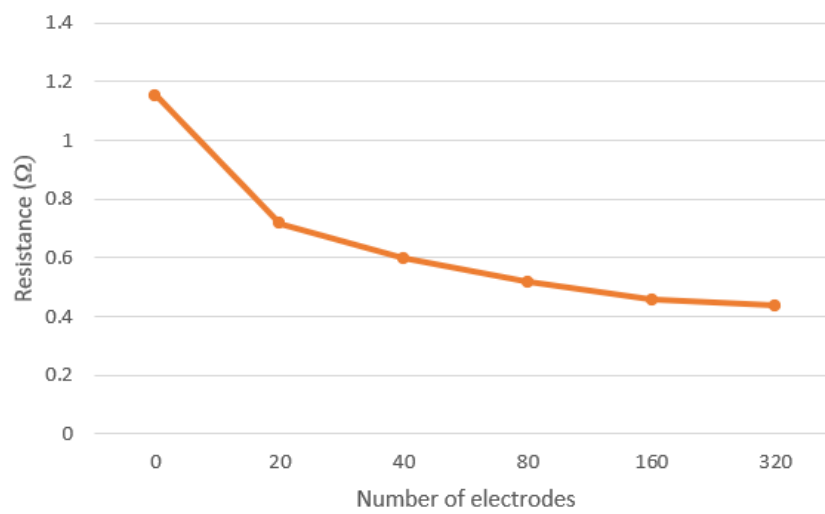


Figure 12.21 - Resistance of the grounding system as a function of number of 10m electrodes

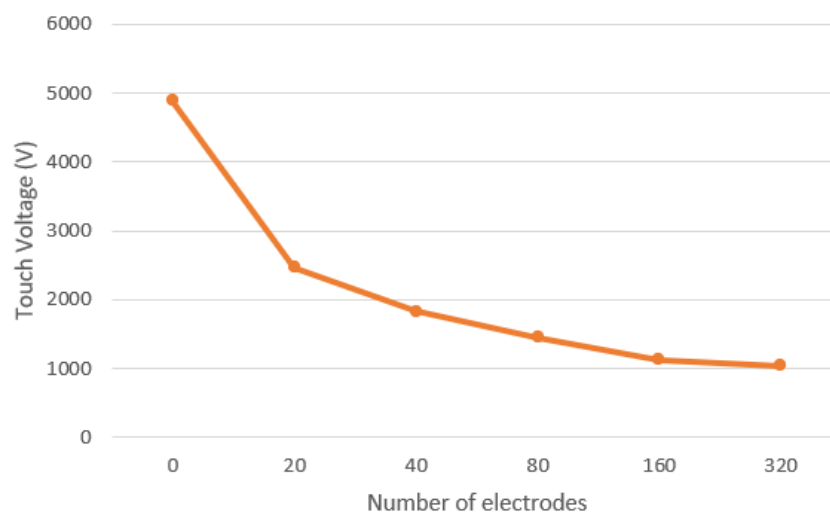


Figure 12.22 - Touch voltage of the grounding system as a function of number of 10m electrodes

12.2.2.3 - Influence of 50m Electrodes

Table 12.15 - Touch voltage and resistance as a function of number of 50m electrodes

Number of 50m electrodes [m]	Touch Voltage [V]	Resistance [Ω]
0	4885.0	1.152
20	491.4	0.270
40	360.4	0.241
80	324.4	0.230
160	281.5	0.220
320	278.4	0.218

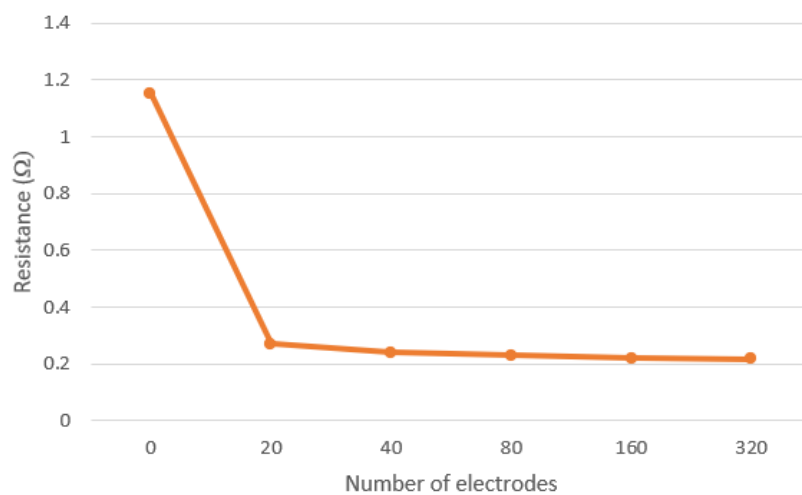


Figure 12.23 - Resistance of the grounding system as a function of number of 50m electrodes

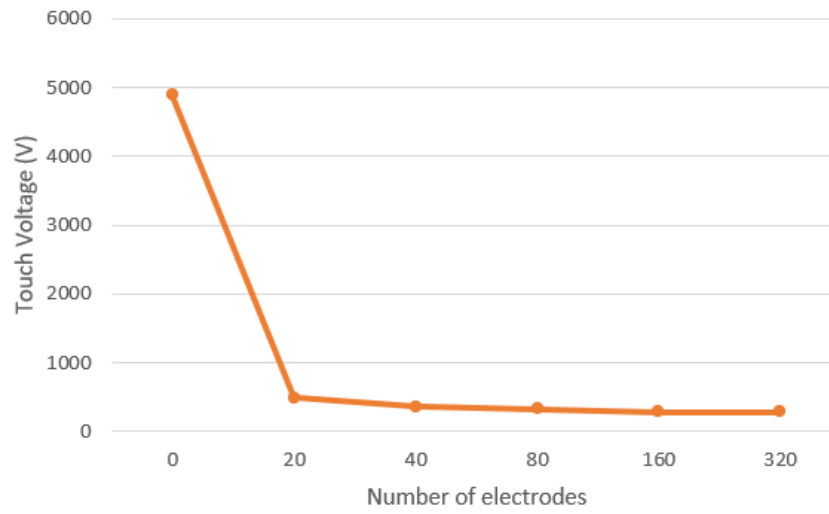


Figure 12.24 - Touch voltage of the grounding system as a function of number of 50m electrodes

12.2.2.4 - Influence of 100m Electrodes

Table 12.16 - Touch voltage and resistance as a function of number of 100m electrodes

Number of 100m electrodes [m]	Touch Voltage [V]	Resistance [Ω]
0	4885.0	1.152
20	259.3	0.175
40	197.4	0.160
80	183.3	0.155
160	161.7	0.150
320	~1	~1

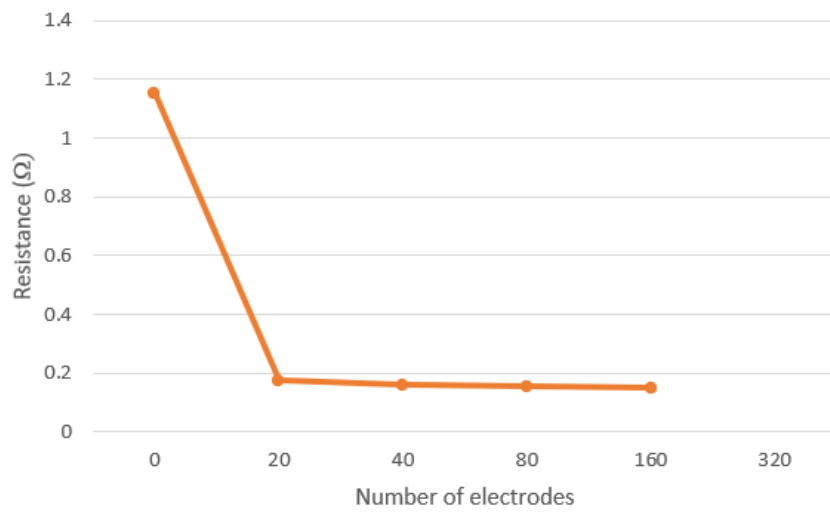


Figure 12.25 - Resistance of the grounding system as a function of number of 100m electrodes

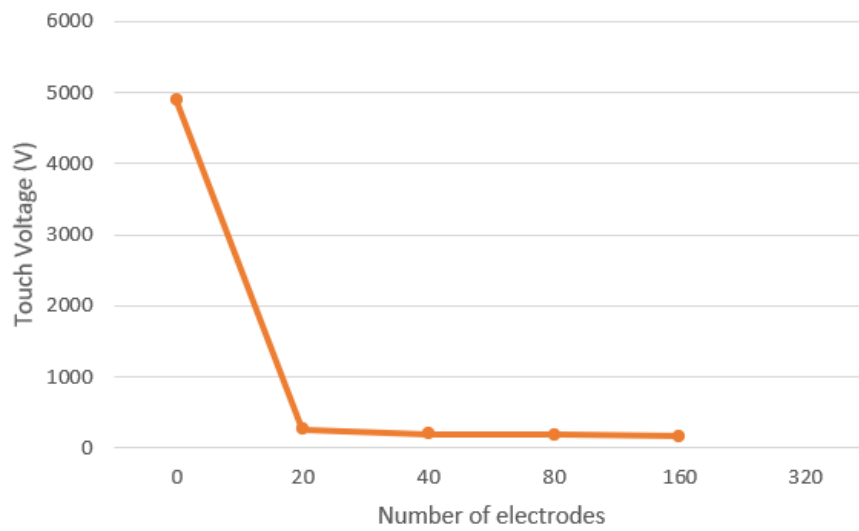


Figure 12.26 - Touch voltage of the grounding system as a function of number of 100m electrodes

12.2.3 - Case 3 - One Layer

Table 12.17 - Soil measures (less resistive second layer)

	Depth [m]	Spacing [m]	Measure 1 [Ω .m]	Measure 2 [Ω .m]	Measure 3 [Ω .m]	Measure 4 [Ω .m]	Average [Ω .m]
First Layer	0.5	0.7	184.64	196.35	190.32	192.34	190.91
	1.5	2.1	264.52	282.46	275.12	278.94	275.26
	3.0	4.3	296.42	305.23	308.65	287.22	299.38
	5.0	7.1	324.59	316.57	311.17	329.43	320.44
	10.0	14.3	376.94	394.28	367.14	384.74	380.78
Second Layer	15.0	21.4	277.02	269.82	274.60	266.39	271.96
	20.0	28.6	297.00	285.98	304.59	287.06	293.66
	30.0	42.9	306.62	300.13	317.29	312.72	309.19
	40.0	57.1	324.73	319.06	325.32	324.30	323.35
	50.0	71.4	406.15	385.92	390.43	407.99	397.62
	60.0	85.7	418.71	383.33	443.13	460.37	426.38
	70.0	100.0	460.12	478.96	429.65	422.73	447.86
	80.0	114.3	500.02	462.31	532.39	548.42	510.79
	90.0	128.6	583.59	637.511	552.84	601.93	593.96
	100.0	142.9	626.06	591.36	676.88	692.72	646.75

12.2.3.1 - Influence of 2m Electrodes

Table 12.18 - Touch voltage and resistance as a function of number of 2m electrodes

Number of 2m electrodes [m]	Touch Voltage [V]	Resistance [Ω]
0	9275.2	3.117
20	8931.9	3.070
40	8722.7	3.036
80	8630.9	3.019
160	8201.3	2.950
320	7968.6	2.905

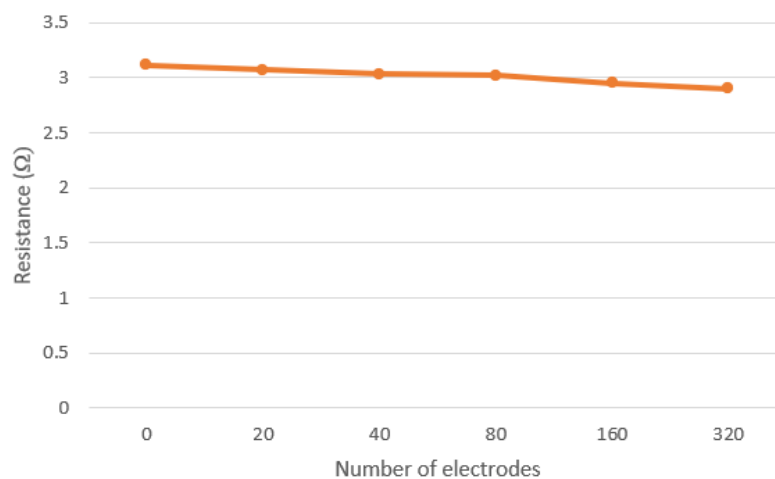


Figure 12.27 - Resistance of the grounding system as a function of number of 2m electrodes

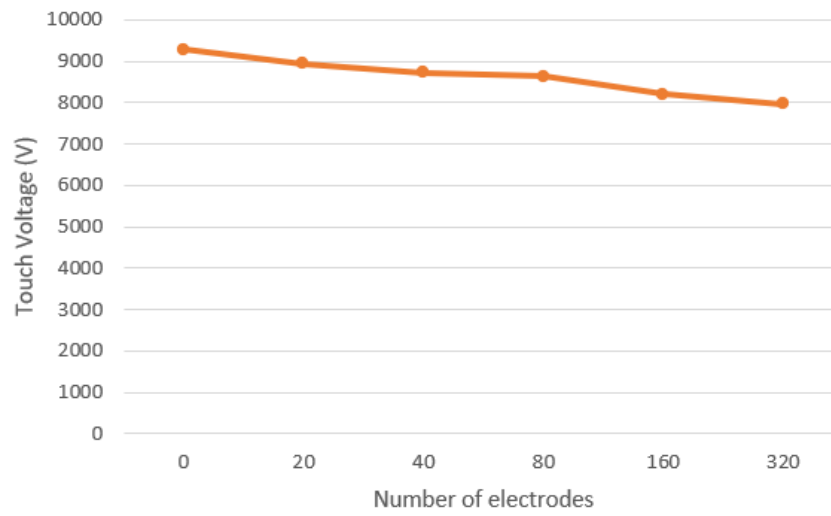


Figure 12.28 - Touch voltage of the grounding system as a function of number of 2m electrodes

12.2.3.2 - Influence of 10m Electrodes

Table 12.19 - Touch voltage and resistance as a function of number of 10m electrodes

Number of 10m electrodes [m]	Touch Voltage [V]	Resistance [Ω]
0	9275.2	3.117
20	6946.7	2.733
40	6000.8	2.562
80	5535.8	2.460
160	4777.2	2.321
320	4579.5	2.275

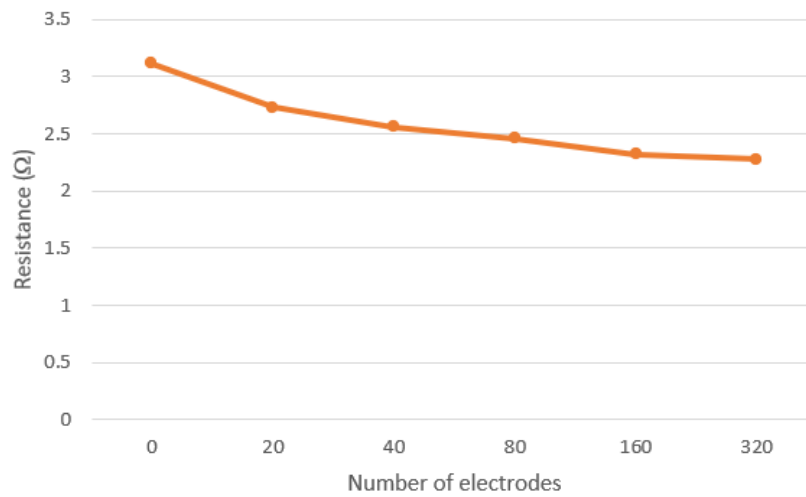


Figure 12.29 - Resistance of the grounding system as a function of number of 10m electrodes

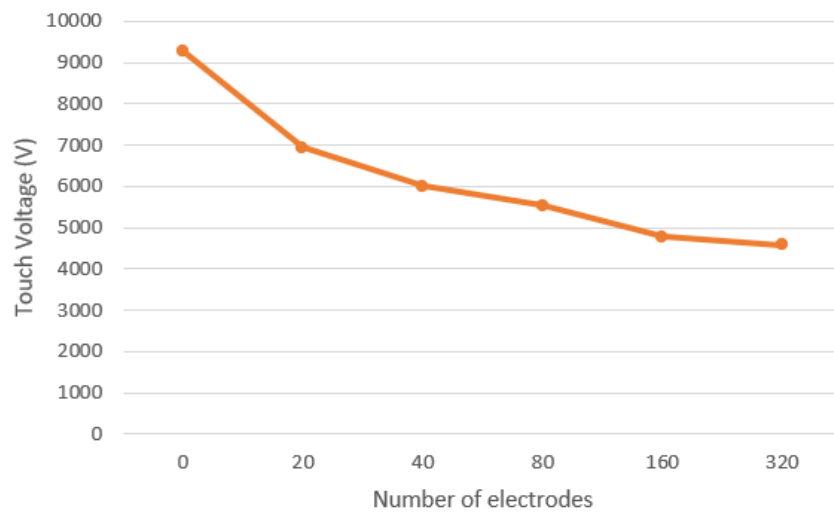


Figure 12.30 - Touch voltage of the grounding system as a function of number of 10m electrodes

12.2.3.3 - Influence of 50m Electrodes

Table 12.20 - Touch voltage and resistance as a function of number of 50m electrodes

Number of 50m electrodes [m]	Touch Voltage [V]	Resistance [Ω]
0	9275.2	3.117
20	2519.5	1.575
40	1951.1	1.436
80	1784.8	1.380
160	1564.9	1.327
320	1533.1	1.315

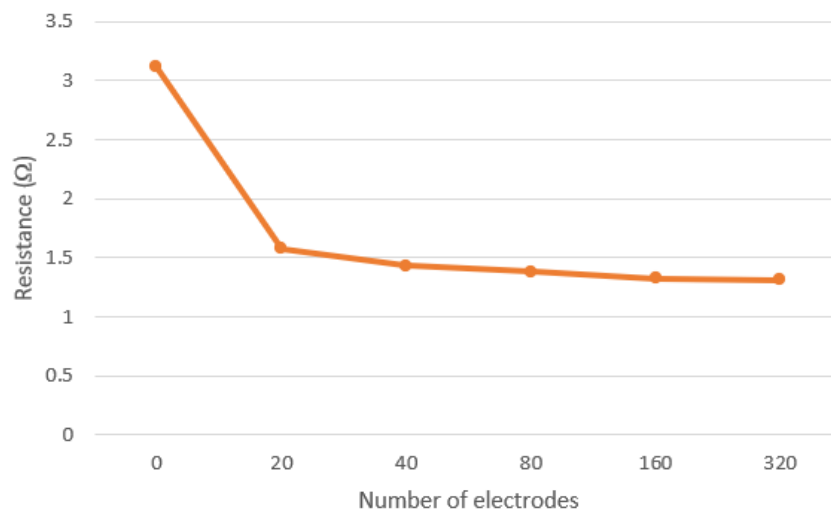


Figure 12.31 - Resistance of the grounding system as a function of number of 50m electrodes

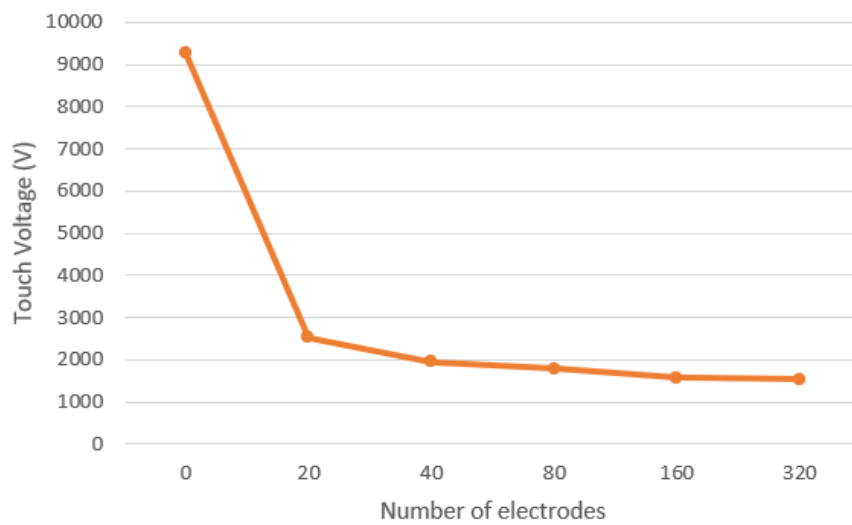


Figure 12.32 - Touch voltage of the grounding system as a function of number of 50m electrodes

12.2.3.4 - Influence of 100m Electrodes

Table 12.21 - Touch voltage and resistance as a function of number of 100m electrodes

Number of 100m electrodes [m]	Touch Voltage [V]	Resistance [Ω]
0	9275.2	3.117
20	1366.1	1.073
40	1075.1	0.993
80	1005.4	0.966
160	893.9	0.937
320	~1	~1

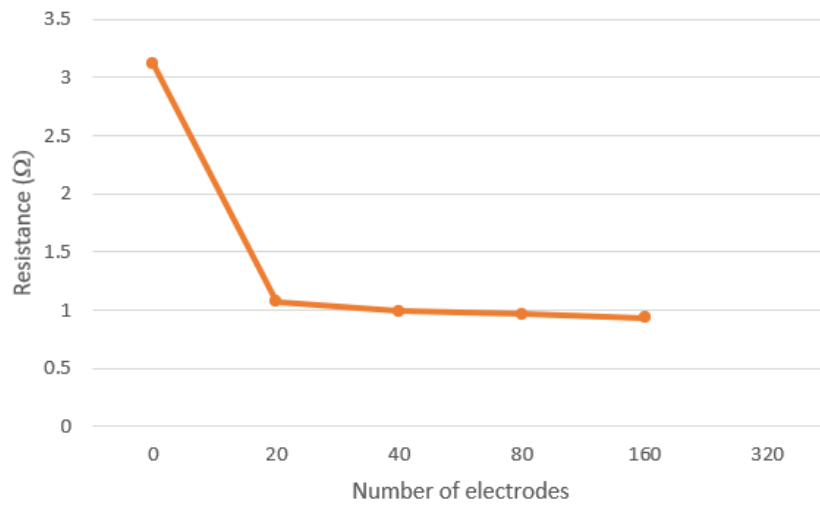


Figure 12.33 - Resistance of the grounding system as a function of number of 100m electrodes

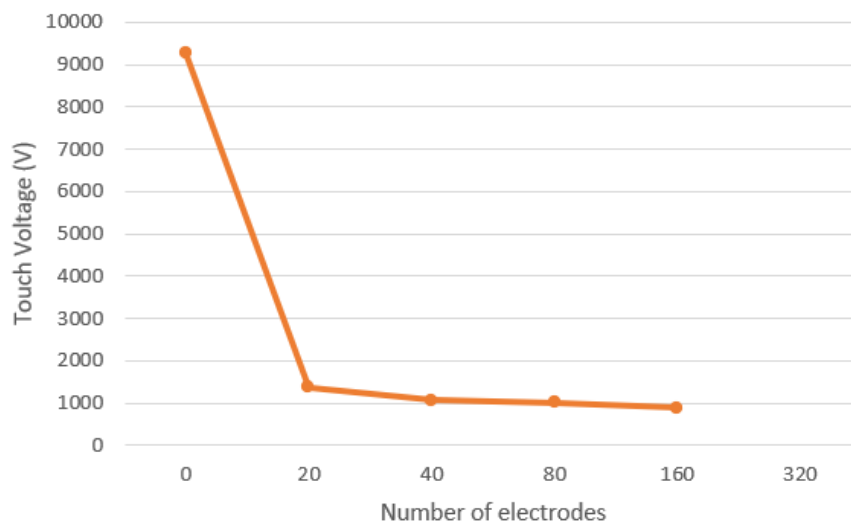


Figure 12.34 - Touch voltage of the grounding system as a function of number of 100m electrodes

It is verified that the 2m and 10m electrodes are the ones that present more linear results. After using 20 electrodes of 50m or 100m there is no significant improvement in mesh resistance and contact voltages.

12.3 - Mesh Grid Density

In this subchapter it was considered only in the soil model of a layer since it will rarely reach the second layer, and it was already verified with the depth test that more or less resistive soil in the second layer does not have much influence on the resistance and on the stresses of contact and step.

Table 12.22 - Touch voltage and resistance as a function of number of the quantity of cable per m^2

Quantity of cable per m^2 [m]	Touch Voltage [V]	Resistance [Ω]
0.24 ²	3051.4	0.960
0.44 ³	2693.1	0.894
0.84 ⁴	2490.8	0.859
1.64 ⁵	2379.7	0.841

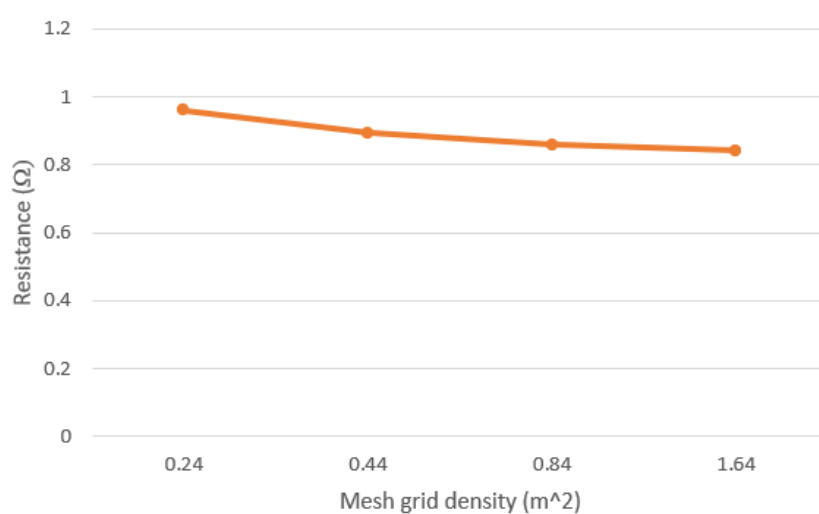


Figure 12.35 - Resistance of the grounding system as a function of number of the quantity of cable per m^2

² Value obtained in a 10x10m checkered mesh.

³ Value obtained in a 5x5m checkered mesh.

⁴ Value obtained in a 2.5x2.5m checkered mesh.

⁵ Value obtained in a 1.25x1.25m checkered mesh.

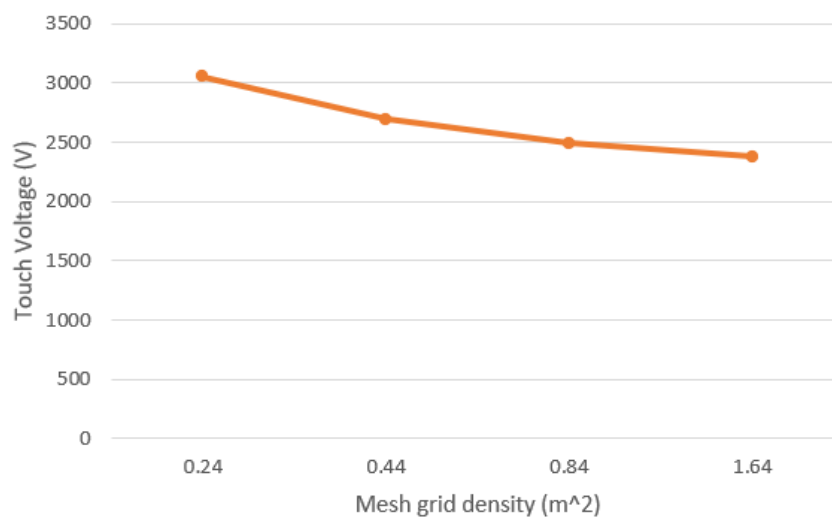


Figure 12.36 - Touch voltage of the grounding system as a function of number of the quantity of cable per m^2

It turns out that the increase from 0.44 mm^2 to 0.84 mm^2 has the most significant effect on both resistance and voltage. However, the rise to 1.64 mm^2 continues to have significantly better results than the previous one.

12.4 - Soil Resistivity

For this study a single layer was considered.

Table 12.23 - Touch voltage and resistance as a function of soil resistivity

Soil Resistivity [$\Omega\cdot\text{m}$]	Touch Voltage [V]	Resistance [Ω]
207.50	5478.5	1.833
330.92	8735.2	2.934
442.68	11684.1	3.932
549.92	14514.0	4.891
654.88	17283.6	5.829
758.50	20017.8	6.756
861.26	22729.4	7.675
963.45	25425.7	8.590
1065.21	28111.1	9.501
1166.68	30788.4	10.409
1267.91	33459.5	11.316

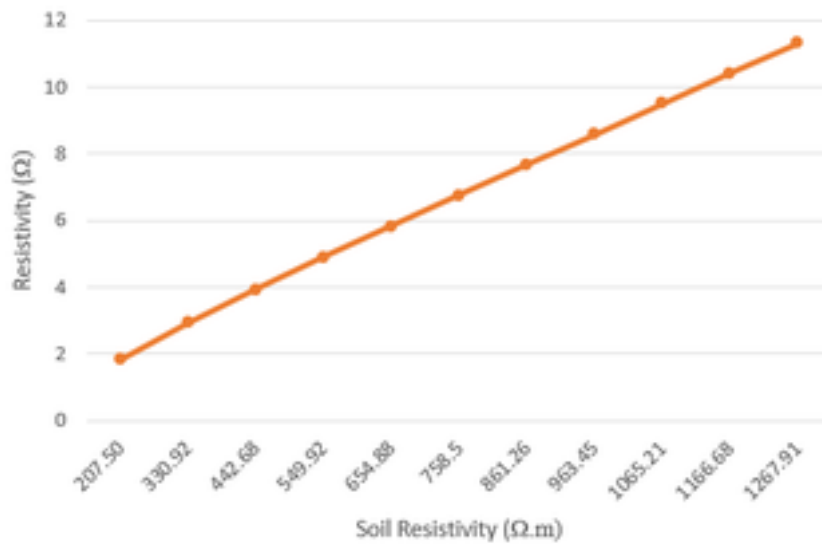


Figure 12.37 - Resistance of the grounding system as a function of soil resistivity

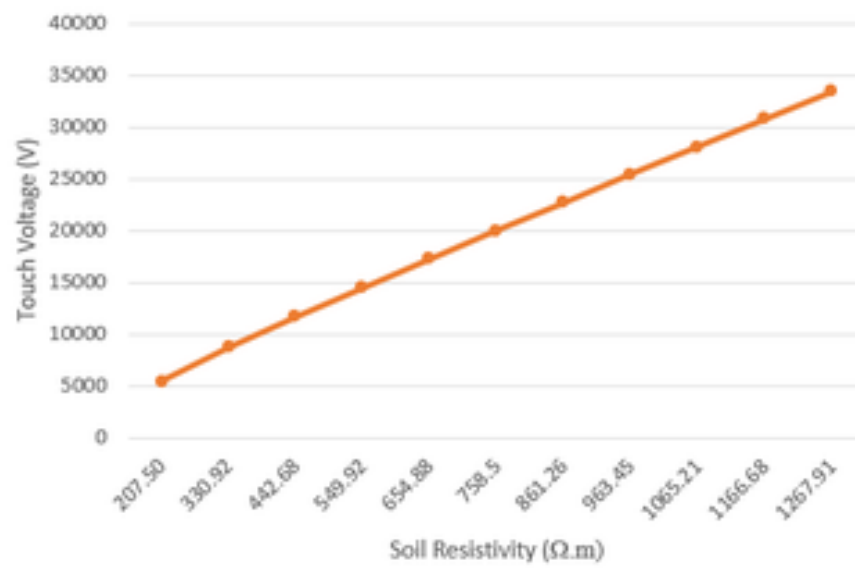


Figure 12.38 - Touch voltage of the grounding system as a function of soil resistivity

Observing the graphs above, it can be concluded that there is a practically proportional increase in resistance and touch voltage when soil resistivity is increased.

12.5 - Cable Cross-Section

For this study a single layer was considered. The mesh was considered to be at a depth of 0.8m.

Table 12.24 - Touch voltage and resistance as a function of soil resistivity

Cable Cross- Section [mm^2]	Touch Voltage [V]	Resistance [Ω]
16	2208.8	0.716
25	2183.3	0.712
35	2165.6	0.709
50	2147.9	0.706
70	2131.8	0.703
95	2117.5	0.701
120	2106.8	0.699
150	2096.6	0.697
185	2087.1	0.696
240	2075.4	0.694
300	2065.3	0.692

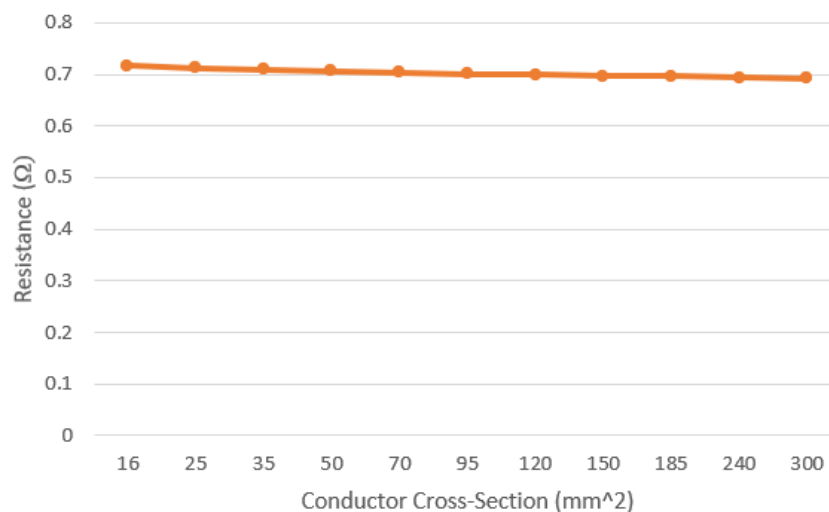


Figure 12.39 - Resistance of the grounding system as a function of cable cross-section

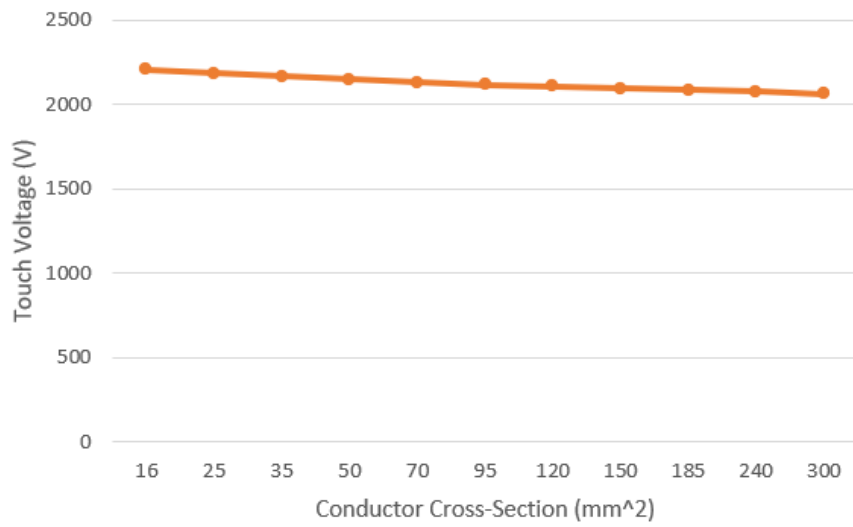


Figure 12.40 - Touch voltage of the grounding system as a function of cable cross-section

It is verified that there is a very little significant increase when the cable section is increased. Comparing these results with the grid mesh density, it is easily concluded that in terms of cost and performance it is more efficient to increase the mesh density then the conductor cross-section.

Chapter 13

Conclusion and Future Work

With the transition to renewable energies accelerating, it is necessary to build grounding systems that keep pace with technological evolution, continuing to ensure the efficiency of systems and the safety of people. This thesis focused on deepening the knowledge of grounding systems in wind farms and PV plants, shedding light on the challenges of ensuring safe and reliable renewable energy installations.

This study highlighted the significance of proper grounding, considering factors such as soil conditions, system properties and local regulations. For this kind of system, the interdisciplinary collaboration is crucial, as engineers and environmental experts must cooperate to ensure balance between technical feasibility, regulatory compliance, and ecological considerations.

Although there is a procedure to be followed, it is up to the designer and the customer to decide the measures to be taken to validate the grounding system, so there is not a recipe for all grounding systems. This study sought to validate the grounding systems of a wind farm and a PV plant in difficult conditions, so that several options could be shown. The study of the influence of each solution on resistance and contact voltage aims to complement the validation studies.

As this thesis concludes its research, it becomes evident that there are several directions investigators can take in order to enhance our understanding of grounding systems and address emerging challenges. With the energy sector becoming more digitalized, research can be developed with the integration of smart systems, to optimize the grounding systems.

By exploring the most commonly used solutions, this thesis is intended to be a reference document making the study of other grounding systems faster and more efficient.

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