GROUNDING SYSTEM DESIGN OF A WIND FARM

Also for Wind plants the same introduction as for photovoltaic plants is valid.
Wind plants, much like photovoltaic plants, can also achieve a power capacity of about 1 GW.
In case of large wind plants, this capacity is distributed across turbines ranging from a few megawatts up to approximately 15 MW or also 20 MW in the future. The optimal spacing between wind turbines is typically set between 8 and 12 times the rotor diameter in the direction of the wind, and between 2 and 4 times in the direction perpendicular to the wind.
For instance, for wind turbine with a power capacity of 5 MW, the height of nacelle over the soil surface and the rotor diameter can be approximatively 125 m. The optimal spacing between wind turbines is between 1000 and 1500 m in the direction of the wind, and between 250 and 500 m in the direction perpendicular to the wind.
Consequently, it is evident that wind farm sizes can span tens or also hundreds of square kilometers.

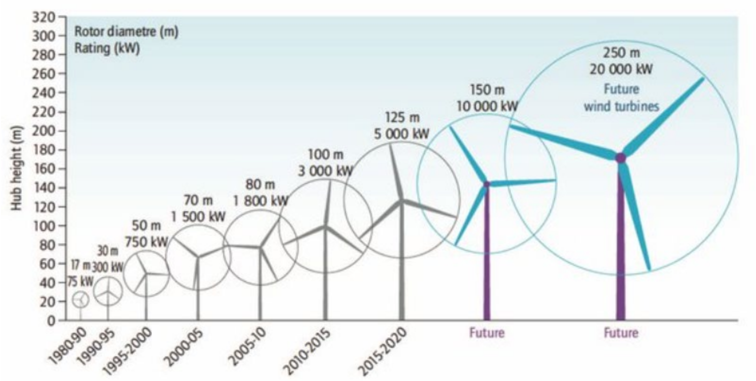

Figure 1: Evolution of wind turbine size and future prospects

In order to showcase the capabilities of GSA_FD in designing grounding systems for a wind farm installation, let us consider a plant connected to the high-voltage grid via its own substation. The total power of the installation is 100 MW (20 wind turbines each with a rated power of 5 MW), but the aspects and issues addressed in this example are also applicable to larger-scale installations.

Each individual wind turbine typically generates AC electric power at a variable frequency and integrates an AC/DC/AC converter to maintain a consistent output frequency. When the rated power exceeds a few megawatts, a step-up transformer to AC medium voltage is also incorporated.
If the wind farm comprises as usual multiple wind turbines, they are organized into strings with power ranging from a few MW to tens of MW. Each string is linked to a power line bus with AC medium voltage.
All strings are connected to a central substation where they are converted into AC high voltage.
Finally, the high voltage power is transferred to the power grid.

In the specific case, the wind turbines are grouped into 5 strings, each with a power capacity of 20 MW.
Often, the power lines of onshore wind plants are underground cables.
The following figure represents a simplified single-line diagram of an offshore wind plant.

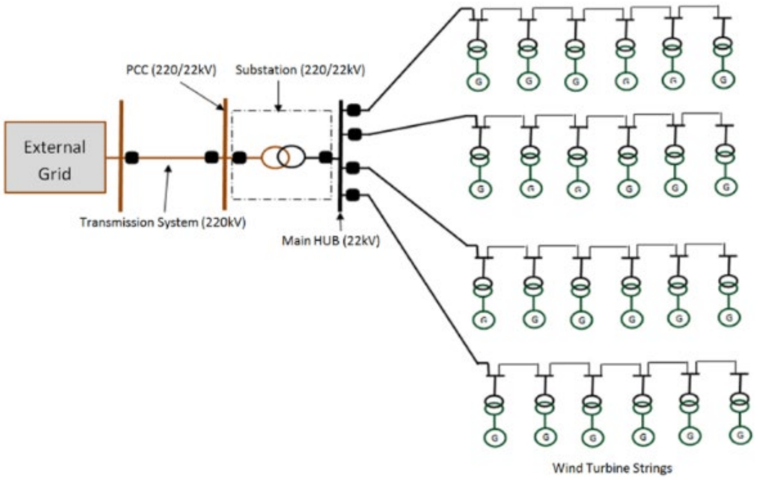

Figure 2: Simplified single line diagram of a wind plant

In the following the main data and information used for this specific example study.

<u>Reference Standard</u>

IEEE Std 81-2012 “IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding System”

IEEE Std 80-2013 “IEEE Guide for Safety in AC Substation Grounding”

IEEE Std 2760-2020 “IEEE Guide for Wind Power Plant Grounding System Design for Personnel Safety”

<u>Current to Earth</u>

In wind plants, fault currents to earth can occur in the following system parts:

- In wind turbines installations
- Medium voltage AC systems
- High voltage AC systems

Generally, the worst-case scenarios for touch and step voltages occur in high and medium voltage AC systems.

While the fault current to earth in medium voltage AC systems is typically lower than that in high voltage AC systems, the intervention time can be longer.

However, in wind plants with a substation, where the grounding system is typically a single one, the most challenging condition to evaluate often is related to a fault to earth in the AC high voltage system. Anyway, it is good practice to evaluate conditions related to a ground fault in the AC medium voltage system in each individual wind turbine.

In the following the following main data has been assumed:

High voltage AC systems (considered in the following):

- Rated Voltage: 220 kV
- Fault current to earth: I_f = 30 kA ∟ 0.00°
- Clearance time: t_f = 0.5 s

Medium voltage AC systems (valid for all wind turbines):

- Rated Voltage: 33 kV
- Fault current to earth: I_e = 150 A ∟ 0.00°

– Clearance time: t_f = 1.0 s

In both cases frequency is 60 Hz.

Soil Resistivity Measurements and Soil Models

Soil resistivity measurements should be conducted with outmost care.

For wind plants, it is recommended to perform measurements for substation and for each wind turbine.

At each measurement site, it is important to take measurements in two orthogonal directions. Using methods such as the Wenner method, the probe distances "a" should range from 0.5 to about 100 m for substation and from 0.5 to about 20 m for each wind turbine. These measurements should adhere to the guidelines outlined in IEEE Std 81.

Each measurement set must be analyzed separately.

Generally, each measurement site yields a unique uniform or multilayer soil model.

In the specific case measurements have been taken in 1+20 sites (substation + 20 wind turbines). In order to simplify the example study report, the same resistivity measurement set has been imposed for 5 random wind turbines as follows:

– Measurement set ELR.01: associated to WT1, WT6, WT12, WT14, WT19
– Measurement set ELR.02: associated to WT2, WT5, WT11, WT15, WT20
– Measurement set ELR.03: associated to WT3, WT8, WT9, WT16, WT17
– Measurement set ELR.04: associated to WT4, WT7, WT10, WT13, WT18
– Measurement set ELR.05: HV Substation

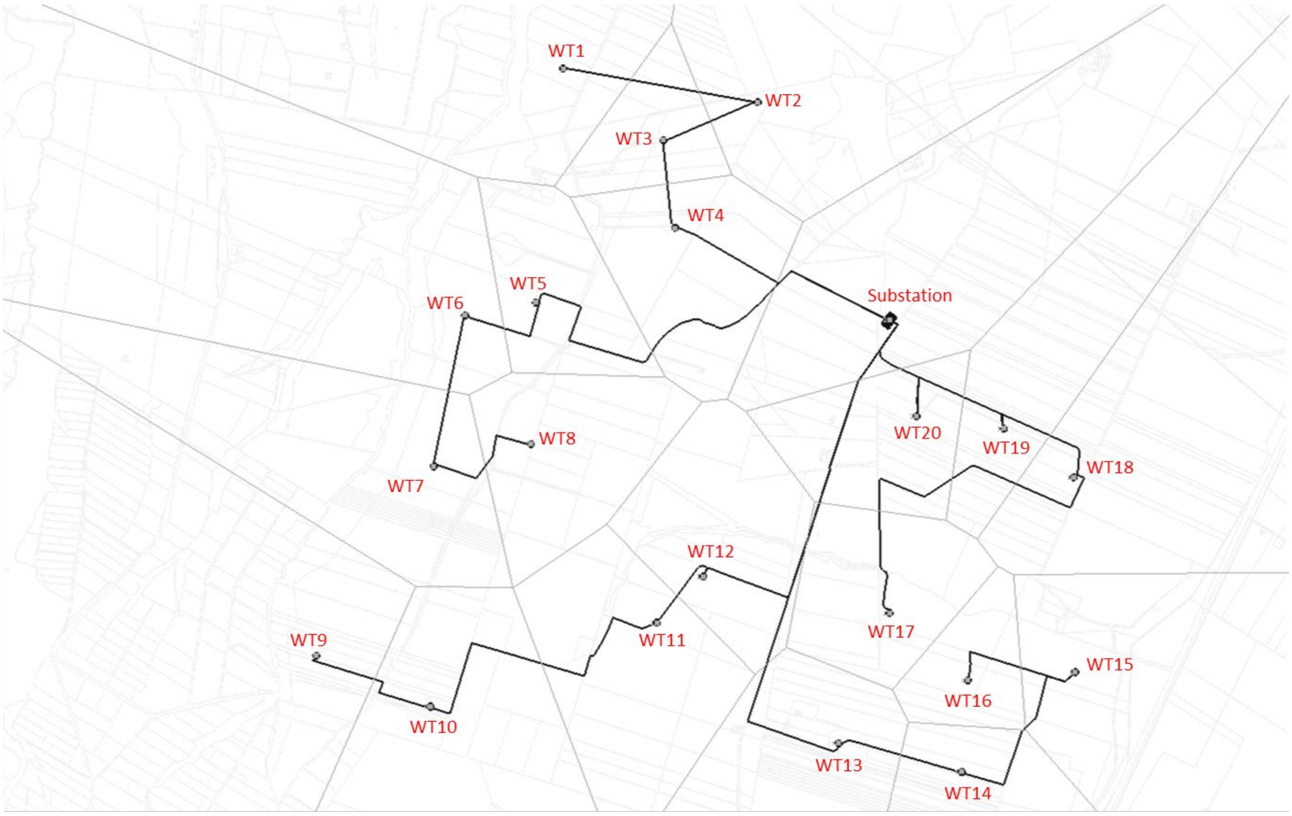

Figure 3: Measurement sites location

In the following table, the uniform soil model calculated by SRA for each single site.

	Soil Model	
Site	**ρ (Ωm)**	**RMS Error (%)**
Substation	283.9	78.15
WT1, WT6, WT12, WT14, WT19	336.7	52.33
WT2, WT5, WT11, WT15, WT20	229.5	99.61
WT3, WT8, WT9, WT16, WT17	308.9	46.29
WT4, WT7, WT10, WT13, WT18	209.1	105.6

The use of superficial covering layers may be beneficial, particularly around substation or wind turbines. As previously mentioned, the vast expanse of large plants typically results in limited values for touch and step voltages.

<u>Grounding System Layout</u>

The grounding system of a wind plant typically encompasses AC medium voltage and AC high voltage components, consisting of the following main parts:

- Substation for connection to the high-voltage power grid: Typically constructed based on a grid of buried conductors, supplemented with rods when necessary
- Wind turbines: Typically organized in a ring or more rings of buried conductors, also integrated with rods as needed. Often the iron bars used for wind tower foundations represent the main component of the grounding system of each wind turbine
- Metal fences: Metal fences surrounding the substation require specific attention. These fences may necessitate an additional grounding system connected to the main system. Sometimes, metal fences are far enough from the main system to be managed separately. In all cases, metallic fences must be evaluated carefully, especially regarding touch voltage outside the fence

Usually, grounding system of substation and wind turbines are connected together through AC medium voltage cable screens. Sometime in same trench of these cables is installed an auxiliary grounding conductor, sometime insulated sometime bare. If bare, this conductor can strongly contribute to increase grounding system performance.

The layout of the overall grounding system is depicted in the following figures.

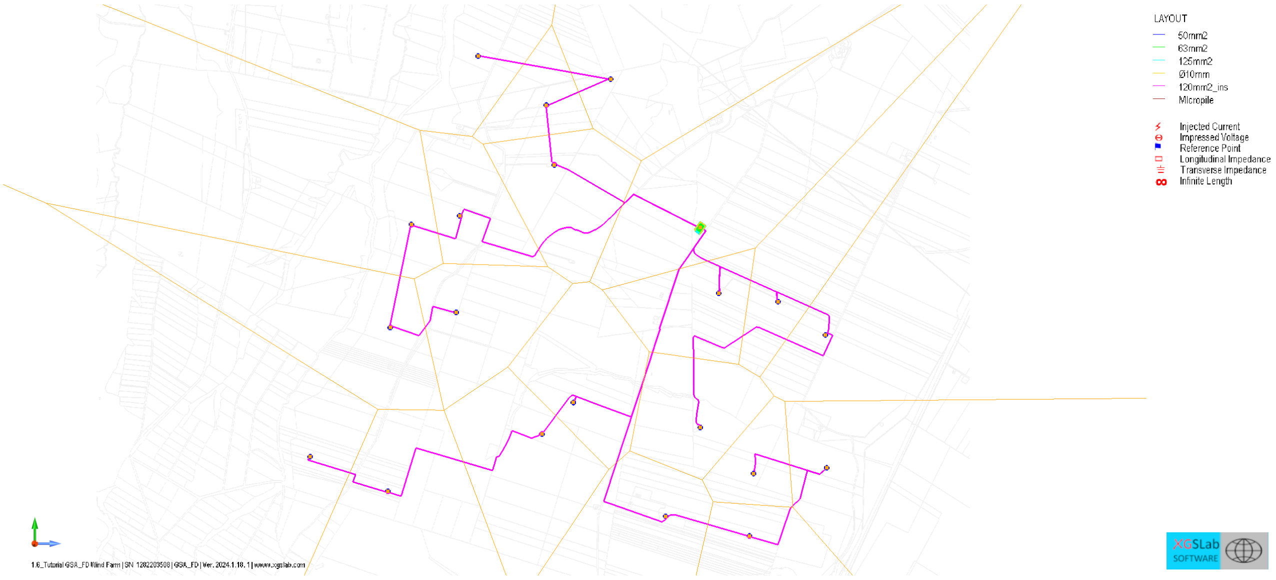

Figure 4: Grounding System - General View

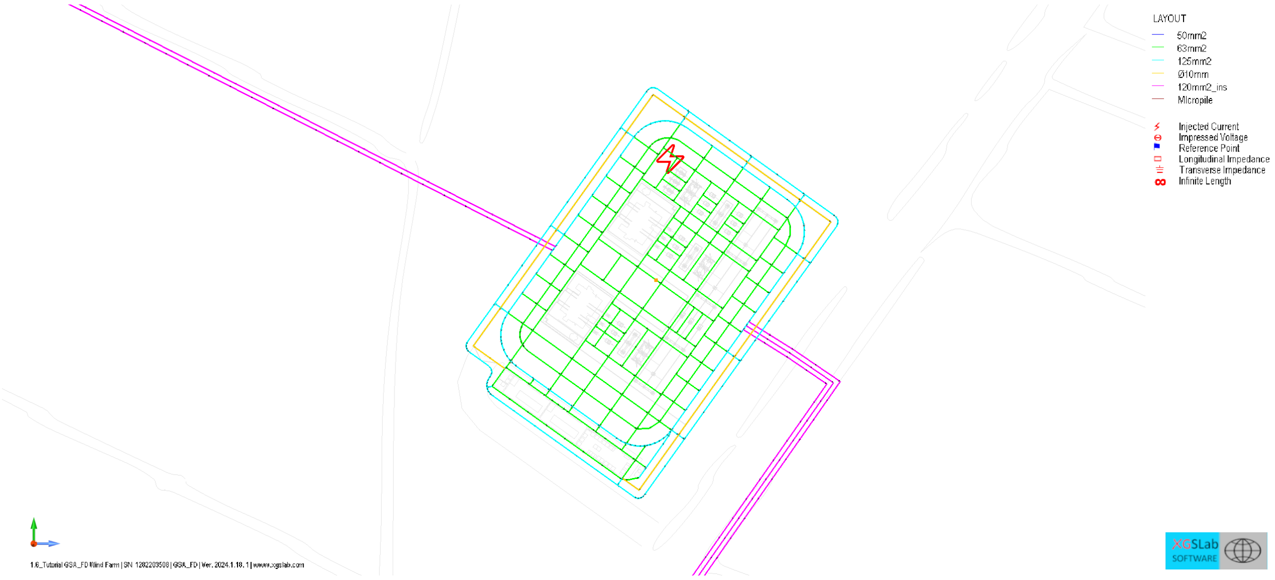

Figure 5: Grounding System - Substation

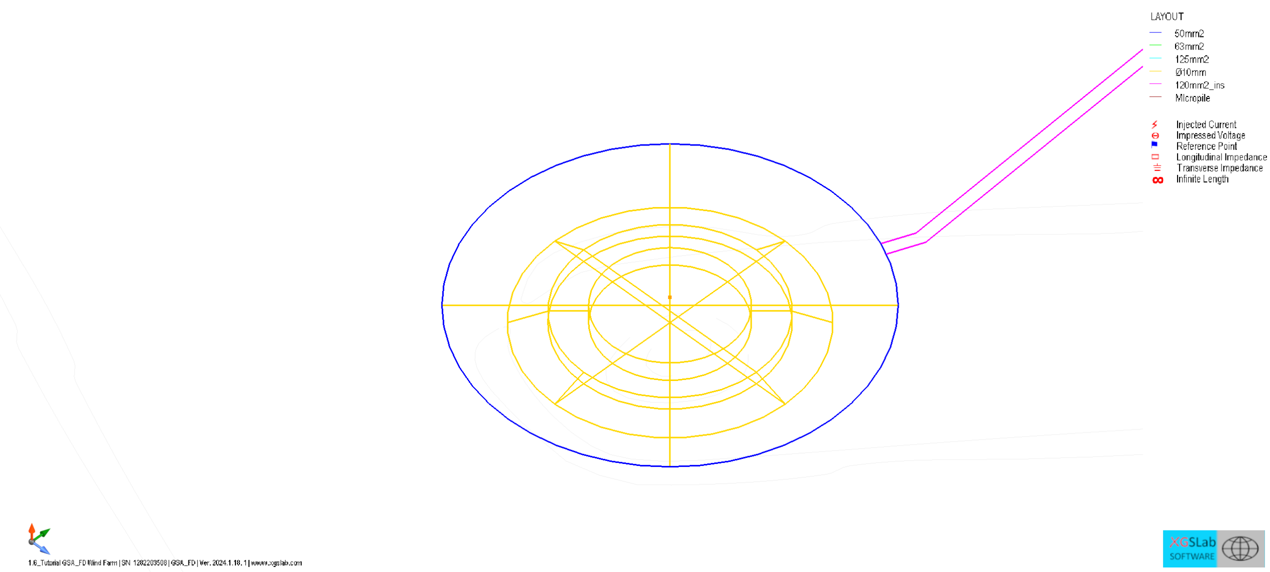

Figure 6: Grounding System – Wind Turbine

It is important to consider that each individual wind turbine earthing system is required to have an earth resistance of 10 Ω or less, as specified in the IEC 62305-3 2010 standard.

Conductor Materials and Sizing

All underground conductors will be made of copper.

The conductor cross section has been set as following:

- High voltage AC system: S = 63 mm^2 and S = 125 mm^2
- Medium voltage AC systems: S = 50 mm^2
- Connections among High and Medium voltage AC systems: S = 125 mm^2 (insulated)

Permissible Touch and Step Voltages

Taking into account reference standard and clearance times, the touch and step permissible voltages are the following.

Substation area:

- Without any soil covering layer:
  - U_{stp}: 236.8 V
  - U_{ssp}: 455.2 V
- Taking into account a 150 mm thickness layer of gravel with resistivity equal to 5000 Ωm:
  - $U_{stp + SCL}$: 1167 V
  - $U_{ssp + SCL}$: 4175 V

Wind Turbine n.20 with fault at High voltage AC systems:

- Without any soil covering layer:
  - U_{stp}: 222.9 V
  - U_{ssp}: 399.3 V
- Taking into account a 150 mm thickness layer of gravel with resistivity equal to 5000 Ωm:
  - $U_{stp + SCL}$: 1164 V
  - $U_{ssp + SCL}$: 4162 V

Wind Turbine n.20 with fault at Medium voltage AC systems:

- Without any soil covering layer:
  - U_{stp}: 157.6 V
  - U_{ssp}: 282.4 V
- Taking into account a 150 mm thickness layer of gravel with resistivity equal to 5000 Ωm:
  - $U_{stp + SCL}$: 822.7 V
  - $U_{ssp + SCL}$: 2943 V

Touch voltage must be evaluated for all electrical equipment within the substation including metal fences, and for each single wind tower (in this example the focus is on the Wind turbine n.20 only).
Step voltages must be evaluated throughout the entire wind plant area.

First, a preliminary calculation injecting the total fault to earth current should be performed. If the touch and step voltage are below the limits, the grounding system can be considered correctly designed. If the limits are overcome, it is appropriate to calculate the split factor and therefore the actual current to earth.

Let's suppose that the Wind Plant is connected to the grid at a 220 kV Substation by means of a 40 km overhead line (OHL). The overhead earth wire (OHEW) is connected to earth at both ends to the Source Substation and Wind Plant Substation grounding systems (solid bonding), and so, in case of a fault at the Wind Plant Substation, the fault current will split between the Wind Plant grounding system and the Source Substation (through the OHEW).
The split factor can be evaluated by using the module NETS. It is then possible to evaluate the actual current to earth of the Wind Plant and to design the grounding system with respect to this current, avoiding expensive oversizing.

Split factor

The general layout is represented in in the following figure.

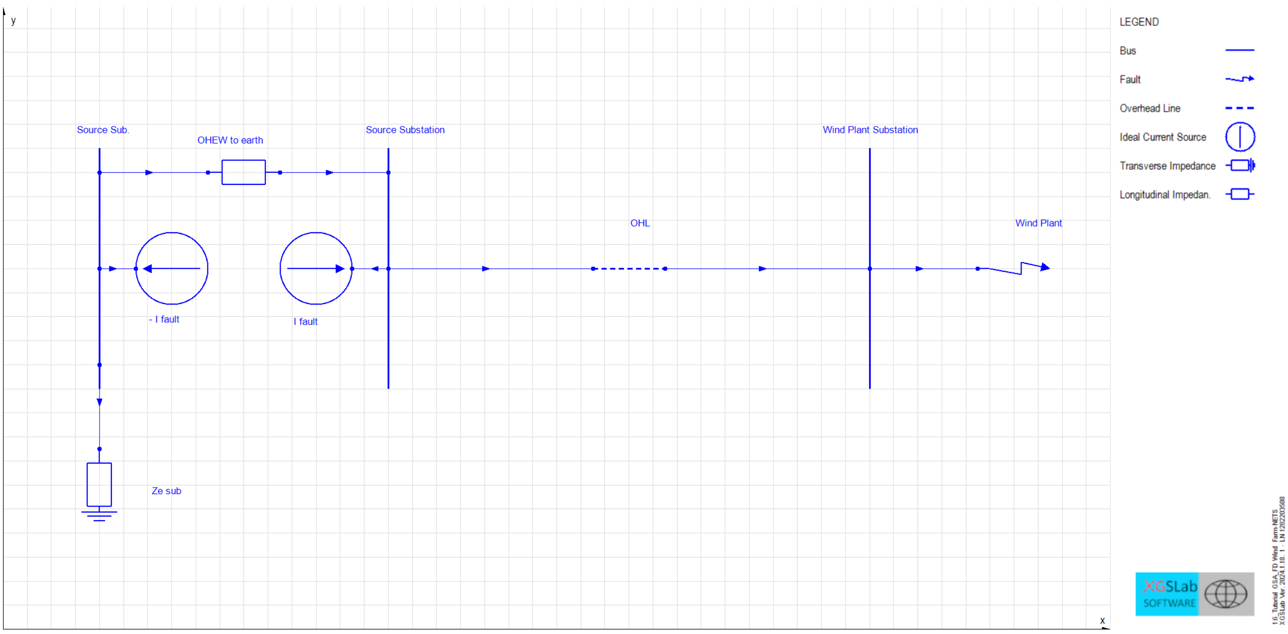

Figure 7: Single Line Diagram of Source + Overhead line + Solid Bonding + Load

In the following the main input data.

Main input data of the source:

- Phases number = 3 (symmetrical and balanced)
- Rated line voltage = 220 kV

OHL main input data:

- Phases number = 3
- Rated line voltage = 220 kV
- Frequency = 60 Hz
- Low frequency soil resistivity = 275 Ωm
- High frequency soil relative permittivity = 6
- Line length = 40 km
- Span length = 250 m (160 spans)
- Phase conductors layout: A (bottom-left), B (right), C (top-left)
- Maximum and minimum distance to the soil surface phase A: 25 and 12 m
- Maximum and minimum distance to the soil surface phase B: 28 and 15 m
- Maximum and minimum distance to the soil surface phase B: 31 and 18 m
- Maximum and minimum distance to the soil surface overhead earth wires: 37.6 and 29.6 m
- Position with respect to the tower axis: A -5.10 m, B +4.00 m, C -3.80 m
- Phase conductors: ACSR (Aluminum Conductor Steel Reinforced: the steel is inside and the aluminum is outside) with external diameter = 31.5 mm, cross section of steel and aluminum 65.81 and 519.5 and mm^2 respectively, resistance = 0.05564 Ω/km at 20 °C
- Overhead wires: steel and aluminum conductors with external diameter = 11.5 mm, cross section 80.66 mm^2, resistance = 1.062 Ω/km at 20 °C
- Resistance to earth of each single tower: 10 Ω
- Resistance to earth of the Source grounding system: 0.1 Ω
- Resistance to earth of the Wind Plant grounding system: 0. 4713 Ω (calculated with GSA_FD with a preliminary calculation)

The results of the split factor calculation are highlighted in the following figure.

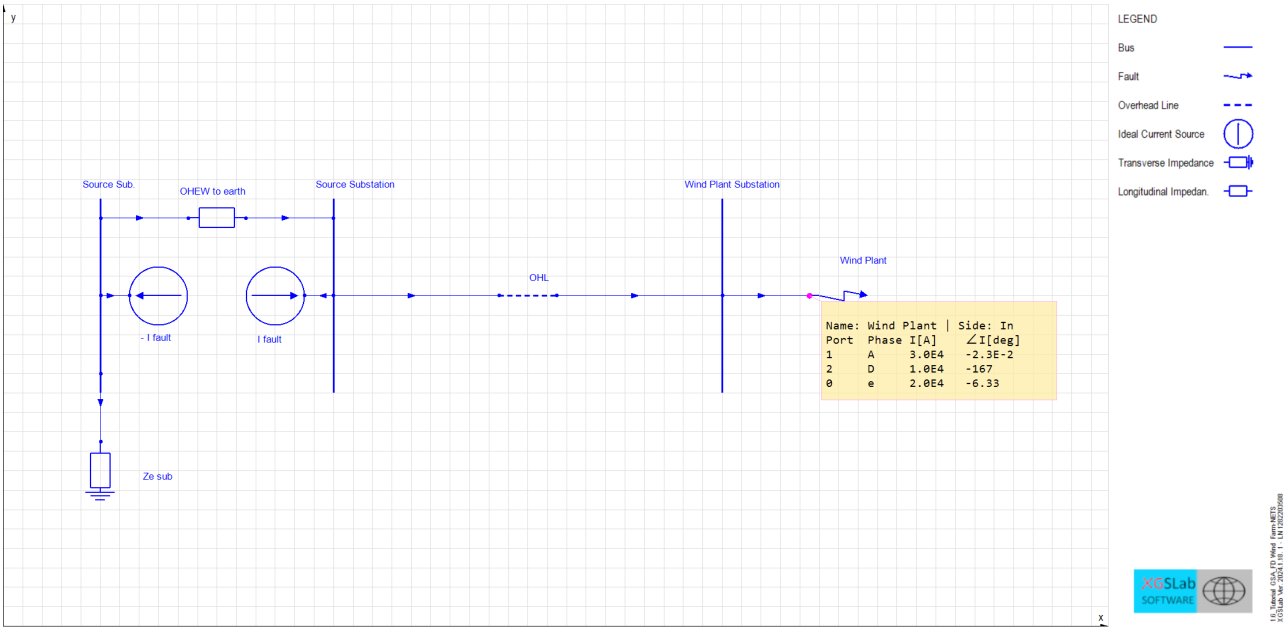

Figure 8: Graphical results provided by NETS

The numerical results are as in the following:

- Fault current magnitude I_f = 30000 A
- Current to earth magnitude: I_e = 20340 A
- Split factor = $S_f = I_e / I_f$ = 20340 / 30000 = 0.678

It is thus possible to conclude that the Wind Plant grounding system has to be designed for a fraction I_e of the entire fault current I_f.

<u>Calculation Results using a Multizone Soil Model</u>

In the following the main results that can be obtained by using GSA_FD.

The GPR and Earthing Impedance are:

- Reference Point: GPR = 9586 V ∟ 35.71°, Z_e = 0.4713 Ω ∟ 35.71°

The Current and Potential Distributions are represented in the following figures.

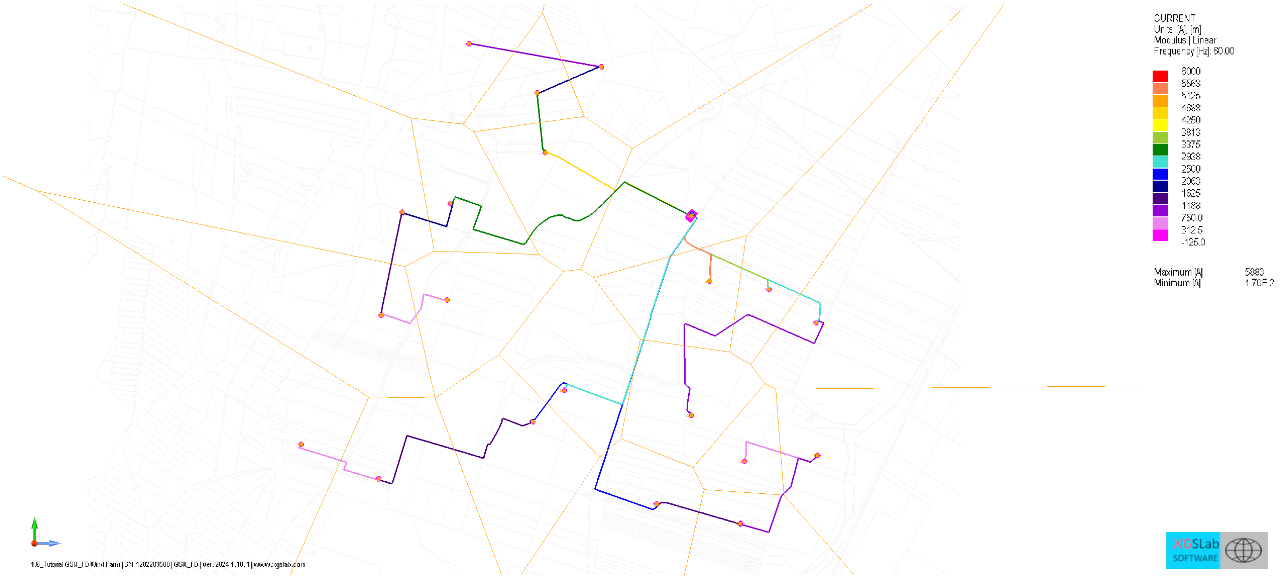

Figure 9: Current distribution along the earthing system

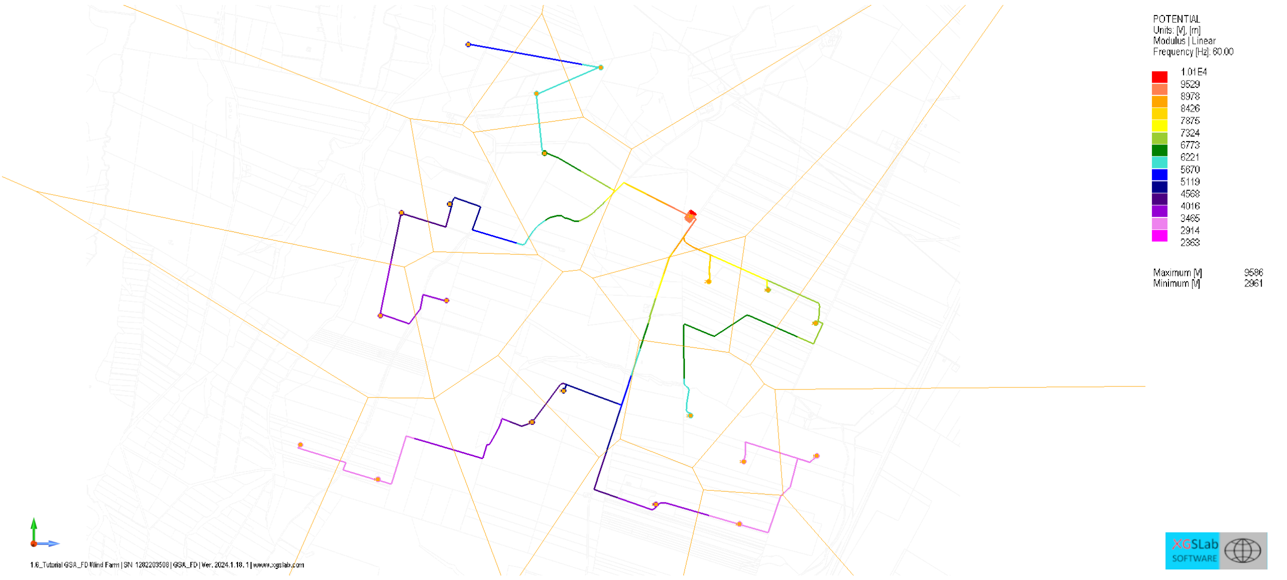

Figure 10: Potential distribution along the earthing system

Earth potential and touch and step voltages along the Wind Plant can be evaluated by means of multiple area calculations. Area calculations can be either directly drawn in the model or their parameters can be set in the dedicated panel. In the specific case, two main area calculations are used:

- Substation area: x origin = 519284 m, y origin = 4636110 m, z origin = 0 m, α x = 54.402°, Length = 96 m, Width = 67 m, Step Length = 1 m, Step Width = 1 m
- Wind turbine n.20: x origin = 519390 m, y origin = 4635710 m, z origin = 0 m, α x = 0°, Length = 40.5 m, Width = 40.5 m, Step Length = 0.5 m, Step Width = 0.5 m

The Earth Surface Potential distribution in the substation area is depicted in the following figure.

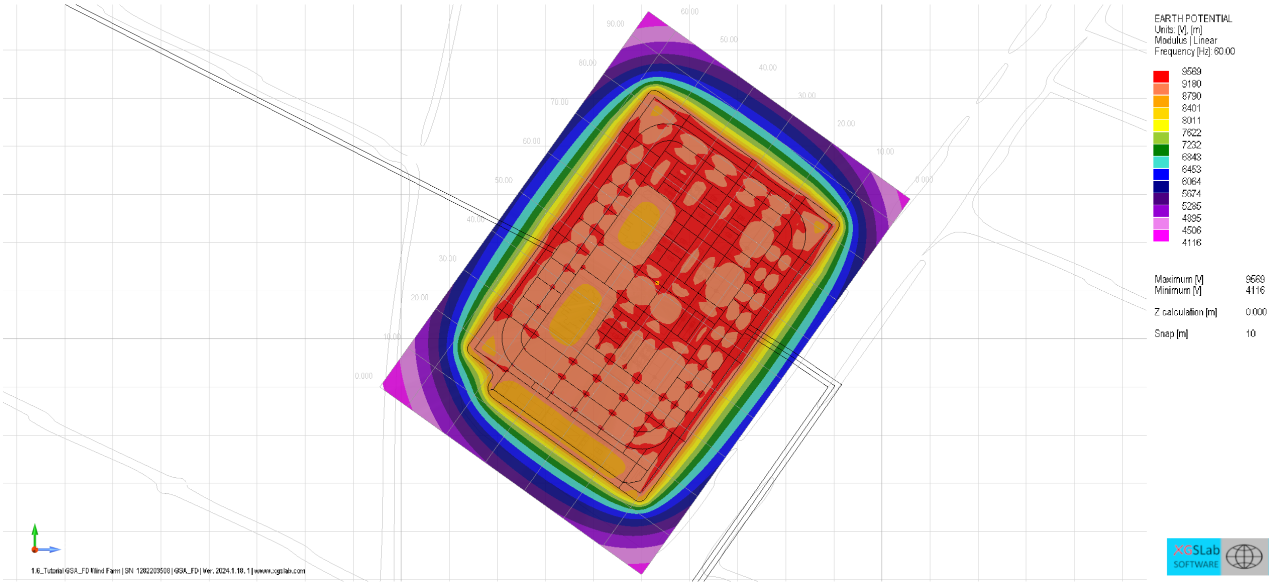

Figure 11: Earth surface potential distribution in the substation area

Safe areas without any soil covering layer (SCL) based on the above earth surface potential distribution are as it follows.

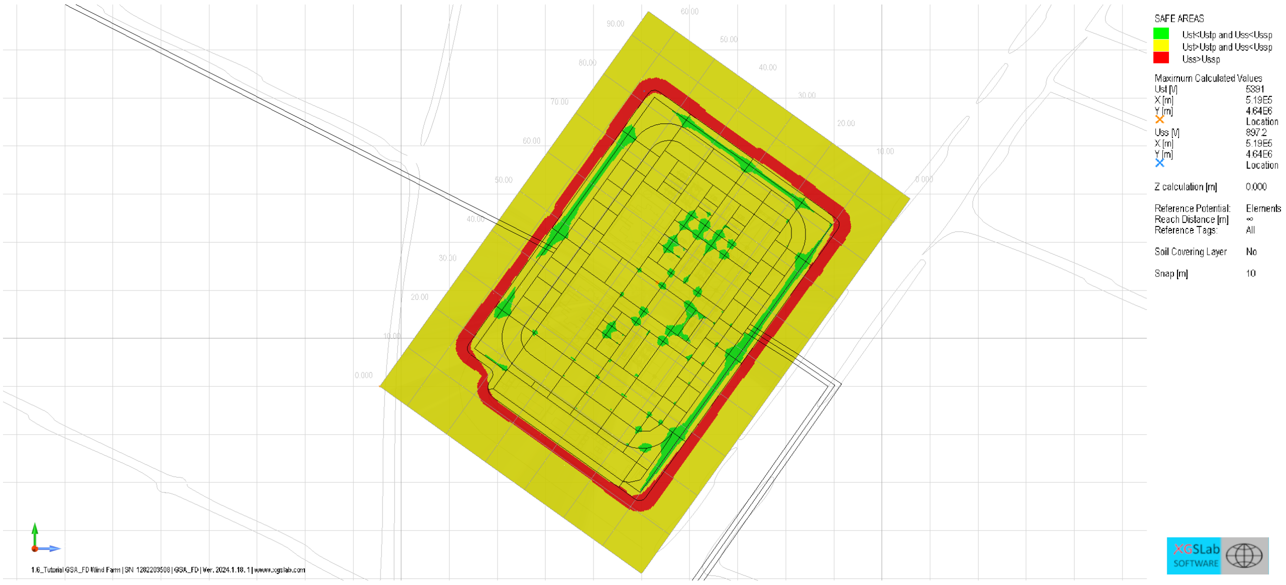

Figure 12: Safe areas by setting: reference mode “all elements”, all Tags, reach distance “∞”, SCL off

In order to reduce touch and step voltages in the substation area below the limits, a gravel soil covering layer with the characteristics reported above will be considered.

Safe areas with a gravel soil covering layer (SCL) based on the above earth surface potential distribution are as it follows.

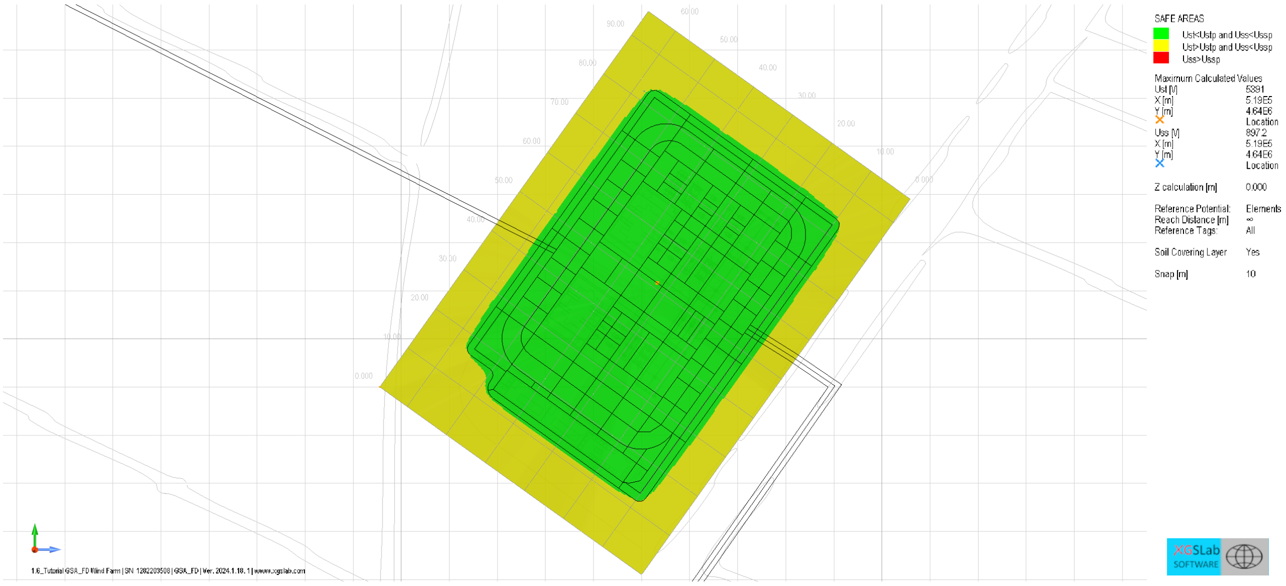

Figure 13: Safe areas by setting: reference mode "all elements", all Tags, reach distance "∞", gravel as SCL

Another useful result that can be highlighted by using XGSLab is the safe areas referred to the external fence of the Wind Plant substation.

In order to do that, by using again the Touch and step voltages reference mode "All elements", the tag "Fence" can be selected and, by setting a reach distance "1.5 m", the safe areas up to 1.5 m from the fence can be evaluated.

In the legend, the maximum value referred to the touch and step voltages is reported, so it is possible to understand if the limits are respected or not, at a glance.

Figure 14: Safe areas by setting: reference mode "all elements", Tag "Fence", reach distance "1.5 m", gravel as SCL

From the results, it can be seen that in the North and East corners of the substation, touch voltages against the fence are again above the limits.

Before taking any other actions in order to try to reduce them, a closer look at those corners should be taken. In the following, safe areas related to the fence area, with a gravel soil covering layer and a smaller calculation step (0.25 m x 0.25 m) are reported.

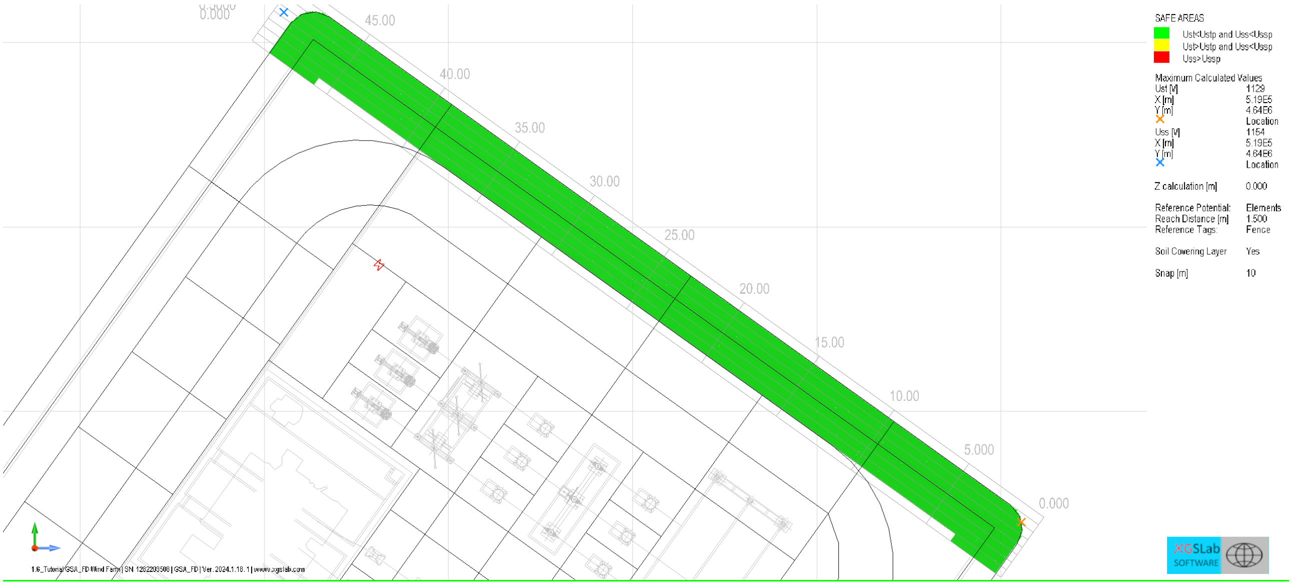

Figure 15: Safe areas of the North corner by setting: reference mode “all elements”, Tag “Fence”, reach distance “1.5 m”, gravel as SCL

With a smaller calculation step, touch voltages against the fence are now below limits.

In cases like this one, in which safe areas calculations provide results in terms of touch voltages close to the limits, a new calculation area, with a smaller calculation step, especially on peripheral areas, should be performed, before taking other mitigation measures.

Wind turbines grounding systems must be evaluated for both High and Medium voltage fault conditions.

Anyway, in fault conditions in High voltage system, the minimum fault current to earth is in Wind turbine n 16 and it is equal to 438.5 A, while in fault conditions in Medium voltage system current to earth in all Wind turbines is 150 A.

The ratio between High and Medim voltages current to earth is 2.92, more than the ratio between Touch and Step voltage limits 1.41.

This means that turbines grounding systems can be evaluated for High voltage fault conditions only.

The Earth Surface Potential distribution in the Wind turbine n.20 area is depicted in the following figure.

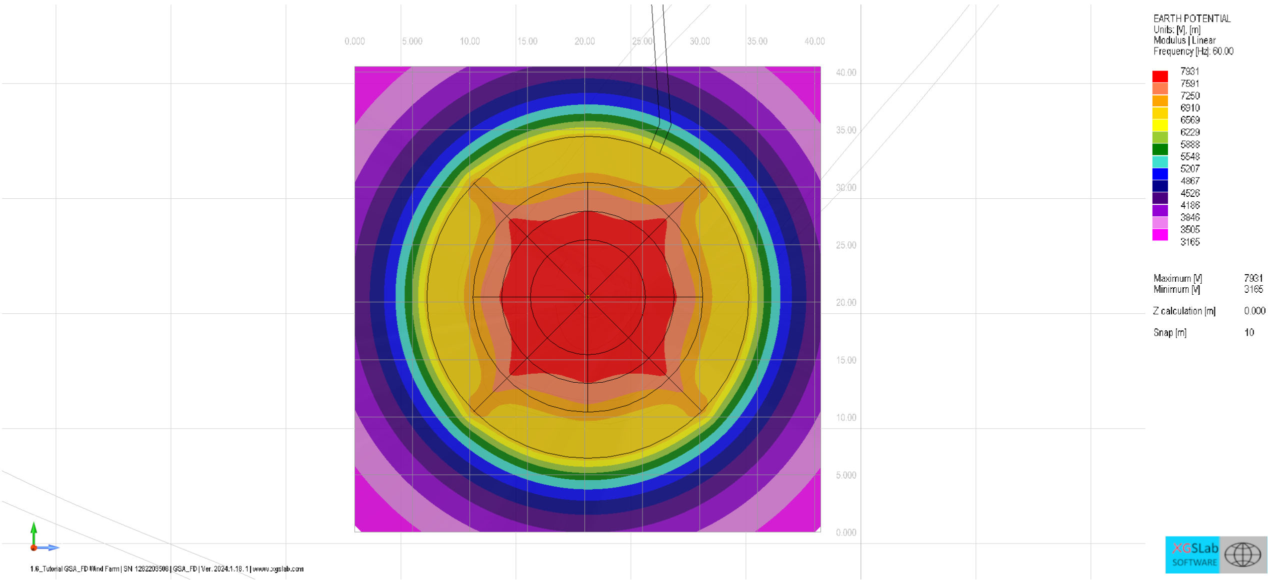

Figure 16: Earth surface potential distribution in the Wind turbine n.20 area

Safe areas without any soil covering layer (SCL) based on the above earth surface potential distribution are as it follows.

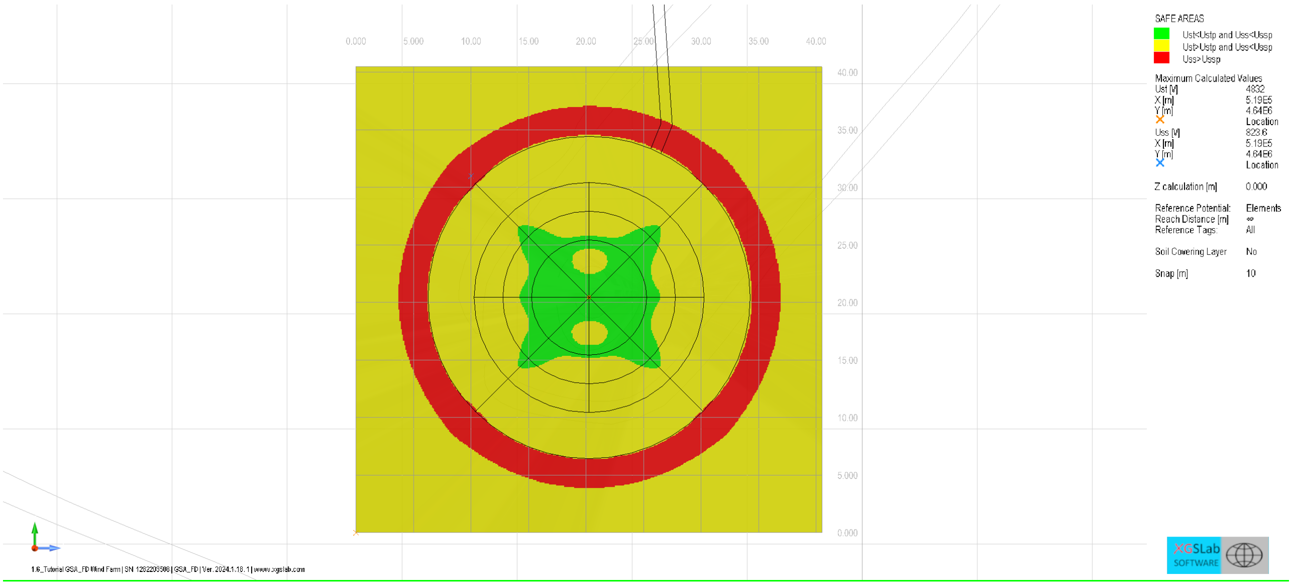

Figure 17: Safe areas by setting: reference mode “all elements”, all Tags, reach distance “∞”, SCL off

In order to reduce touch and step voltages around Wind tower n.20 below the limits, a gravel soil covering layer with the characteristics reported above will be considered.

Safe areas with a gravel soil covering layer (SCL) based on the above earth surface potential distribution are as it follows.

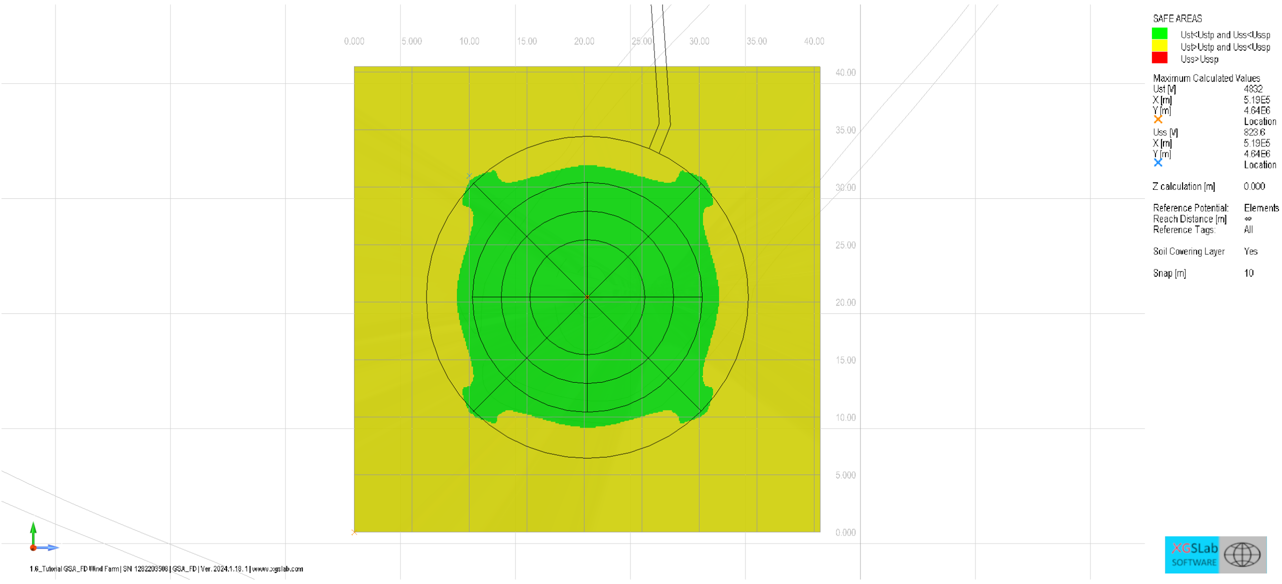

Figure 18: Safe areas by setting: reference mode “all elements”, all Tags, reach distance “∞”, gravel as SCL

The final required verification is to ensure that the standalone grounding system of Wind turbine n 20 complies with the requirements of the IEC 62305-3 2010 standard, regarding earth resistance.
In the following the result that can be obtained by using GSA_FD.
The Wind turbine n 20 Earthing Impedance is:

– Reference Point: $Z_e = 4.229\ \Omega \angle\ 0.126°$

This value ensures compliance with the relevant standards.
This analysis must be performed for all the other Wind turbines of the Wind Plant.

<u>Testing</u>

Touch and step voltages in a wind plant can be measured similarly to those in a substation. However, due to their large size, measuring earth resistance can be challenging or even impossible. Conducting remote earth injections at a distance of 5 times the size of the wind plant would mean covering distances of kilometers.
IEEE Std 2778-2020 states that in such cases, measuring earth resistance may not be necessary if the grounding system has been designed using an accurate model and sufficient soil resistivity data.
Validation testing for the grounding system of large wind plants can indeed be challenging.