1. SCREENED CONDUCTORS

Cases of close proximity between underground power cables and pipelines (or other buried metallic structures) are becoming increasingly common. This trend is also driven by the growing tendency to install new high and medium voltage transmission and distribution lines underground rather than overhead, especially in urban areas, environmentally sensitive zones, and wherever visual impact or right-of-way constraints must be minimized.

Such configurations can lead to hazardous conditions for personnel operating on or near the pipeline, as well as damage to the pipeline coating, to connected equipment, or to cathodic protection systems.

XGSA_FD can be effectively used to evaluate this kind of scenario.

Unlike the classical case of an overhead line running close to a buried pipeline, when the power line is itself underground the coupling mechanisms are somewhat richer. Inductive coupling remains the dominant phenomenon, but conductive coupling through the soil can also play a role, depending on the cable screen bonding configuration (solid bonding, single-point bonding, cross-bonding) and on the grounding conditions at the cable ends. Correctly representing the cable screens, and not just the phase conductors, is therefore essential to obtain reliable results.

The inductive coupling produces an electromotive force distributed along the pipeline and, as a consequence, longitudinal currents, leakage currents to soil, and a potential distribution along the metallic structure. As is well known, interference effects grow with the power line current, with the length of parallelism, and with soil resistivity, while they decrease as the separation distance between the cable route and the pipeline increases.

Under steady state conditions, induced voltages are normally small; significant induced voltages instead appear under fault conditions, and in particular under single-phase-to-earth faults. Since the permissible induced voltage limits given by the relevant standards differ between steady state and fault conditions, both operating conditions should in general be assessed. In the present case, however, only the fault condition is analysed, since it represents the most severe scenario in terms of induced voltage along the pipeline.

To illustrate the approach, a 132 kV underground cable line running parallel to a buried steel pipeline over a certain distance is considered. The cable line is modelled in XGSA_FD using Screened Conductors, which allow an accurate representation of phase conductors, metallic screens, screen bonding, and grounding conditions at the cable terminations — a level of detail that a simple "equivalent conductor" representation could not capture.

The general layout of the interference is shown in Figure 1-1, with the following color code:

- Orange: underground cable line between Substations A and B
- Green: Pipeline 1
- Blue: Pipeline 2

The pipeline is assumed to be divided into two sections by one insulating joint. The joint is protected by a longitudinal surge arrester and the pipeline ends at the joints are grounded through transverse surge arresters, reproducing a typical cathodic-protection-compatible interference mitigation scheme.

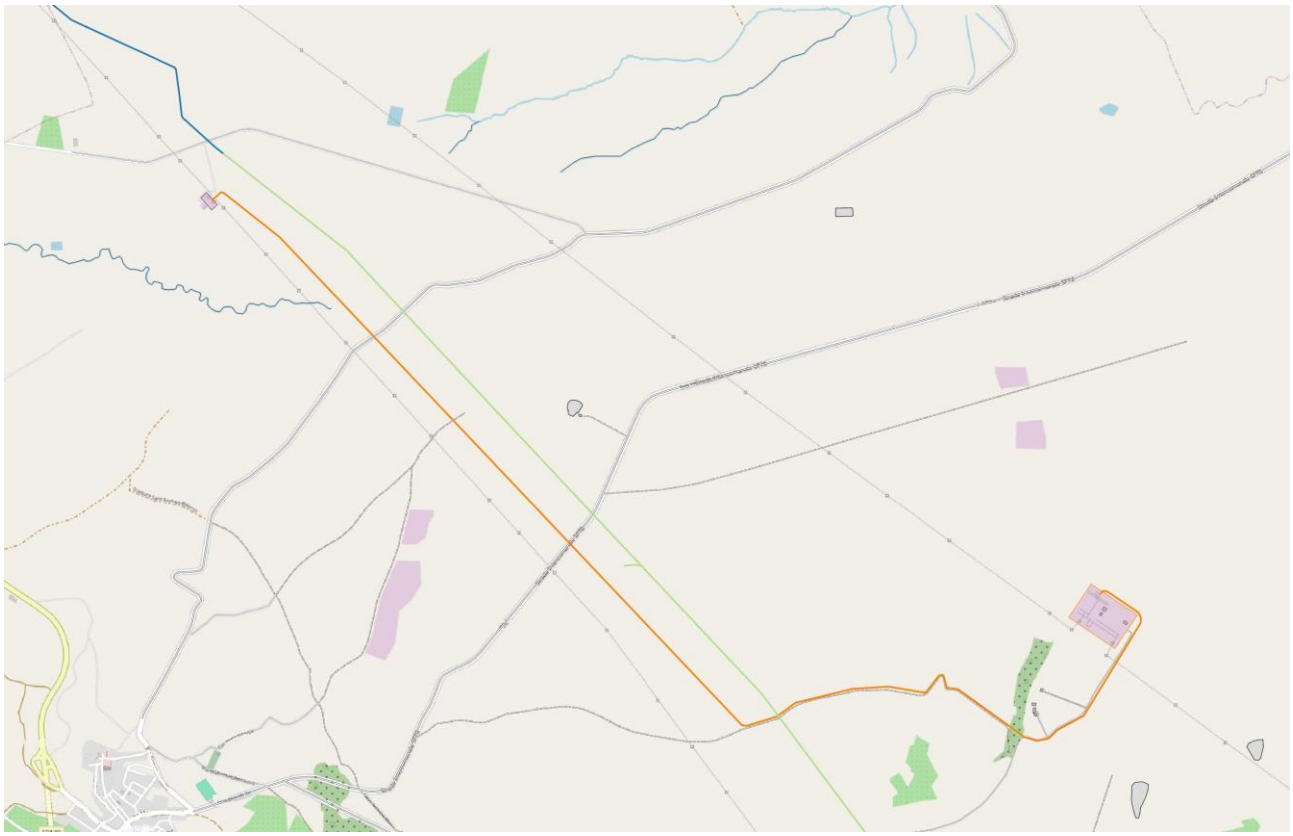


Figure 1-1: General layout of the interference

Main input data:

- Cable line voltage: 132 kV
- Frequency: 50 Hz
- Cable screens: cross-bonding configuration
- Fault condition: single-phase-to-earth fault on the cable line, worst-case position with respect to the parallelism
- Fault current on L1: 20 kA ∟0.0°
- Fault duration = 0.5 s
- Soil resistivity: uniform model
- Pipeline 1: steel, with bitumen insulating coating, outer diameter and coating resistivity as per manufacturer data
- Pipeline 2: steel, with polyethylene insulating coating, outer diameter and coating resistivity as per manufacturer data
- Insulating joint, with longitudinal and transverse surge arresters

The analysis is carried out considering a single-phase-to-earth fault on the cable line at Substation B, in the position along the parallelism that maximizes the induced effect on the pipeline.
Under the assumed single-phase-to-earth fault condition, the induced longitudinal voltage along the pipeline can reach considerable values, and the surge arresters at the insulating joint may be triggered; when this occurs, the corresponding pipeline end is temporarily grounded through the resistance to earth of the arrester grounding system, which modifies the boundary conditions of the calculation and must be handled with an iterative approach.

The 132 kV cable line connects Substation A to Substation B and is divided into three major sections, each consisting of three minor sections, for a total of nine minor sections. The screen bonding is arranged according to a cross-bonding

scheme: within each major section, the metallic screens of the three phases are transposed at the intermediate joint bays, so that each screen occupies, in turn, the position of each phase along the major section, cancelling — ideally — the net electromotive force induced in the screen circuit under balanced load conditions.

The screens are solidly grounded only at the line terminations, i.e. at Substation A and Substation B, as well as at the joint bays marking the boundary between major sections (JB3 and JB6), where the screens are transposed and directly earthed. At the remaining, intermediate joint bays within each major section (JB1, JB2, JB4, JB5, JB7, JB8), the screens are likewise transposed but are not solidly earthed: they are instead connected to earth through Sheath Voltage Limiters (SVLs), which keep the screen sections floating with respect to earth during normal operation while providing a protective path to earth in case of transient overvoltages, for instance during a fault on the cable line.

This configuration is a classical example of cross-bonding with SVL protection at the intermediate cross-bonding points, and it is precisely this arrangement that must be reproduced in the model, since the bonding and grounding conditions at each joint bay directly affect the screen currents and, consequently, the electromagnetic interference induced on the nearby pipeline.

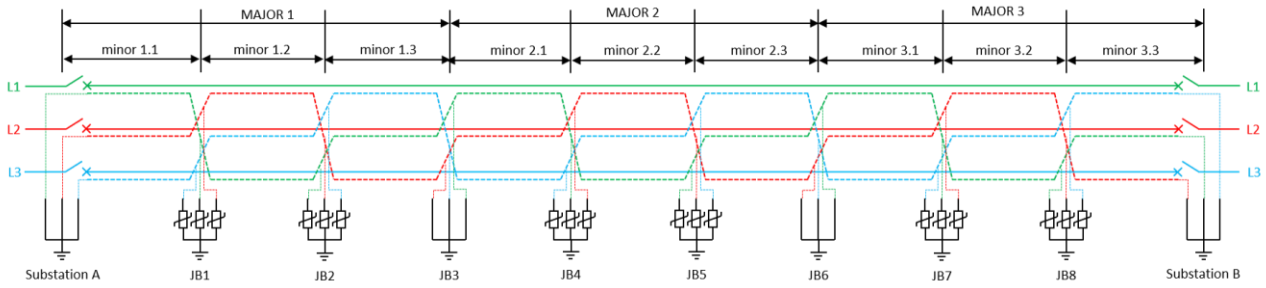


Figure 1-2: Electrical layout of the cable line – cross-bonding scheme with three major sections (JB3 and JB6 solidly grounded) and SVL-protected intermediate joint bays

Once the geometrical layout has been prepared in CAD, the cable line and the pipeline are imported into XGSA_FD by assigning to each CAD layer the corresponding electrode number, library, and type. Table 1 summarizes the assignment used for the present case.

Layer	Assigned Electrode Number	Notes
Minor x.x_L1	1	Screened Conductor: electrode 1 automatically assigned to the screen, electrode 2 to the core
Minor x.x_L2	3	Screened Conductor: electrode 3 automatically assigned to the screen, electrode 4 to the core
Minor x.x_L3	5	Screened Conductor: electrode 5 automatically assigned to the screen, electrode 6 to the core
Substation A & B conductors	1	Earthing conductors at the line terminations
Joint bay_xx	1	Earthing conductors at the solidly grounded joint bays (JB3, JB6)
Pipeline 1 and 2	10	Buried pipeline sections

Table 1: Electrode numbers assigned to each layer during CAD import

For each screened conductor layer, the electrode number entered by the user during import is automatically assigned to the screen, while the core part is assigned the next electrode number (assigned electrode + 1). This is why, for the three phase conductors L1, L2 and L3, electrode numbers 1, 3 and 5 were entered for the screens, with electrodes 2, 4 and 6 automatically assigned for the corresponding cores.

A specific remark applies to the screens. At every joint bay the screens of the three phases are transposed, and the screen segments that are physically spliced together at each transposition point must be assigned the same electrode number,

so that the model correctly represents the electrical continuity of the screen circuit along the transposition. This applies uniformly at all joint bays, regardless of whether the earthing arrangement at that point is solid bonding (JB3 and JB6, as well as Substation A and B) or an SVL (the intermediate joint bays). At the solidly bonded points, the screens additionally share the same electrode number as the earthing conductor, since screens and earthing system form a single electrically continuous node there.

The easiest way to carry out this assignment is by using the Conductor List. By applying the appropriate filter, all the tags that need to be assigned to electrode 1 can be selected together. Once all the corresponding records have been selected (right click → Select all, right click → Conductor Editor), electrode 1 can be assigned to all of them at once through the Conductor Editor.

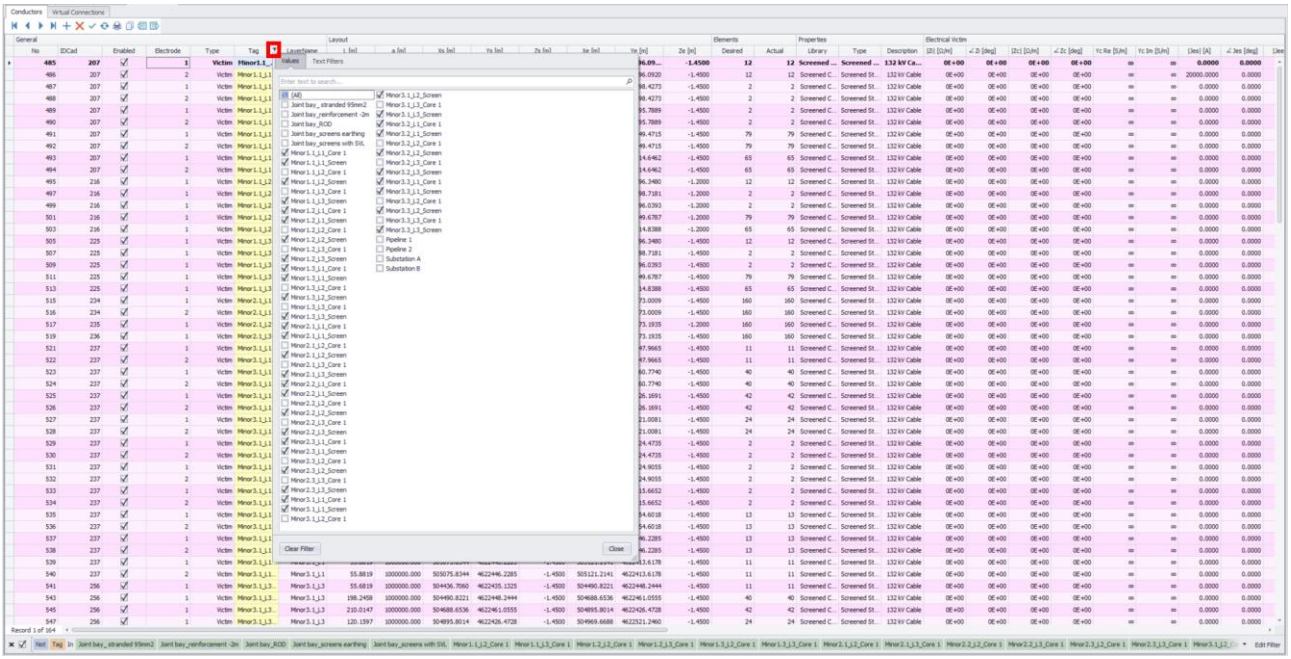


Figure 1-3: Conductor List – filtering and bulk electrode assignment via the Conductor Editor

At this point, the cross-bonding along the major sections of the cable line has to be set. This is done through the Xgl-CAD view by selecting the three virtual connection symbols at the relevant joint bay — the screen connections are the "external" ones of the two superimposed connections visible at each transposition point, one for the screen and one for the core.

By right-clicking on a connection symbol and selecting "Edit Connection", the Connection Editor opens. Following the connection scheme shown in Figure 1-2, it can be seen that, because of the cross-bonding, "Minor1.1_L1_Screen" has to be connected to "Minor1.2_L3_Screen", rather than to "Minor1.2_L1_Screen" as a straight-through connection would imply.

To edit the connection accordingly, right-click on the corresponding row in the Connection Editor and, in the "TO CONDUCTOR" field at the bottom of the window, change the conductor number from 430 to 432. Once the correct conductor has been selected, the change can be applied.

Note: the conductor numbers quoted in this article may differ from those found by the user when reproducing the example. In that case, the same procedure applies using the numbers shown in the user's own model.

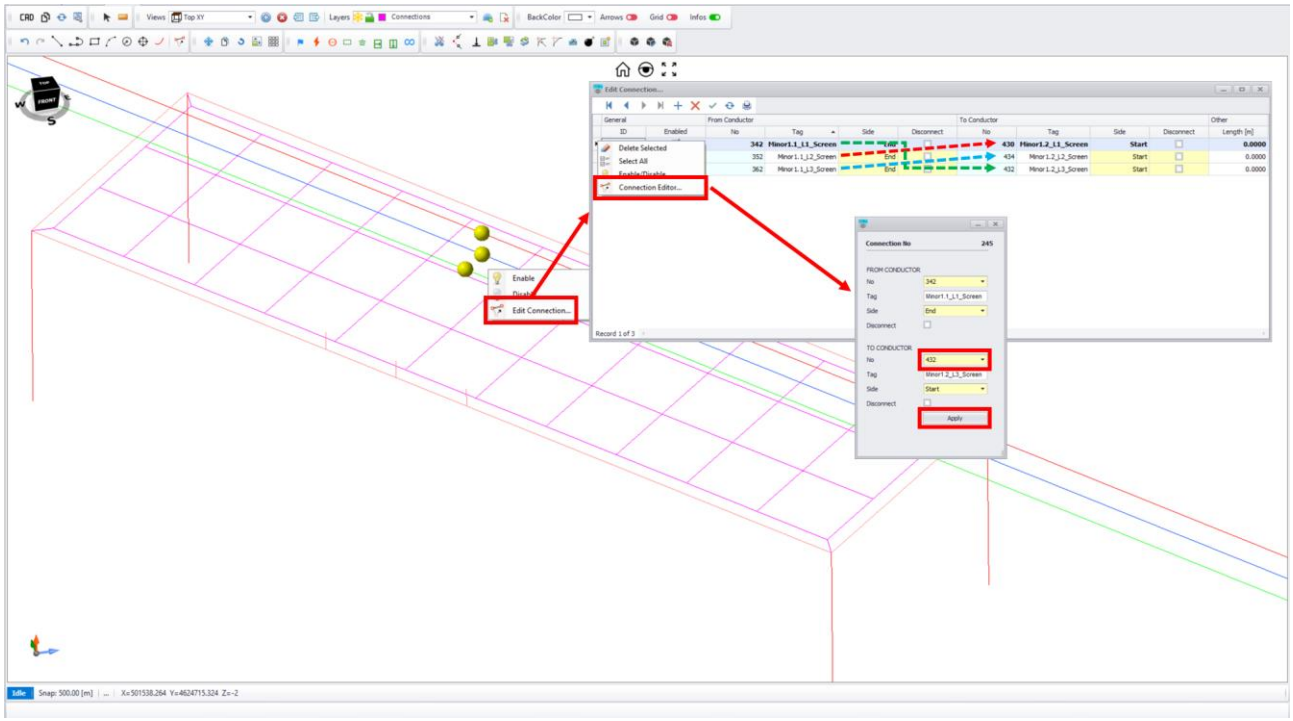


Figure 1-4: Connection Editor – rerouting the screen connection from "Minor1.1_L1_Screen" to "Minor1.2_L3_Screen" (conductor 432) at the cross-bonding joint

The same procedure is repeated for the remaining two screen connections at the joint bay, following the connection scheme in Figure 1-2: "Minor1.1_L2_Screen" is connected to "Minor1.2_L1_Screen", and "Minor1.1_L3_Screen" is connected to "Minor1.2_L2_Screen". Once all three connections have been rerouted, the cross-bonding pattern for that section is correctly represented in the model.

At this point, the connections between each screen and the earthing system of the joint bay can be set (the SVL will be introduced later). It is worth noting that, when a virtual connection is drawn starting or ending at a screened conductor, the screen is, by default, the part of the screened conductor to which the connection is attached.

It should also be clarified that the green, blue and red dashed lines used in the initial layout scheme of Figure 1-5 represent the electrical connection scheme conceptually, i.e. which screen is connected to which earthing point, and do not correspond to the actual virtual connections drawn in XGSA_FD, which are shown by default in pink.

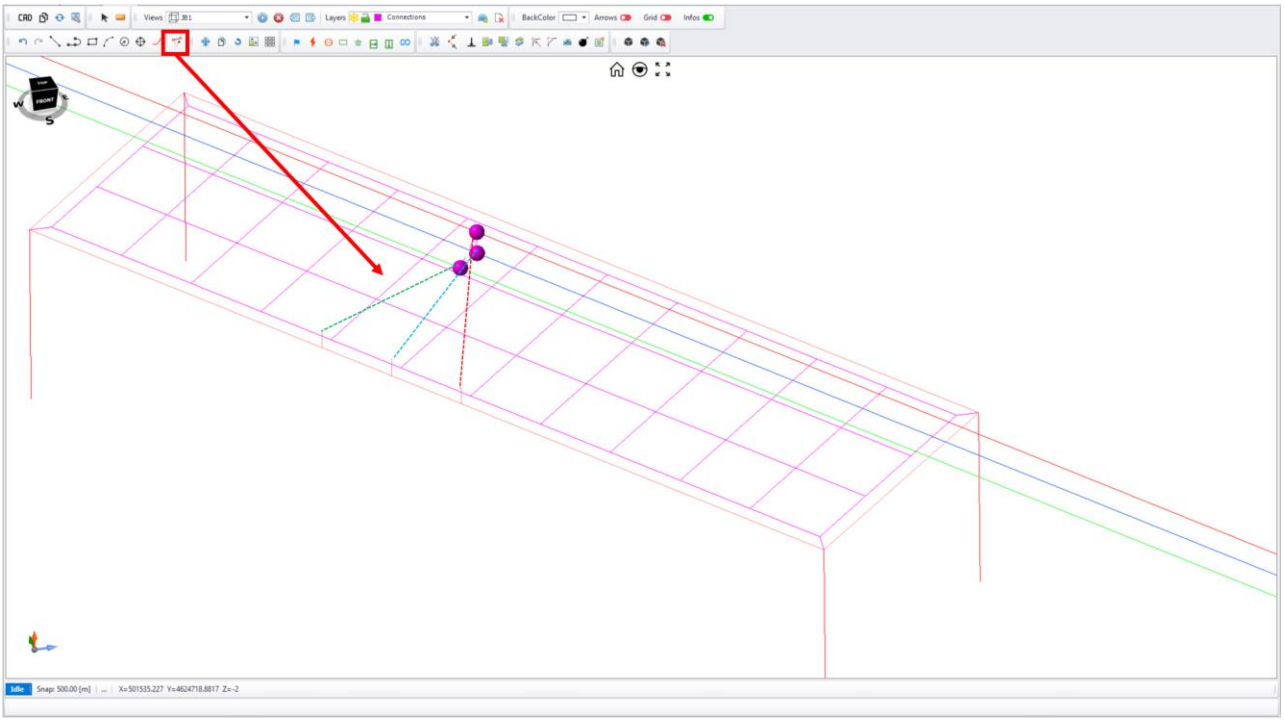


Figure 1-5: Virtual connections between the screens and the joint bay earthing system in the Xgl-CAD view

The next step is to set the SVLs at the intermediate joint bays, i.e. all joint bays except JB3 and JB6, where the screens are instead solidly connected to earth, as described above. This is done by selecting the conductors on which the SVLs have to be applied and, by right-clicking, choosing "Edit Conductor". The SVLs are then represented by properly configuring the corresponding longitudinal impedances.

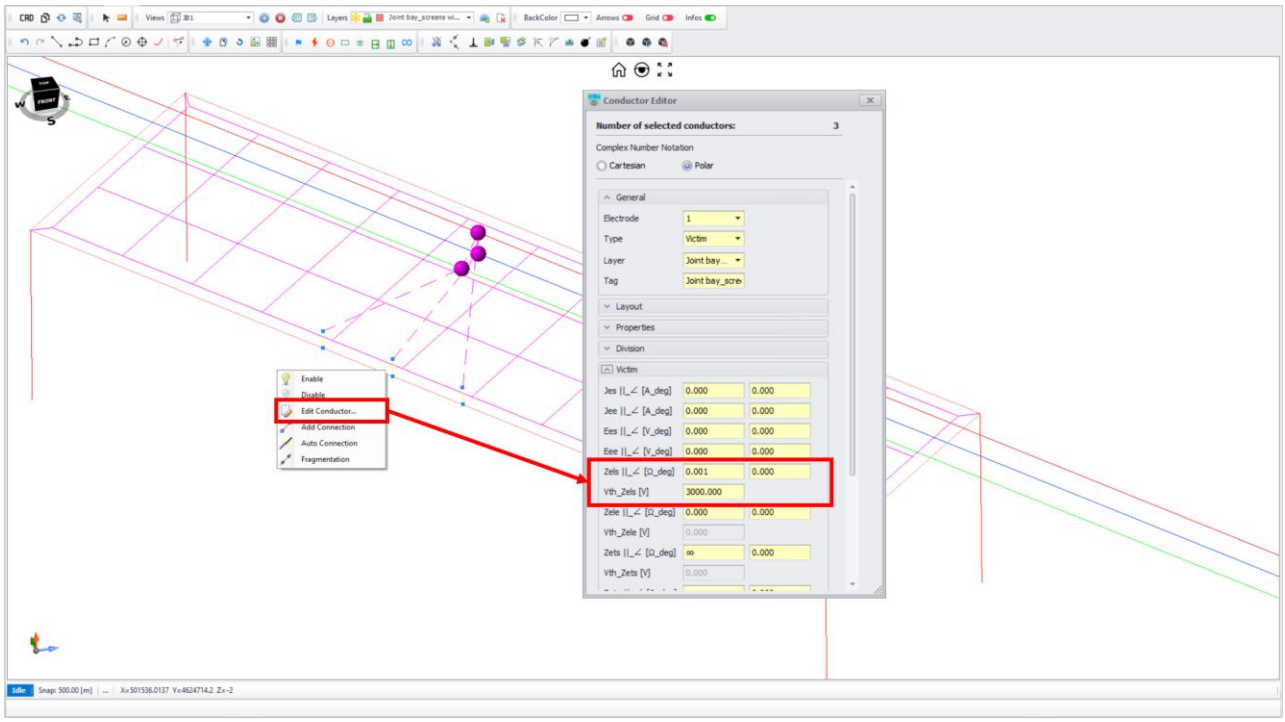


Figure 1-6: Conductor Editor window – longitudinal impedance settings used to represent the SVL

The screens now have to be connected to earth at both cable ends. This is done by drawing the virtual connections between each screen and the earthing system conductor of Substation A and Substation B, following the same procedure used at the solidly bonded joint bays (JB3 and JB6).

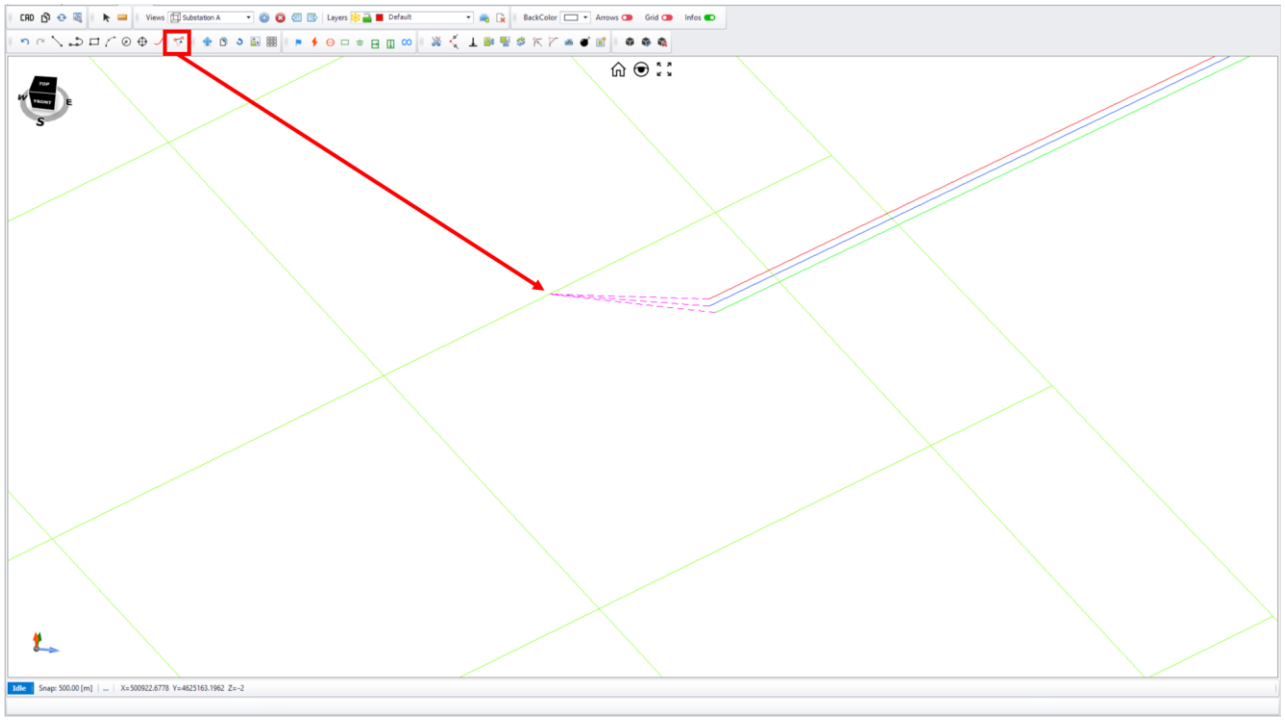


Figure 1-7: Virtual connections between the screens and the earthing system at Substation A

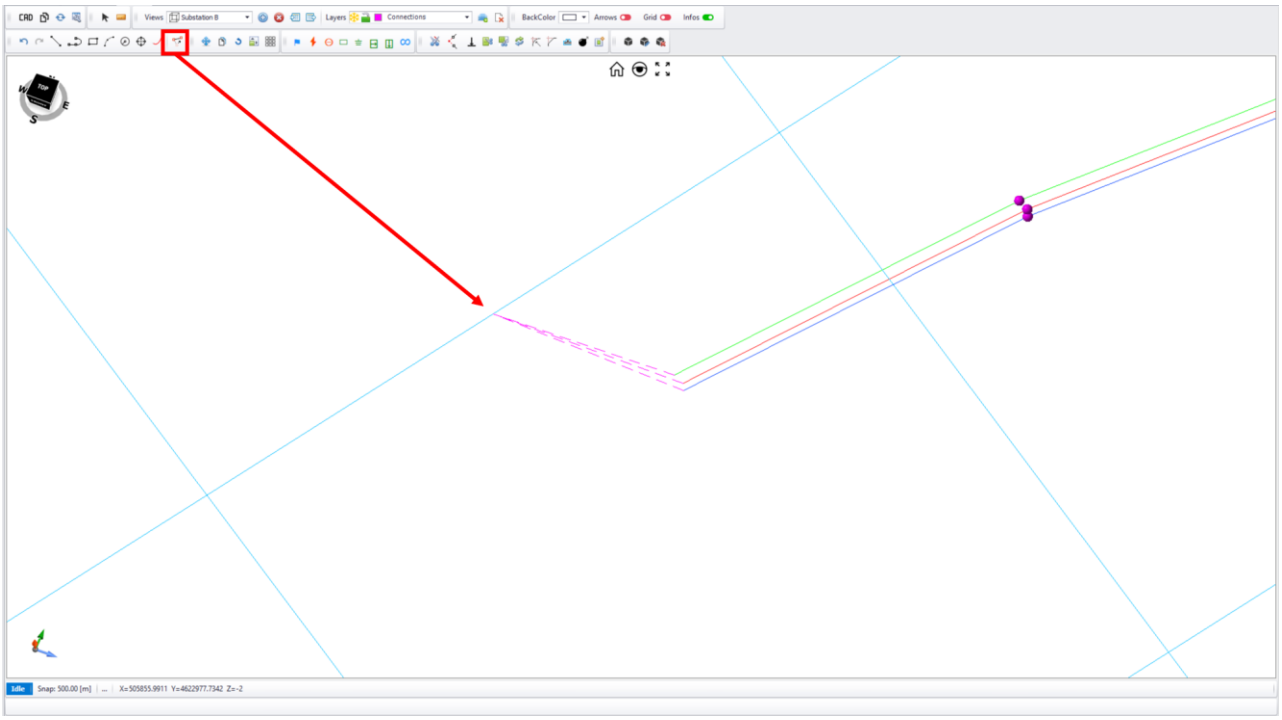


Figure 1-8: Virtual connections between the screens and the earthing system at Substation B

At Substation B, the fault has to be set between core and screen of cable L1. The first step is to identify the conductors involved. By switching on the "Arrows" toggle and clicking on the segment of the L1 polyline where the fault has to be set, it is possible to see that the arrowhead indicates the connection should be set at the end side of the segment, and that the connection has to be set between conductor 542 (screen) and conductor 543 (core).

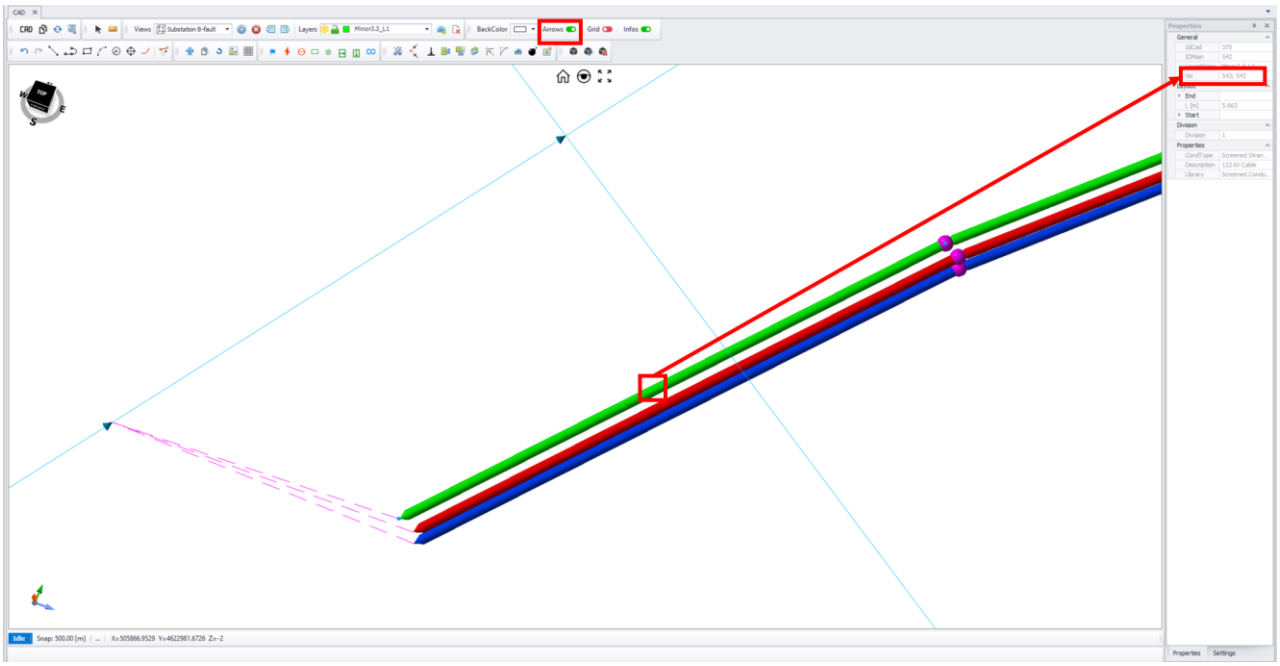


Figure 1-9: Identification of the conductors involved in the fault, using the "Arrows" toggle in the Xgl-CAD view

To set the fault, double-clicking on the polyline opens the conductor list related to that polyline. Both rows corresponding to conductors 542 and 543 are then selected and, by right-clicking, "Connection Editor" is chosen. It must be ensured that the "End" side is selected for both conductors, after which the connection can be applied.

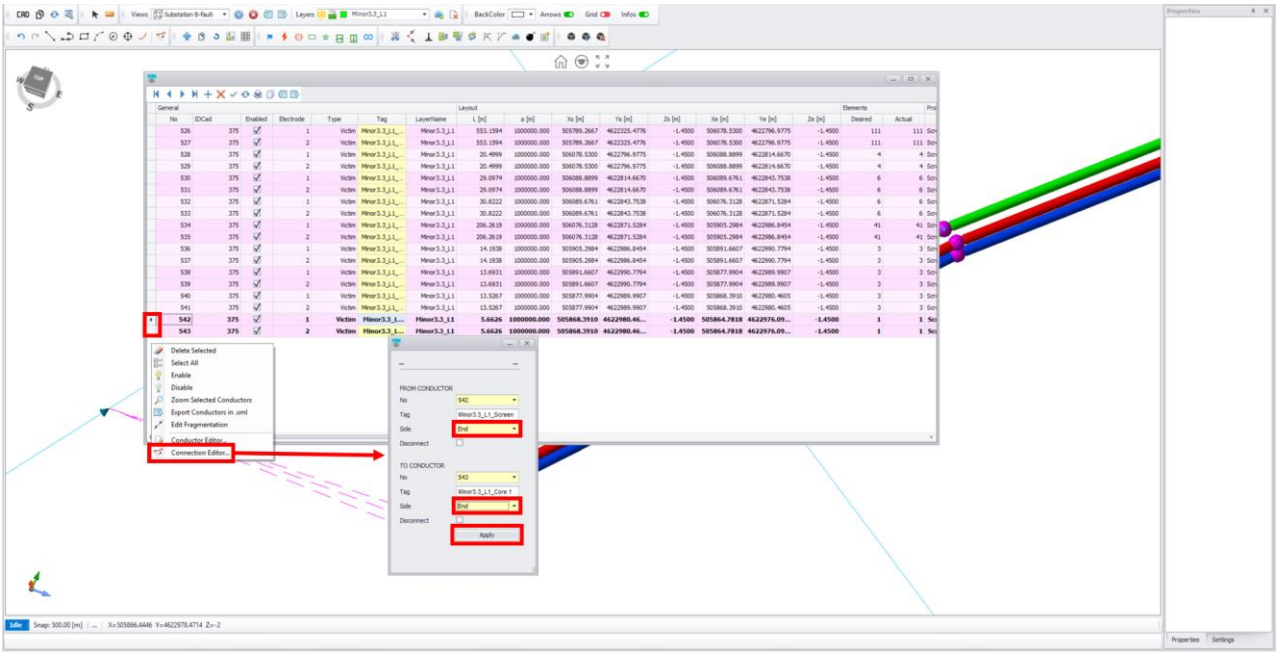


Figure 1-10: Connection Editor – setting the fault connection between conductors 542 (screen) and 543 (core) at the "End" side

The fault current now has to be set. Using the relevant current injection tool, the extremity where the current has to be injected can be selected. When a screened conductor is selected, it is possible to choose which part of the screened conductor is to be energised, either the core or the screen. In this case, the core is selected, after which the current value, as given in the input data, can be set together with a name for the injection point.

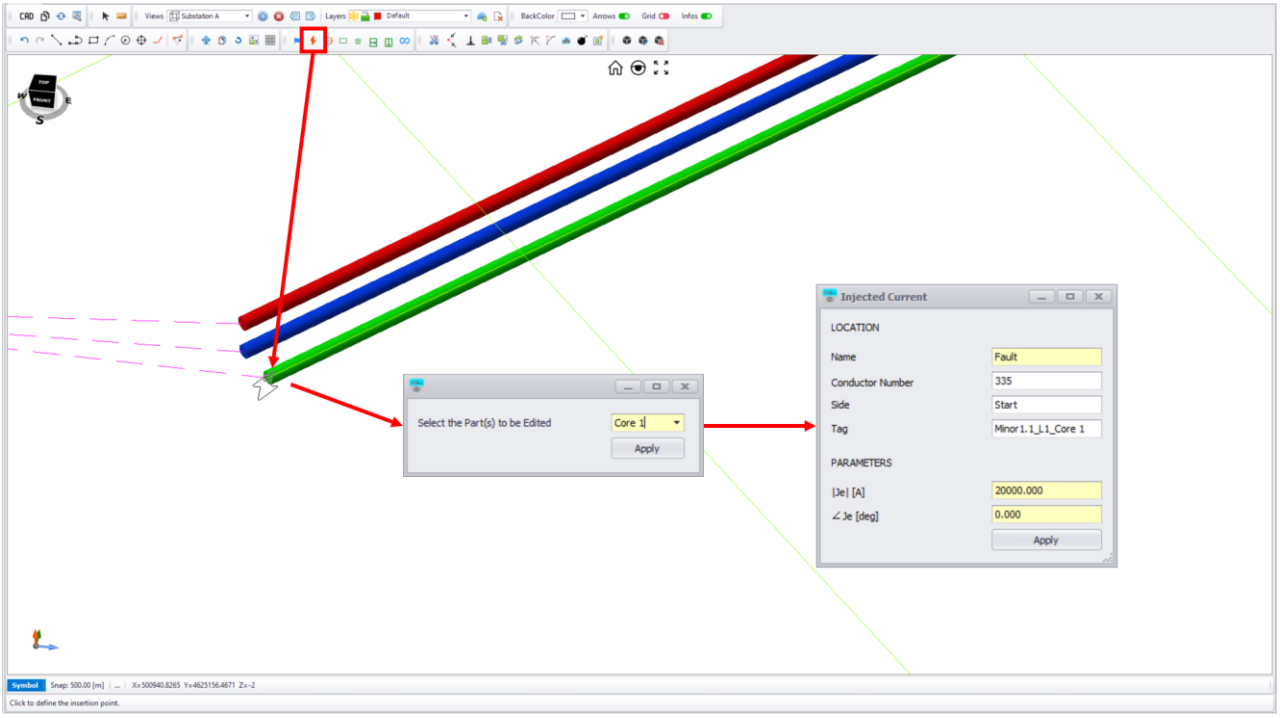


Figure 1-11: Current injection settings – energisation of the core at the fault point

As anticipated, the pipeline is assumed divided into two sections by an insulating joint between the two.
The insulating joint is protected with a longitudinal surge arrester and the pipeline ends at the insulating joint are grounded by means of transverse surge arresters.
The threshold voltages of the longitudinal and transverse SPDs are respectively:

- $V_{th_longitudinal}$ = 650 V
- $V_{th_transverse}$ = 70 V

When the surge arresters are triggered, the corresponding pipeline end is grounded through a grounding system having the known resistance to earth.
Resistance to earth of surge arresters:

- R_e = 10 Ω (both surge arresters at the joint)

The section of pipeline 2 preceding the joint is assumed to be of infinite length, while pipeline 1 terminates, grounded, at the entrance to the end-user facility.

Using the relevant longitudinal and transverse SPD tools, the extremity where the surge arresters have to be set can be selected. It is not recommended to set different inputs on the same extremity. For this reason, a small conductor has been created between the two pipeline sections (its length depends on the pipeline diameter, but the minimum length generally suitable to avoid triggering the "too short element" error has been used): the longitudinal surge arrester is set on this conductor, while the transverse surge arresters are set directly on the pipeline ends, each at its own extremity.

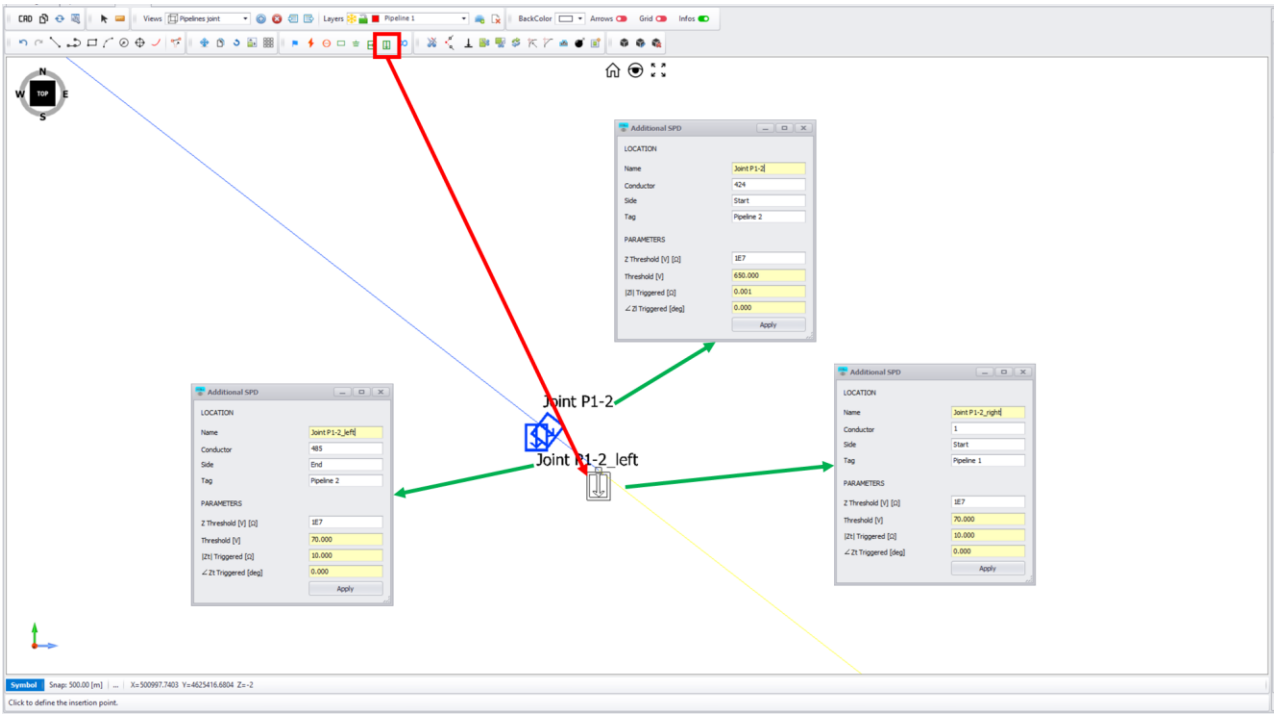


Figure 1-12: Longitudinal and transverse SPD tools – setting of the surge arresters at the pipeline insulating joint

The free end of pipeline 1 now has to be grounded at the entrance to the end-user facility, without any surge arrester.

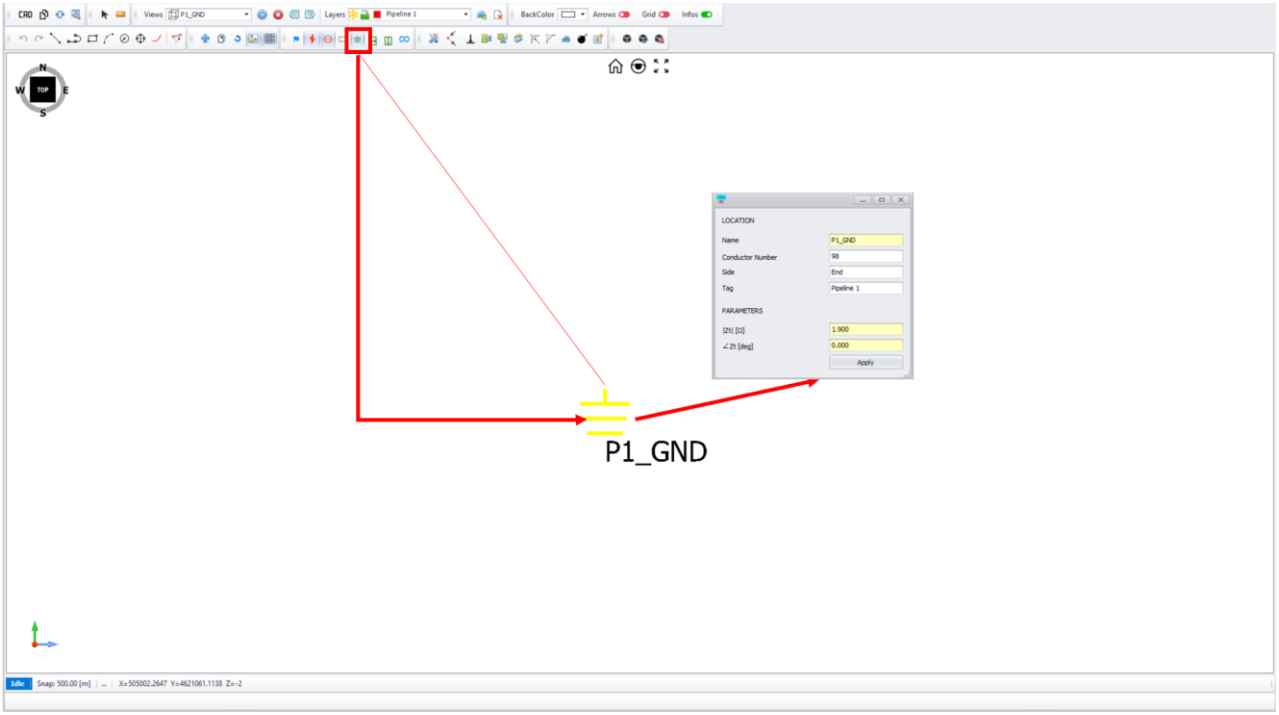


Figure 1-13: Direct earthing connection at the free end of pipeline 1, at the entrance to the end-user facility

At the free end of pipeline 2, the infinite length tool is applied, in order to simulate the continuation of the pipeline beyond that point.

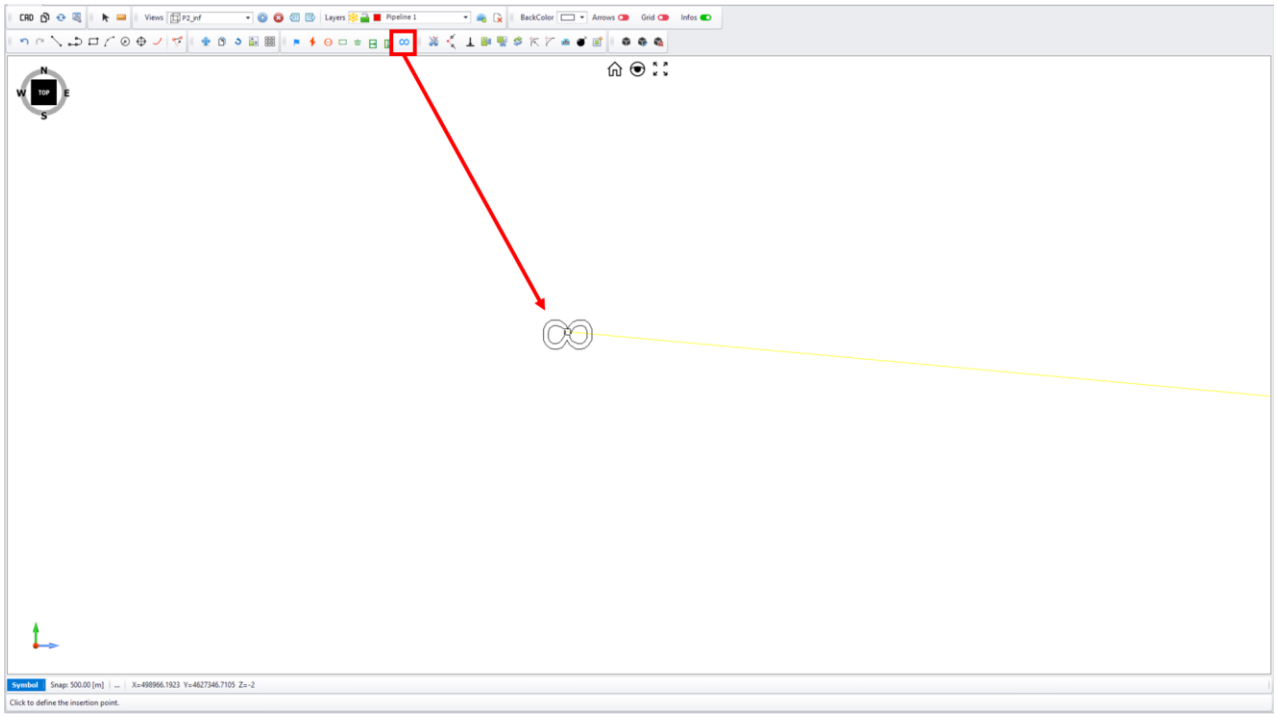


Figure 1-14: Infinite length tool applied at the free end of pipeline 2

At this point, the model is ready to be computed. The "Debug and Compute" icon can be selected, in order to evaluate the system.

Selecting "Analysis → Results → SPD" allows the triggering status of the SPDs to be checked.

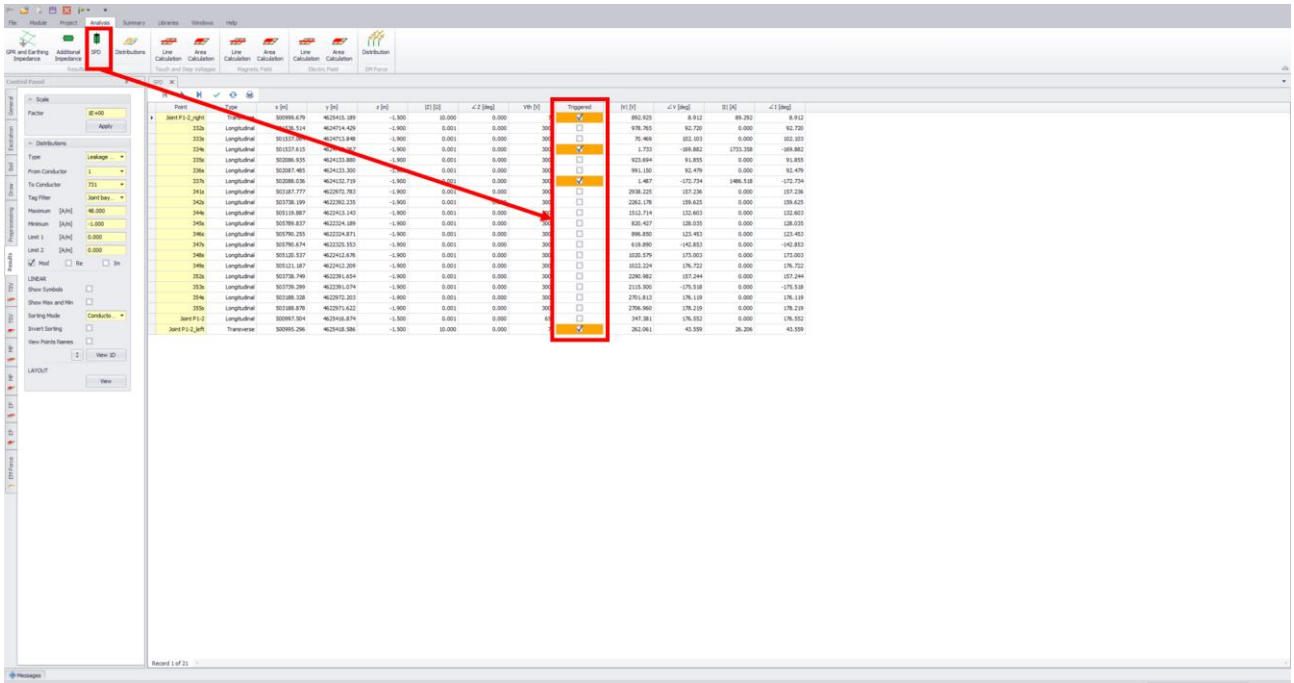


Figure 1-15: SPD results – triggering status of the surge arresters at the insulating joint and of the SVLs in the joint bays

In this case, the two transverse surge arresters placed at either side of the insulating joint between pipeline 1 and pipeline 2 have been triggered, together with a couple of the SVLs installed in the joint bays (JB1 and JB2).

Before analysing the pipelines, it is useful to see how the fault current is distributed among the different return paths. The fault current injected into the core of cable L1 at Substation A (If = 20 kA ∟ 0°) returns to the source partly through the metallic screens of the cable line and partly through the soil.

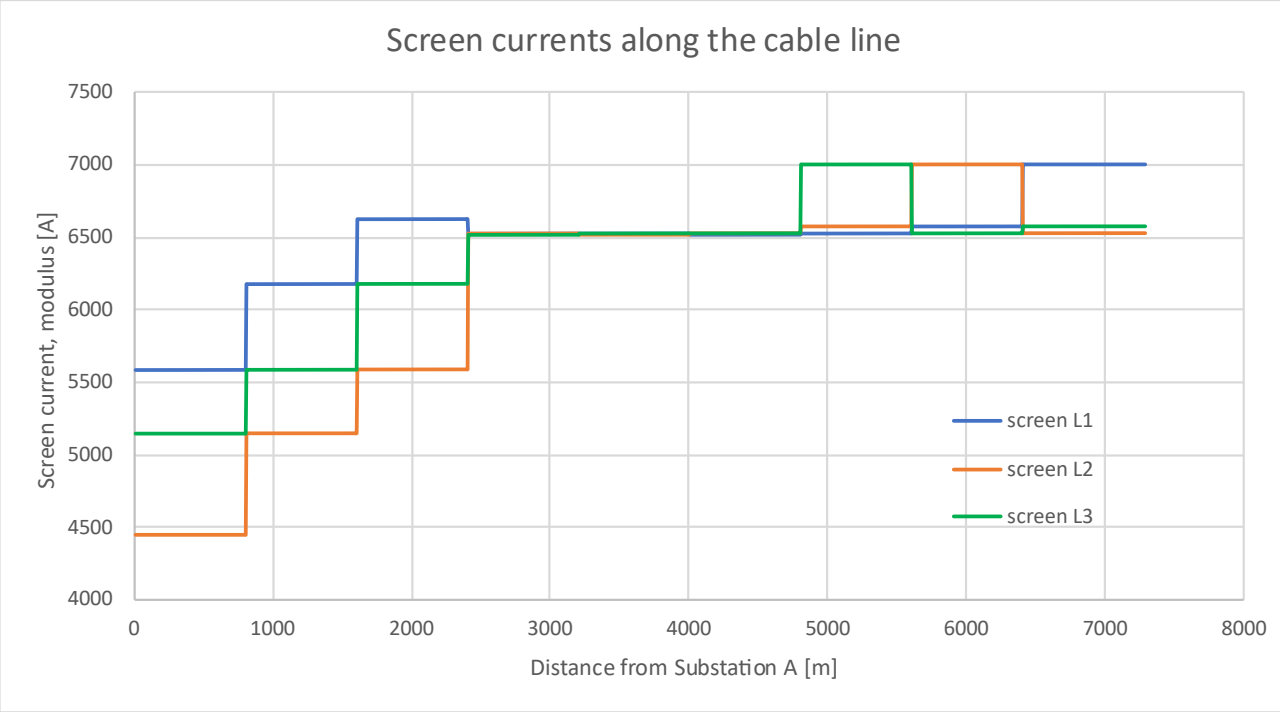


Figure 1-16: Screen currents along the cable line, modulus

The share of current flowing in the screens is relevant for the interference, since the screen current partially compensates the magnetic field produced by the core current and therefore reduces the electromotive force induced on the pipelines.

The currents dispersed into the soil by the earthing systems of the two substations and of the joint bays are shown in the following figures. For each main earthing system, the figure reports the current flowing through the connections between the screens and the earthing conductors.

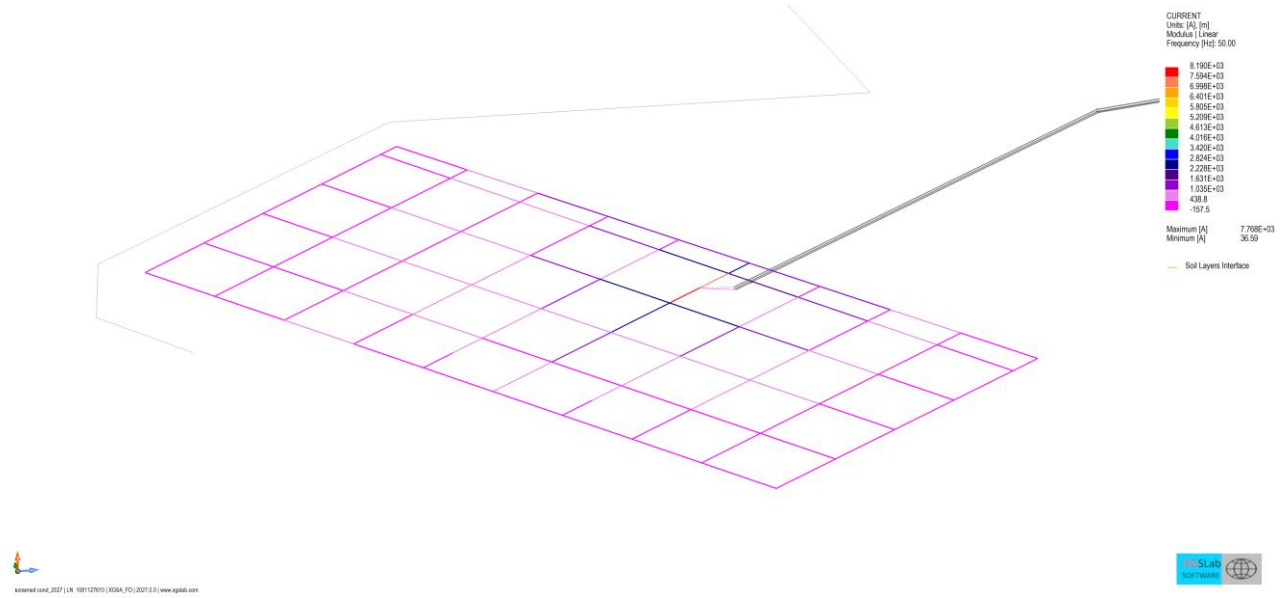


Figure 1-17: Current at Substation A earthing system

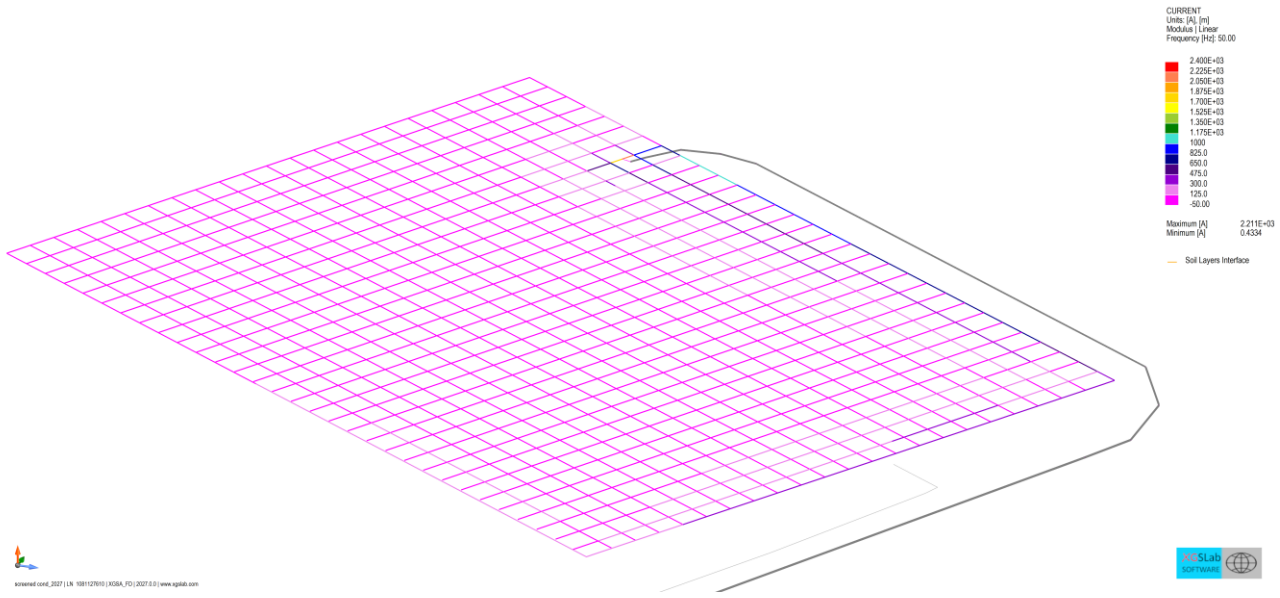


Figure 1-18: Current at Substation B earthing system

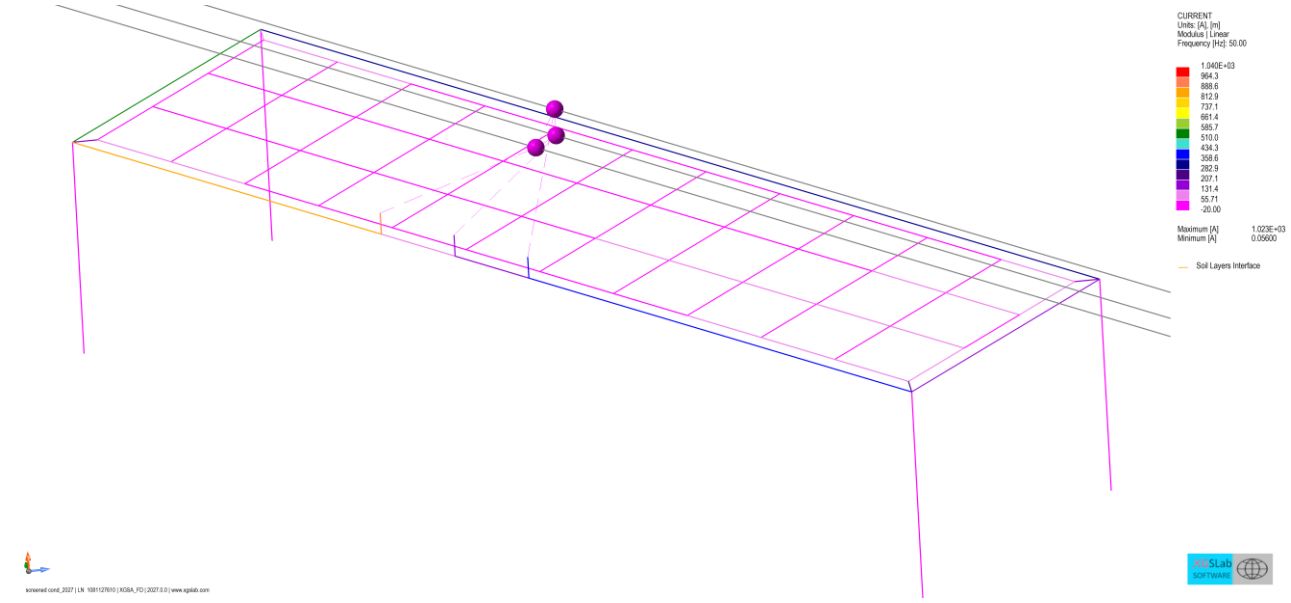


Figure 1-19: Currents at the earthing systems of the solidly bonded joint bay 3

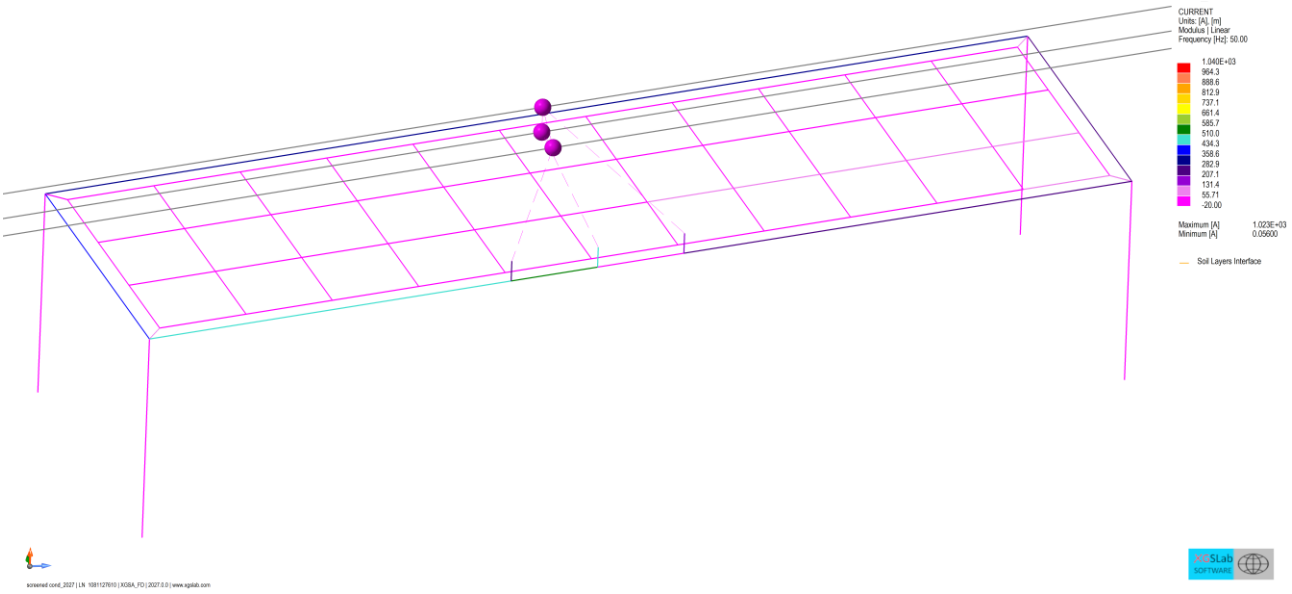


Figure 1-20: Currents at the earthing systems of the solidly bonded joint bay 6

Having described how the fault current is distributed among the screens and the earthing systems, the attention now moves to the effects on the pipelines.

The electromotive force, leakage current, potential and coating stress voltage distributions along the pipelines can be displayed by selecting "Analysis → Results → Distributions". In the panel, the quantity of interest is chosen through "Type", the "Tag Filter" is set to "Pipeline 1" and “Pipeline 2” so that only the pipelines are considered, and the "Mod/Re/Im" checkboxes are used to select the components to be displayed. Clicking "View 1D" then displays the corresponding distribution.

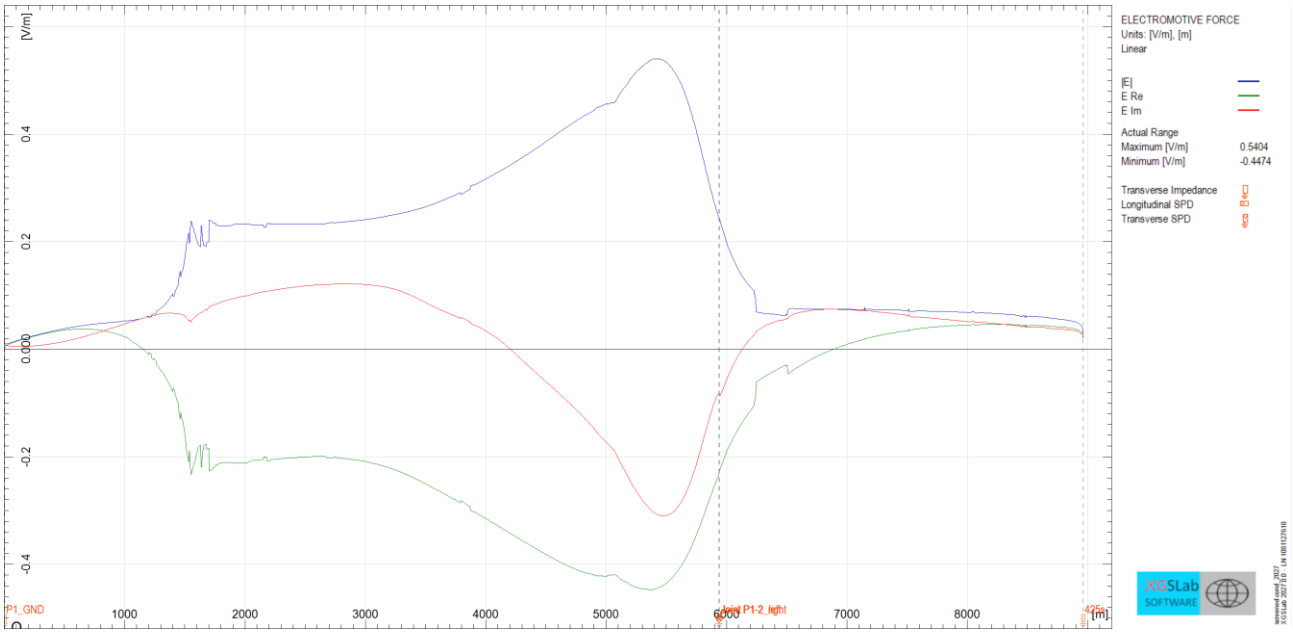


Figure 1-21: Electromotive force distribution along the pipelines

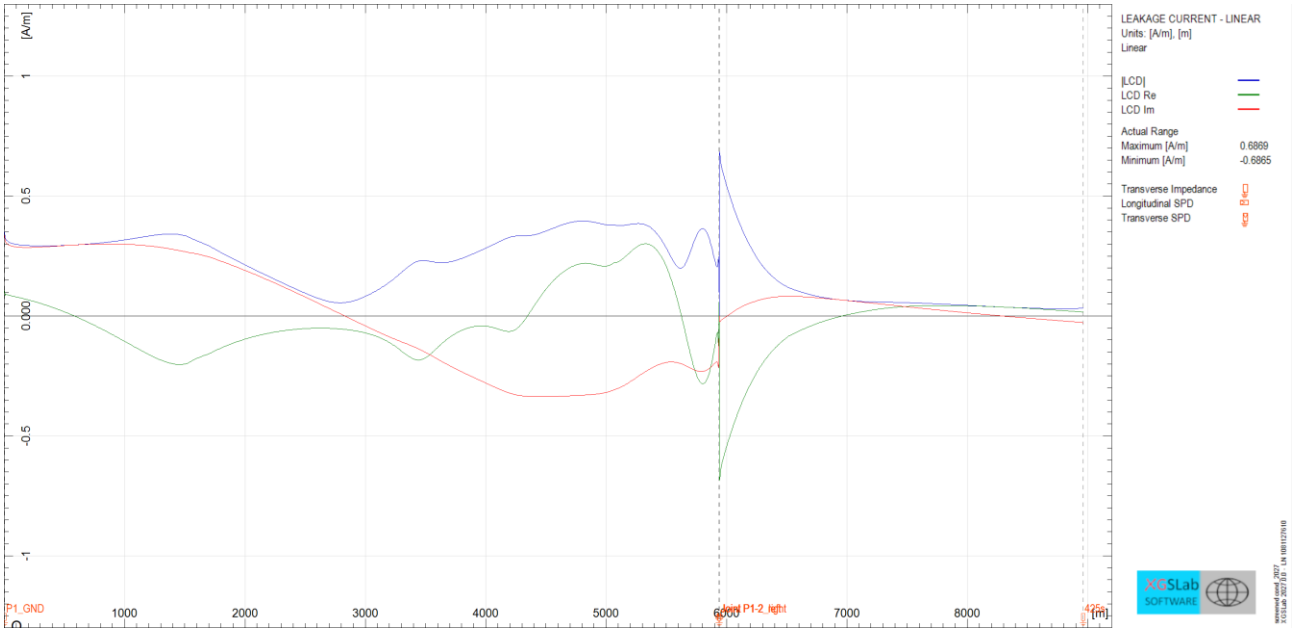


Figure 1-22: Leakage current distribution along the pipelines

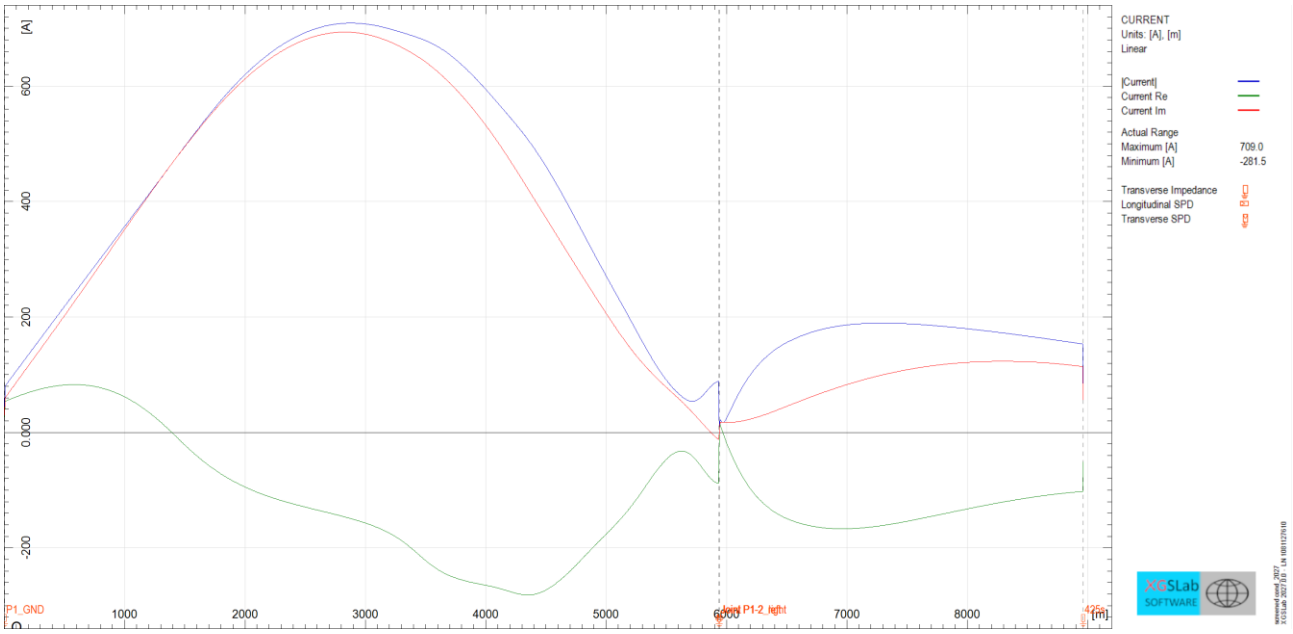


Figure 1-23: Longitudinal current distribution along the pipelines

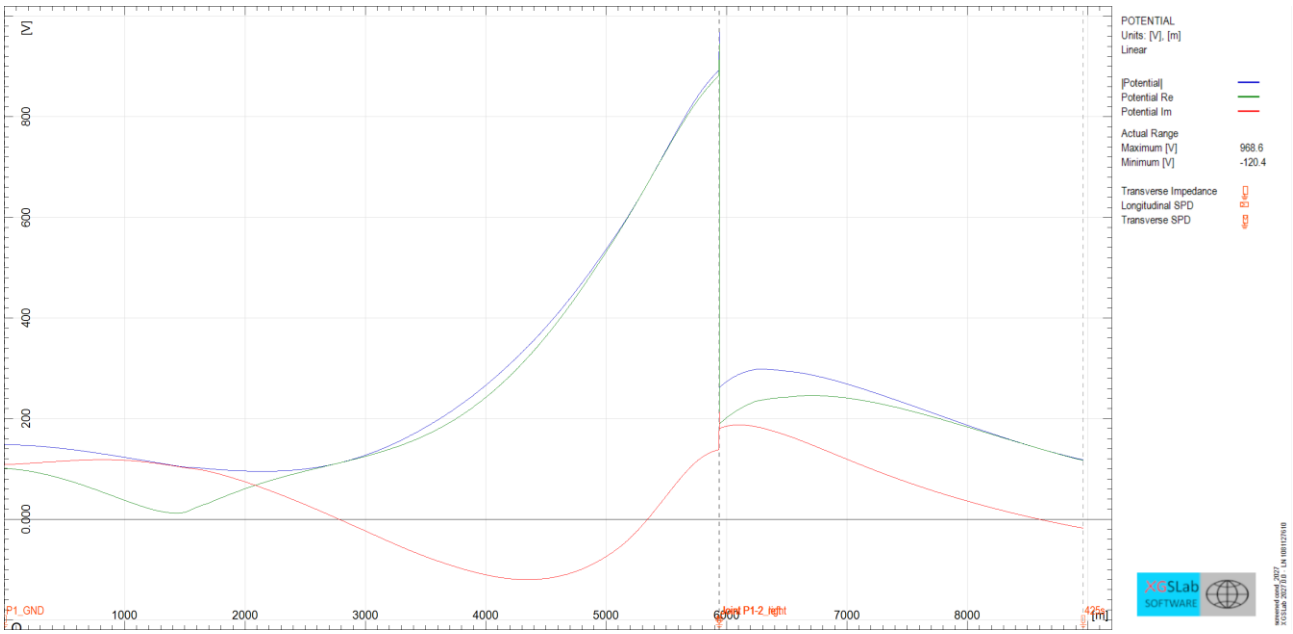


Figure 1-24: Potential distribution along the pipelines



Figure 1-25: Coating Stress Voltage distribution along the pipelines

The maximum potential has to be compared with the permissible voltages. Usually there is a permissible voltage for the safety of people and different limits in order to avoid damage to the pipeline.
In fault conditions, the European standard EN 50443:2012 sets a limit for the safety of workers that depends on the fault duration (for instance 650 V if the fault duration is 0.5 s). This limit refers to accessible metal parts.
For the safety of the general public, the EN 50522:2022 is more stringent than EN 50443:2012 for the same fault duration of 0.5 s, the permissible voltage is 225 V.
In order to avoid damage to the pipeline in fault conditions, EN 50443:2012 sets a limit of 2000 V. This limit refers to all parts.

The potential distribution along the pipeline has been compared with the limits set by EN 50443:2012. As far as the safety of the general public is concerned, however, the relevant quantity is the touch voltage, i.e. the voltage between an accessible metal part of the pipeline and the soil surface point where a person stands while touching it.
According to EN 50522:2022, the touch voltage is evaluated considering a horizontal distance of 1 m between the touched part and the feet of the person. For this reason, the touch voltage towards the pipeline is calculated over a strip area extending along the pipeline, in the region adjacent to it. In this way, the voltage between the pipeline and the soil surface is evaluated at every point of the strip, and the most critical locations along the route can be identified.
The maximum touch voltage obtained over the strip is then compared with the permissible touch voltage given by EN 50522 for the fault duration considered (0.5 s).

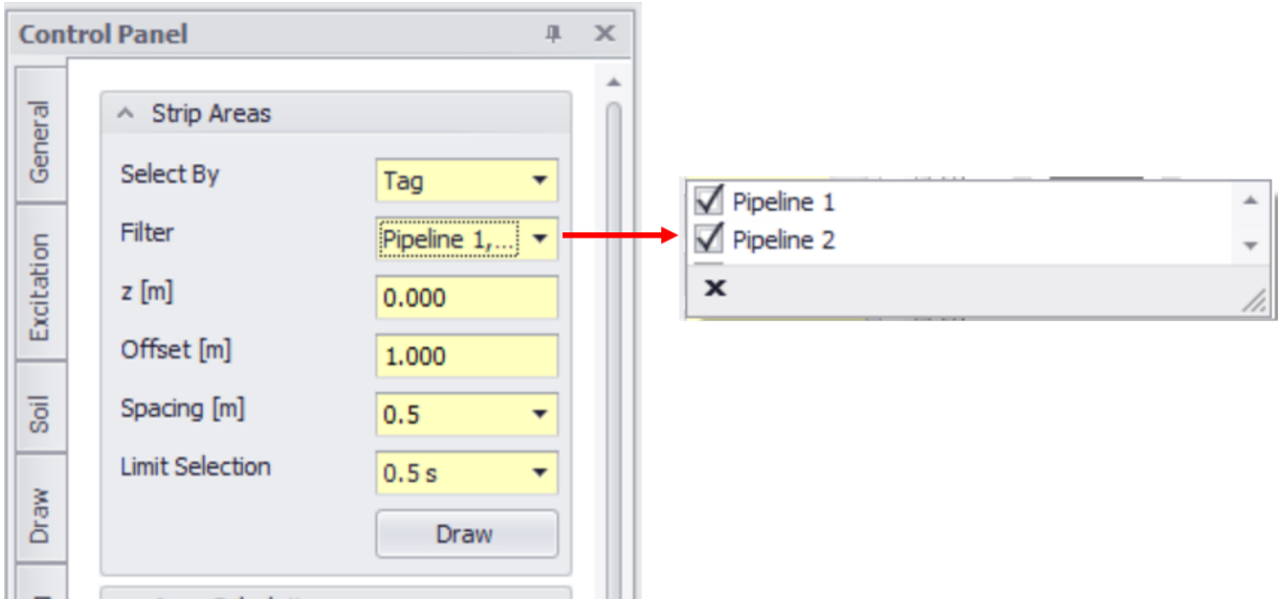


Figure 1-26: Strip area settings

The results in terms of safe areas show that, almost everywhere, the touch voltage is below the limit set by EN 50522:2022. The exception is the area near Substation A, around pipeline 1, between the insulating joint separating pipeline 1 and pipeline 2 and the first bend, where the touch voltages exceed the limits, as shown in the following figure.

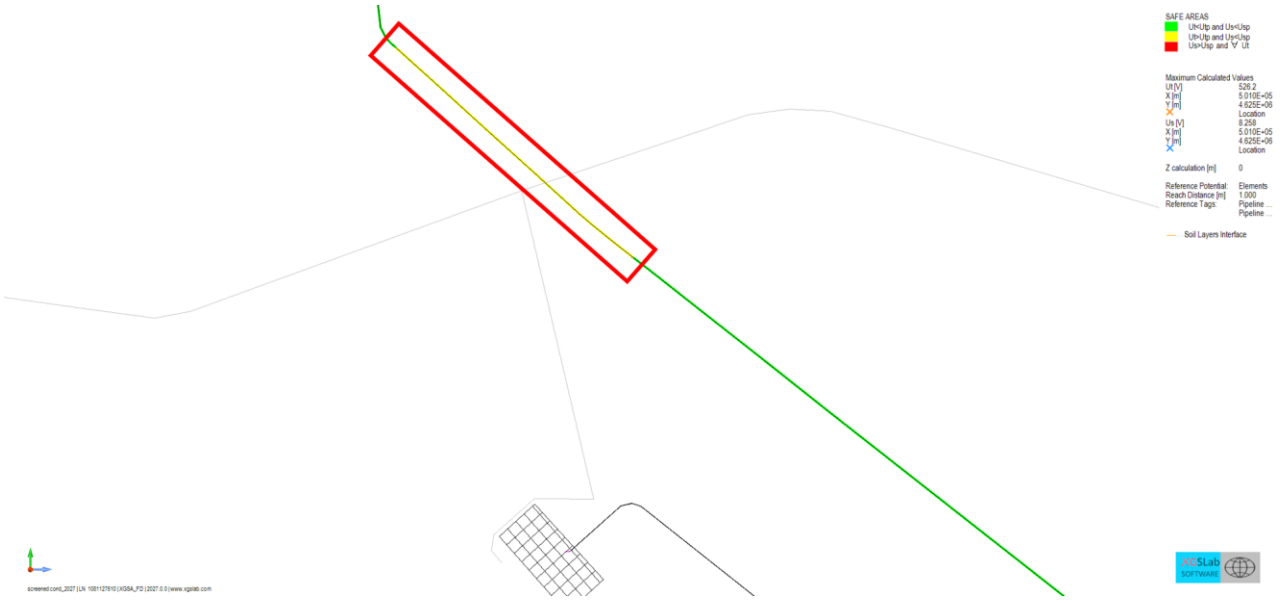


Figure 1-27: Safe areas – areas where the touch voltage towards the pipeline exceeds the EN 50522:2022 limit

It is worth noting that the touch voltage assessment applies only where the pipeline has accessible metal parts. If the pipeline has no accessible parts, the verification of the touch voltages is not required. Otherwise, some mitigation measures have to be taken in the area where the limits are exceeded.