A NUMERICAL SIMULATION TOOL FOR CATHODIC PROTECTION AND ELECTROMAGNETIC INTERFERENCE ANALYSIS

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Abstract

This work relates with two recently released modules of the XGSLab® simulation environment [1] which allow the analysis of cathodic protection systems with impressed currents and the calculation of electromagnetic interference between power lines and buried or aerial pipelines in an increasingly realistic way.
The solver is based on Maxwell equations and Sommerfeld integrals and can be applied for the solution of both aerial and underground systems of conductors taking into account the earth effects in the frequency domain between from DC condition up to a few MHz. Original algorithms have been developed for solving an hybrid method which takes into account transmission line, circuit and electromagnetic theory combined into a single integrated calculation model considering the effects of self impedance, resistive, capacitive and inductive coupling, soil parameters frequency dependence and propagation effects.
In the first theoretical part, a synthetic description of the implemented method is given together with its application limits and range. The second part of the paper is devoted to the description of two specific study cases, which was reckoned the best way for assessing the capabilities of the proposed approach.
The first example is a case study of cathodic protection of a network of buried pipelines. whereas the second one describes a case study of electromagnetic interference between a power line under faulty conditions and a buried pipeline, including the effects of a substation grounding system. The interference effects then include both conductive and inductive coupling effects.
It is then shown how it is possible to perform realistic simulations of increasingly frequent problems as cathodic protection or electromagnetic interference in even complex scenarios, problems traditionally addressed empirically because of the lack of adequate computational tools.
Finally, unlike classical finite elements methods, it is worth noticing that the hybrid approach requires limited CPU power and RAM resources and even if they have room for improvement, they are already adequate for most engineering applications.

1 - Introduction:

The large improvement of power computing performances is contributing to the diffusion of calculation programs for the electromagnetic simulations and, of particular interest to this paper, of the programs who take into account the earth currents and the earth reaction effects.
These latest programs have many engineering applications, as for instance:
- Grounding Systems
- Cathodic Protection

- Electromagnetic Fields
- Electromagnetic Interferences
- Lighting

Each of the above applications has specific needs (such as, for instance, a different frequency range) but there are general methods that are valid for many applications.
One of the most promising and effective methods in this regard is the Partial Element Equivalent Circuit (PEEC) method that in the following for historical or for tradition in the grounding community reasons we prefer to call Hybrid Method.
Calculation models for electromagnetic simulations including the earth effects may be based on following different approaches: 1) Electromagnetic field theory; 2) Transmission line theory; 3) Hybrid methods, 4) Circuit theory. This classification is not rigorous as indicated in [11], but is generally adopted in the literature. For a comprehensive overview on these kind of computational methods refer to [11].
Hybrid methods consider transmission line, circuit and electromagnetic field theory combined into a single model, and are often preferred in the frequency range of interest (from DC to a few MHz). Hybrid methods are very useful for an engineering purpose because they are accurate and flexible, are appropriate for open space problems and can allow an easy way to consider additional external parameters such as electromotive forces, currents, and impedances. Hybrid methods may be used at low frequency and also at high frequency [12].
In the following paper, have been used the modules GSA_FD® and XGSA_FD® which are included in the XGSLab® software (in the following called software). Both modules are based on the same hybrid method.
The main assumptions of the two modules are listed in Table 1.1.

Aspects taken into account	**GSA_FD and XGSA_FD**
Resistive Coupling	Yes
Capacitive Coupling	Yes
Self-Impedance	Yes
Mutual Impedance	Yes
Soil Parameters Frequency Dependence [13]	$\rho, \varepsilon = f(\omega)$
Propagation Law	$e^{-\gamma r}/r$

Table 1.1. Aspects taken into account in the used modules.

2 – Calculation Models

In the following, a short description of the hybrid method implemented in the software is provided.
The implemented method can solve system of conductors arranged in an arbitrary way in the 3D space and including the contemporary presence of sources (conductors with current and voltages known), and victims (conductors with current and voltages unknown).
The system of conductors is partitioned into a suitable number of finite elements and then, the electromagnetic field and transmission line theories are used to calculate the circuit parameters, whereas circuit theory is employed to describe the relations among parameters such as voltages and currents and the metallic connections between elements.
All conductors of the system have to be thin enough in order to be simulated with a suitable number of thin and straight short elements.
The implemented method derives directly from the Maxwell equations. Using the scalar and vector potentials, Maxwell equations can be written as in the following (Helmholtz equations) [3]:

$$\begin{cases} \Delta\dot{\mathbf{A}} - \dot{\gamma}^2\dot{\mathbf{A}} = -\mu\dot{\mathbf{J}} \\ \Delta\dot{V} - \dot{\gamma}^2\dot{V} = -\dfrac{\dot{q}}{\dot{\varepsilon}} \end{cases} \qquad (2.1)$$

where $\dot{\gamma} = \sqrt{j\omega\mu(\sigma + j\omega\varepsilon)}$ represents the propagation coefficient of the medium and $\dot{q}$ and $\dot{J}$ represent charge and current density distribution on the sources respectively.
Solution of (2.1) for sources with linear current and charge density distribution are given by the following equations:

$$\begin{cases} \dot{\mathbf{A}} = \dfrac{\mu}{4\pi}\int_L \dot{I}\,\dfrac{e^{-\dot{\gamma}r}}{r}dl \\ \dot{V} = \dfrac{1}{4\pi\dot{\varepsilon}}\int_L \dot{q}\,\dfrac{e^{-\dot{\gamma}r}}{r}dl \end{cases} \qquad (2.2)$$

Maxwell equations give the following well known relation between electric field and scalar and vector potentials:

$$\dot{\mathbf{E}} = -grad\dot{V} - j\omega\dot{\mathbf{A}} \quad (2.3)$$

Taking into account that electric field and vector potential on the surface of a conductor are parallel to the conductor axis [6], only the magnitude of vectors in (2.3) need to be considered and (2.3) written along the conductor axis gives:

$$\dot{E} = -\frac{\partial \dot{V}}{\partial l} - j\omega\dot{A} \qquad (2.4)$$

On the other hand, the tangential electric field on the surface of a conductor, taking into account their self impedance, gives:

$$\dot{E} = \dot{z}\dot{I} \qquad (2.5)$$

Combining (2.4) and (2.5), the following fundamental differential equation is obtained:

$$\dot{z}\dot{I} + j\omega\dot{A} + \frac{\partial \dot{V}}{\partial l} = 0 \qquad (2.6)$$

Equation (2.6) is derived directly from the Maxwell equations and is then valid in all conditions (also non stationary).
In practical cases, (2.6) can be solved only in a numerical way. The system of conductors is then partitioned into a suitable number of short elements. Each element is oriented between its start point (in) and its end point (out). Integrating (2.6) between the ends of an element, replacing the vector and scalar potential with (2.2) and rearranging, the following linear equation is obtained:

$$\dot{Z}_i\dot{I}_i + \sum_{j\neq i}\dot{M}_{ij}\dot{I}_j + \sum\left(\dot{w}_{outij} - \dot{w}_{inij}\right)\dot{J}_j = 0 \qquad (2.7)$$

with:

$$\dot{M}_{ij} = \frac{j\omega\mu}{4\pi}\int_{in}^{out}\int_{in}^{out}\frac{e^{-\dot{\gamma}r}}{r}dl_i dl_j \qquad (2.7a)$$

$$\dot{w}_{outij} = \frac{\dot{\rho}}{4\pi l}\int_{in}^{out}\frac{e^{-\dot{\gamma}r}}{r}dl_j\Big|_{out} \qquad (2.7b)$$

$$\dot{w}_{inij} = \frac{\dot{\rho}}{4\pi l}\int_{in}^{out}\frac{e^{-\dot{\gamma}r}}{r}dl_j\Big|_{in} \qquad (2.7c)$$

and where $\dot{Z}$ represents the self impedance of the element, $\dot{M}$ and $\dot{w}$ represent partial mutual coupling and partial potential coefficients between elements respectively, and $\dot{I}$ and $\dot{J}$ represent longitudinal and leakage current of the elements respectively.
Writing a linear equation for each element, the hybrid method reduces the Maxwell equations to a linear system.
For the calculation of the linear system coefficients and then of the self and partial mutual coupling and partial potential coefficients between elements, the formulas in [2], [5], [8], the shifting complex images method (SCIM) [10] and the modified images method (MIM) [9] has been used. If these coefficients are calculated taking into account the propagation effects, the resulting model is a full-wave hybrid method.
Each element is represented with a simplified “T” equivalent circuit as shown in Fig. 2.1 and introduces the following unknowns:

- Input and Output currents I_{in} and I_{out}
- Leakage current J
- Potential V of the middle point

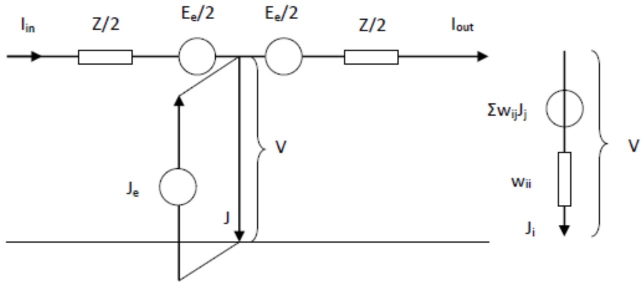

Fig. 2.1. Equivalent circuit of each element.

The resulting linear systems can be written as follows:

$$\begin{cases} \{V\} = [W]\{J\} \\ \{E_z\} + \{E_e\} = -([Z] + [M])\{I\} \\ \{J\} = [A]\{I\} + \{J_e\} \end{cases} \qquad (2.8)$$

where:
- $[W]$ = matrix of self and mutual partial potential coefficient
- $[Z]$ = matrix of self-impedances
- $[M]$ = matrix of mutual impedances
- $[A]$ = incidence matrix which expresses the elements connectivity
- $\{V\}$ = vector of potentials
- $\{I\}$ = vector of currents
- $\{J\}$ = vector of leakage currents
- $\{E_z\}$ = vector of voltage drops
- $\{E_e\}$ = vector of forcing electromotive force
- $\{J_e\}$ = vector of injected currents

The solution of the linear system (2.8), allows to obtain the distributions of currents, potentials and leakage currents along the victims taking into account the influence of eventually sources.
From these main results, it is possible to calculate other important distributions as for instance:
- Earth surface potentials
- Electric Fields
- Magnetic Fields

3 – Soil Model
The soil resistivity value is liable to great variations.
The ranges of variations of the soil resistivity are following:
- Exceptionally Low Values: from 1 up to 10 Ωm
- Usual Values: from 10 up to 1000 Ωm
- Exceptionally High Values: from 1000 up to 10000 Ωm

As a general rule, the soil resistivity depends on moisture, temperature and chemical content and then it is not possible to assign a single value for the resistivity of a soil material. For this reason the resistivity value must not be obtained from literature or tables but must be measured. The only reliable data are those related to the specific site.
The Wenner four-pin method is the most commonly used technique for soil resistivity measurements.
From the soil resistivity measurements it is possible to obtain the soil model to use in the calculations.
The choice of the soil model depends on how the soil resistivity changes in vertical and horizontal directions.
As general rule, a multilayer or multizone soil model are required when the main changing in resistivity are in vertical and horizontal direction respectively. A uniform soil model should be used only when there is a moderate variation in resistivity but for the majority of the soils this assumption is not valid.
In the following a multilayer soil model is assumed. A double layer soil model is often a good approximation of many stratified soil structures and consists of an upper layer of finite depth and a lower layer of infinite thickness with different parameters. The soil model parameters "ρ_1, ρ_2 and h" can be calculated by using the IEEE Std 81-1983 method and the basic formula of the Tagg's master curves. This method yields the equivalent double layer soil model that best fits the measurement data.

The average values of the on site soil resistivity measurements are shown in Tab. 3.1.

a (m)	ρ (Ωm)	RW (Ω)
2	280.0	22.28
4	280.0	11.14
6	250.0	6.632
10	160.0	2.547
14	130.0	1.478
20	120.0	0.9550
26	100.0	0.6122
32	82.00	0.4078

Tab. 3.1: Measured values (a = electrode spacing, ρ = apparent resistivity, RW = Wenner Resistance)

The calculated soil model parameters are the following:

- ρ_1 = 296.5 Ωm
- ρ_2 = 85.12 Ωm
- h = 5.839 m
- RMS Error = 7.199 %

Figure 3.1 represents the measured resistivity values and the soil model parameters that will be used in the following cases study.

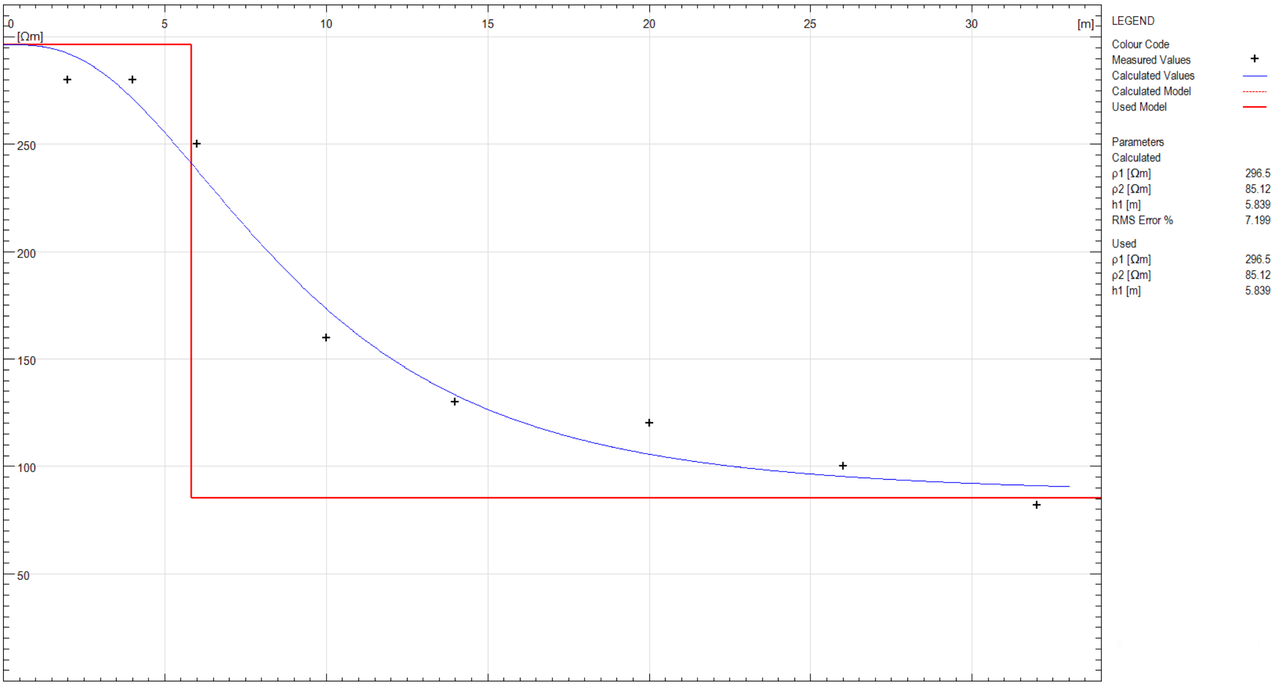

Fig. 3.1: Measured resistivity values (black cross) and soil model parameters (red line)

4 – Cathodic Protection

Corrosion of buried or submerged metals can be controlled and limited in many ways.
Cathodic protection is only one of many methods of corrosion control and should be considered possibly in conjunction with other forms of corrosion control such as the application of protective coating [4].
Cathodic protection uses a flow of direct current to interfere with the activity of the electrochemical cells responsible for corrosion. Corrosion is prevented by coupling the metal being protected with a more active metal when both are immersed in an electrolyte and connected with an external path. In this case, the entire surface of the metal being protected becomes a cathode, thus the term “cathodic protection”.
The current flow can be provided by a source commonly called anode (or anodic groundbed).
Anode made from active metal are commonly called “sacrificial”, as the anode material is sacrificed to protect the structure under protection. Anode made from inert metal are commonly called “impressed current anodes”, as an external energy source is used to impress a current onto the structure under protection.

As example, in the following the calculation performed to size a cathodic protection with an impressed current system of a buried steel pipeline is evaluated.

In order to consider a more realistic case, also a foreign pipeline is taken into account.
The main goal is to calculate the number and the performance of the sources of direct current the cathodic protection plant requires, and the position of the cathodic protection systems and in particular of the anodic groundbeds.
The general layout of the system of conductors is shown in Figure 4.1.

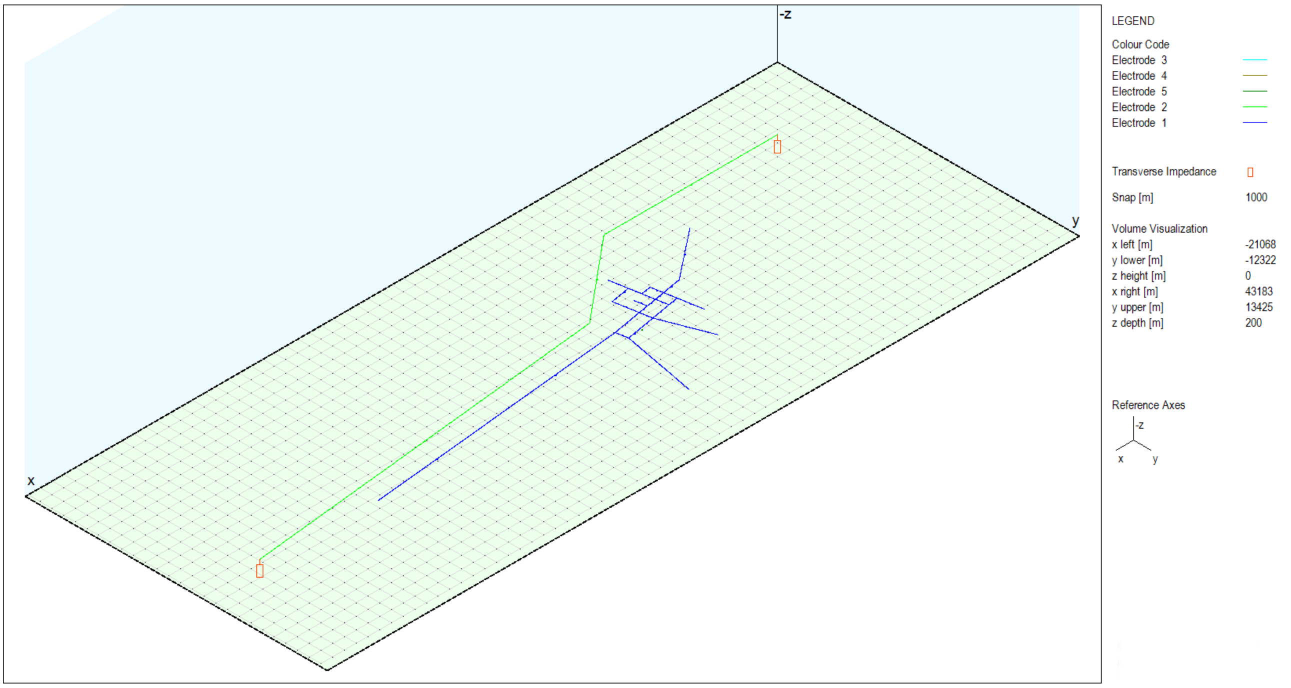

Figure 4.1: Layout of the pipeline to be protected (blue) and of the foreign pipeline (green)

The pipelines to be protected terminate with insulating joints.
The liquid or gas transported by the pipeline is supposed to be non conductive.
Pipelines to be protected are eventually grounded by means of DC decoupling devices with infinite resistance at DC condition and for this reason neglected.
Of course, calculations in the following consider DC conditions.
The soil model as in 3 will be considered.
Other main data as in the following.

Pipeline to be protected:
- Layout: see Figure 4.1
- h = 1 m (axis depth)
- d = 300 mm (outer diameter excluding covering)
- t = 9.5 mm (metal wall thickness)
- ρm: 1.7 10^{-7} Ωm (steel)
- μrm: 300
- tc = 2.5 mm (covering thickness)
- ρc: 8 10^{5} Ωm (polyethylene)
- εrc: 5

Foreign pipeline:
- Layout: see Figure 4.1 (infinite length in both directions)
- h = 1.5 m (axis depth)
- Other data as for the pipeline to be protected

Polyethylene resistivity has been calculated considering a covering resistance “r = 2000 Ωm^2” related to a fair - good covering condition.
The infinite length condition of the foreign pipeline has been simulated at both ends with a transverse impedance corresponding to its characteristic impedance. As known, the characteristic impedance (in this case resistance) of a pipeline can be calculated as following:

$$Z = \sqrt{\frac{z}{y}} \qquad (4.1)$$

where:
- z (Ω/m) = longitudinal impedance per unit length
- y (S/m) = transverse admittance per unit length

As known, the general criterion for cathodic protection is:

$$E_l \leq E \leq E_p \qquad (4.2)$$

where:
- E (V) = potential of the pipeline with respect to the surrounding earth
- E_p (V) = protection potential
- E_l (V) = critical potential

The potential of the pipeline in case of insulated pipelines is very close to the potential of the pipeline with respect to the remote earth.
The protection potential depends on the corrosive environment and on the type of metal used.
Over the critical potential, the pipeline can be subject to hydrogen embrittlement or coating damage.
For buried steel pipe in normal conditions, the following potentials can be used:
- E_p = - 850 mV CSE
- E_l = - 1150 mV CSE

CSE indicates that potentials are relative to a copper/copper sulphate reference electrode.
By introducing the free corrosion potential of the pipeline metal "E_{nC}", previous condition can be rewritten as following:

$$E_l - E_{nC} \leq V \leq E_p - E_{nC} \qquad (4.3)$$

For buried steel pipe in normal conditions, the following free corrosion potential can be used:
- E_{nC} = - 550 mV CSE

The operative criterion for cathodic protection is then:
- -600 mV < V < -300 mV

The protection current density for buried and non perfectly insulated steel pipe can be calculated with the formula:

$$J_p = \frac{E_{on} - E_{off}}{r} \cong \frac{0.5}{r} \qquad (4.4)$$

where:
- J_p (A/m^2) = protection current density for insulated pipeline
- E_{on} (V) = pipeline potential with cathodic protection system "on"
- E_{off} (V) = pipeline potential with cathodic protection system "off"
- r (Ωm^2) = covering resistance

Using the data of the specific case, the protection current density is:
- J_p = 0.25 mA/m^2

The total current provided from the cathodic protection plant will be:

$$I = J_p S \qquad (4.5)$$

where:
- S (m^2) = pipeline outer surface

Using the data of the specific case, the total current provided from the cathodic protection plant will be:
- I = 15.74 A

The total current will be divided among three distinct cathodic protection plants (the current flowing by a single cathodic protection plant is usually among 5 and 50 A).
At first, the anodic groundbeds will be placed as in Figure 4.2.

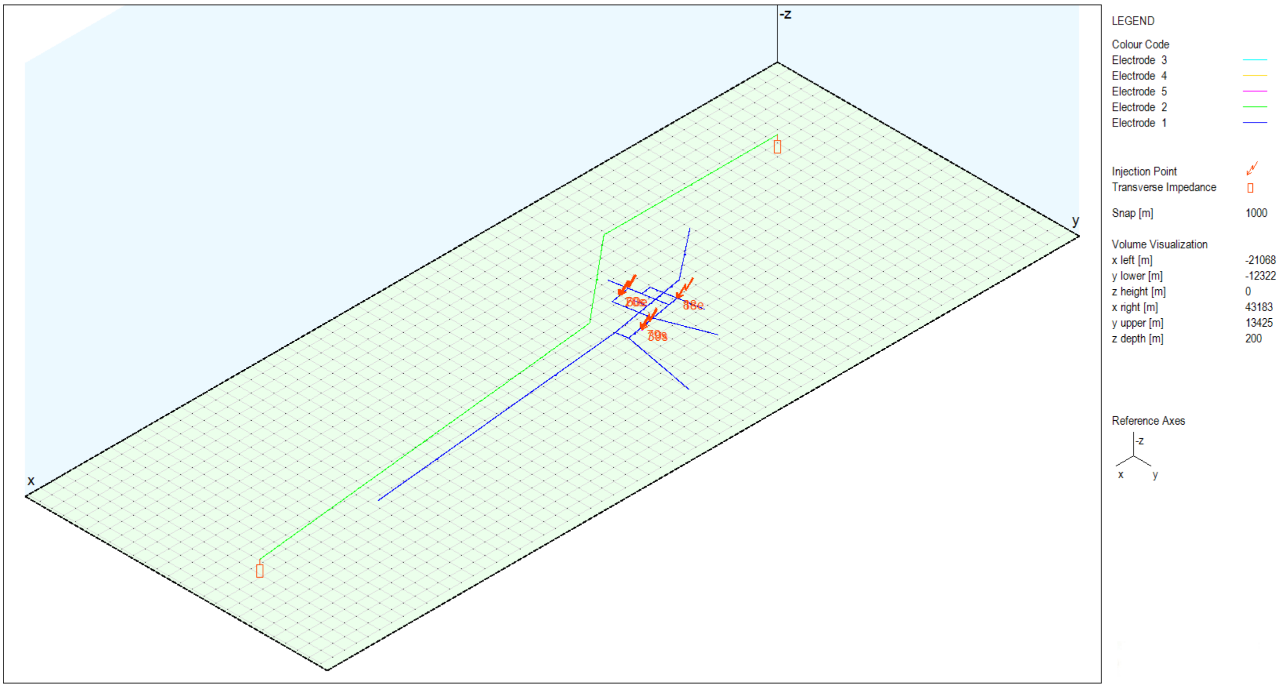

Figure 4.2: General layout including anodic groundbeds (red arrows)

Anodic groundbeds should be placed so as to ensure a uniform distribution of the protection current but in real cases, they will be placed taken into account the availability of a power supply for the cathodic protection stations. In the specific case, the distance between anodic groundbeds and pipeline is about 100 m, a compromise taking into account costs and effectiveness.

The anodic groundbeds will be deppwell type. Each anodic groundbeds will includes 10 anodes realized with MMO/Ti tubular bar with length 1 m and outer diameter 25 mm. Anodes will be uniformly distributed in the depth range between 60 and 80 m.

Each anodic groundbed will be backfilled with a low resistivity material with the purpose of decreasing the effective resistance between the anodes and the earth. In the specific case, calcinated petroleum coke has been considered.

At first, each anodic groundbed injects into the earth a current:

- Ia = 5 A

The consequent distributions of leakage current density and potential are represented in the following Figures.

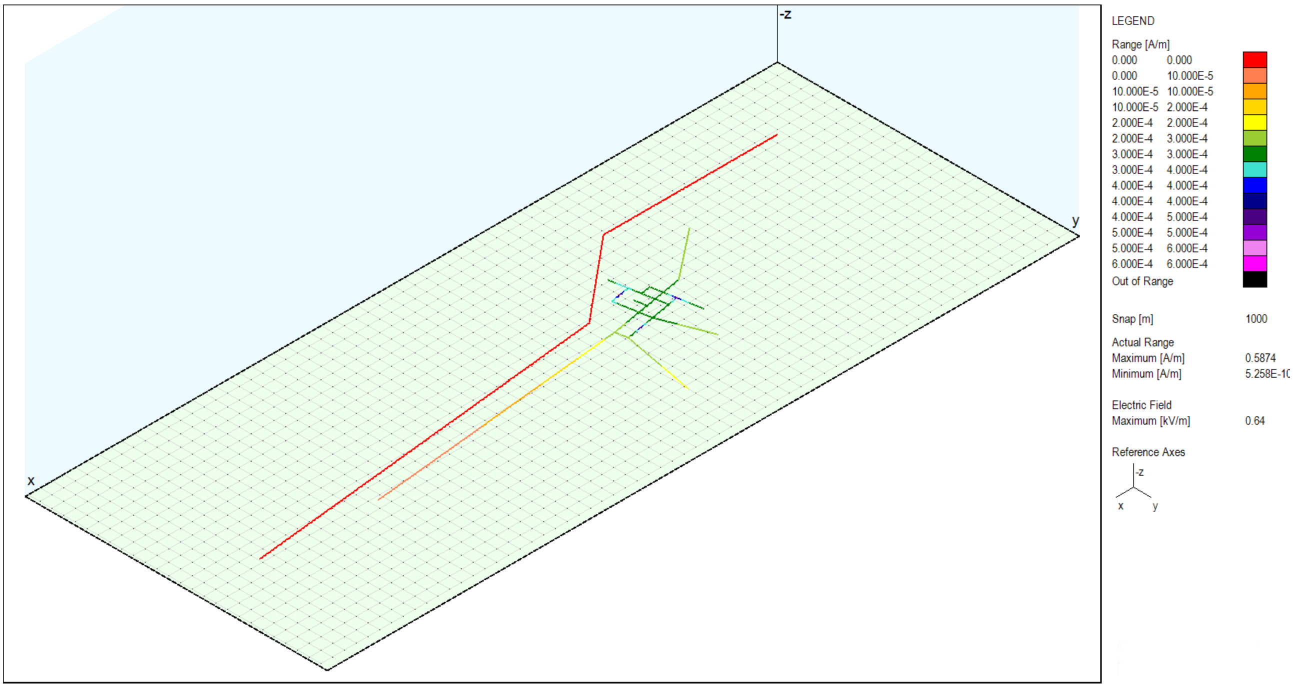

Figure 4.3: Leakage current density distribution (magnitude)

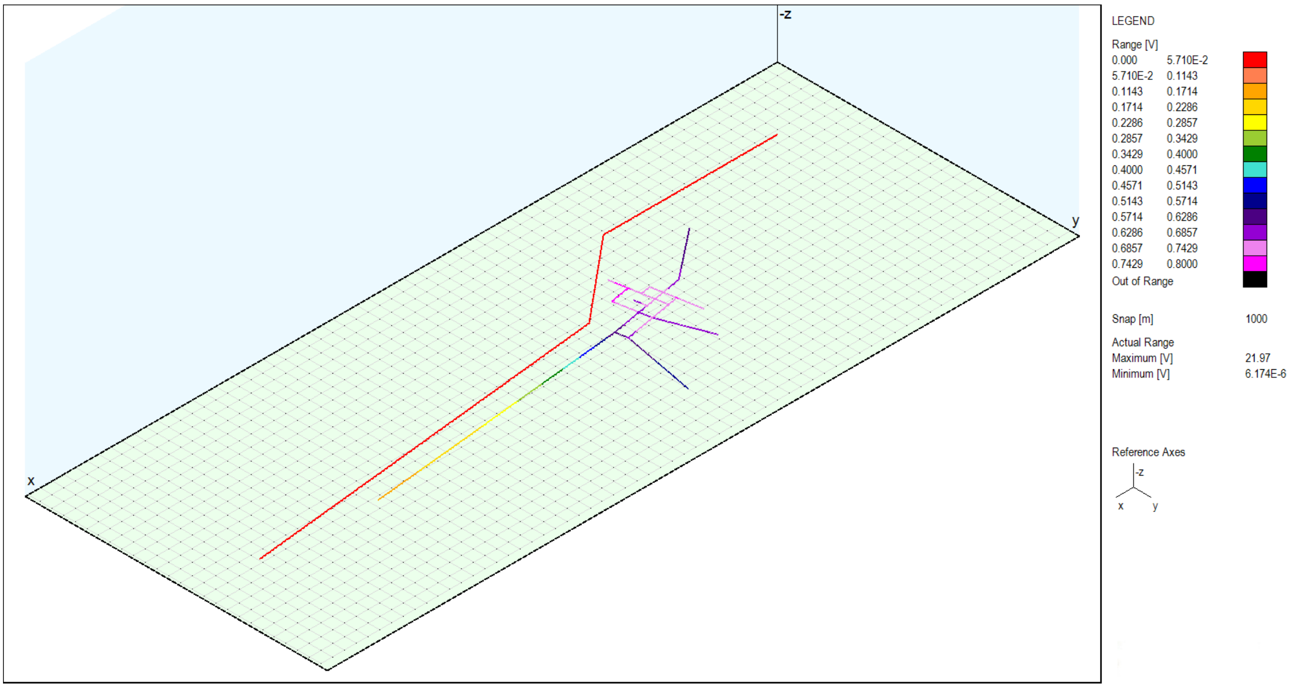

Figure 4.4: Potential distribution (magnitude)

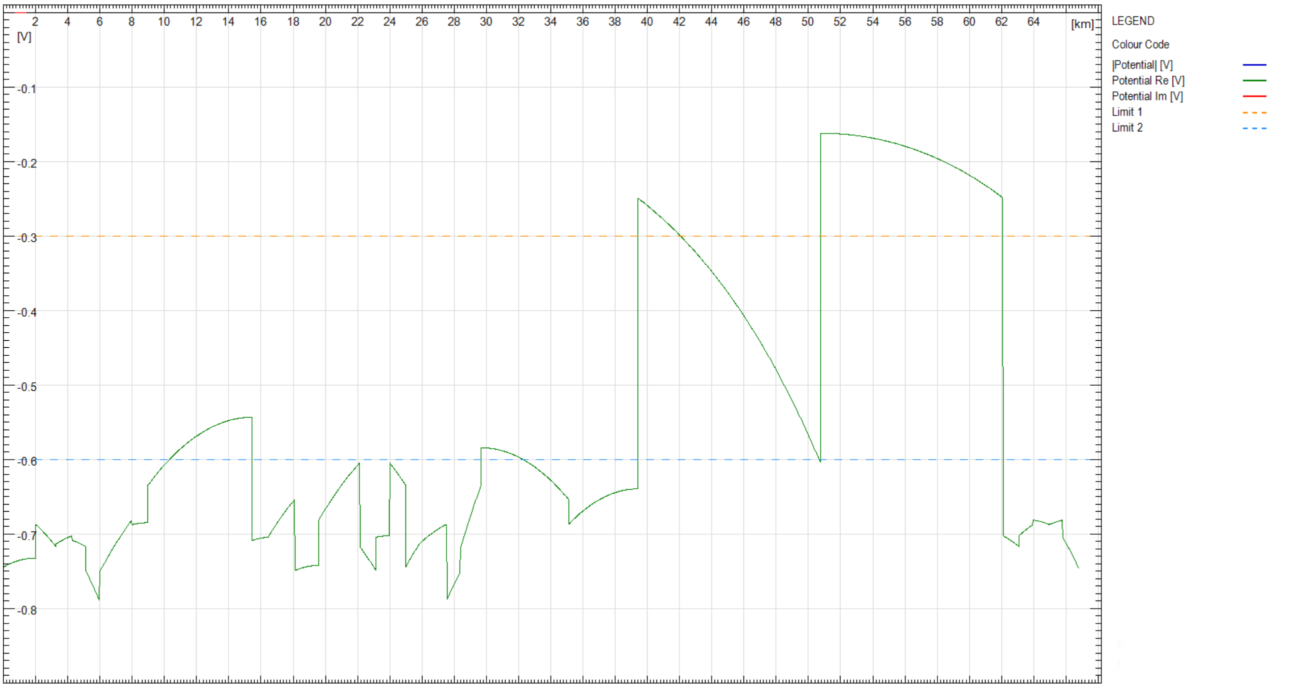

Figure 4.5: Potential distribution on pipeline to be protected

Figure 4.5 represents the potential distribution along a network of pipes and the discontinuities are related to the kind of representation that appends all the pipes. Anyway, Figure 4.5 indicates that some parts of pipeline are under protected (V > - 300 mV) and other parts are over protected (V < - 600 mV).

The situation can be improved by moving the anodic groundbeds or by modifying the anodic groundbeds current. Usually with one or two steps a good final solution can be reached.
In the specific case the final solution has been reached moving the anodic groundbeds as in Figure 4.6 and reducing the currents as follows:

- Ia = 4 A

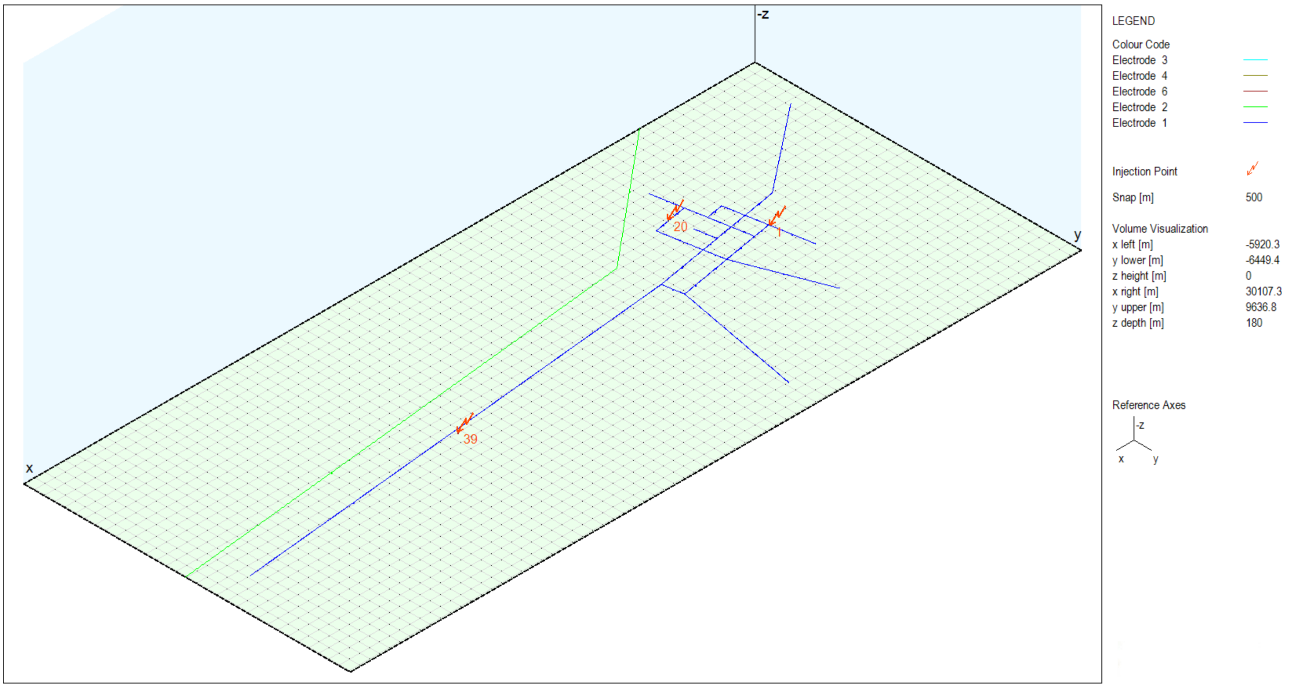

Figure 4.6: New general layout including anodic groundbeds (red arrows)

The new potential distributions is represented in Figure 4.7.

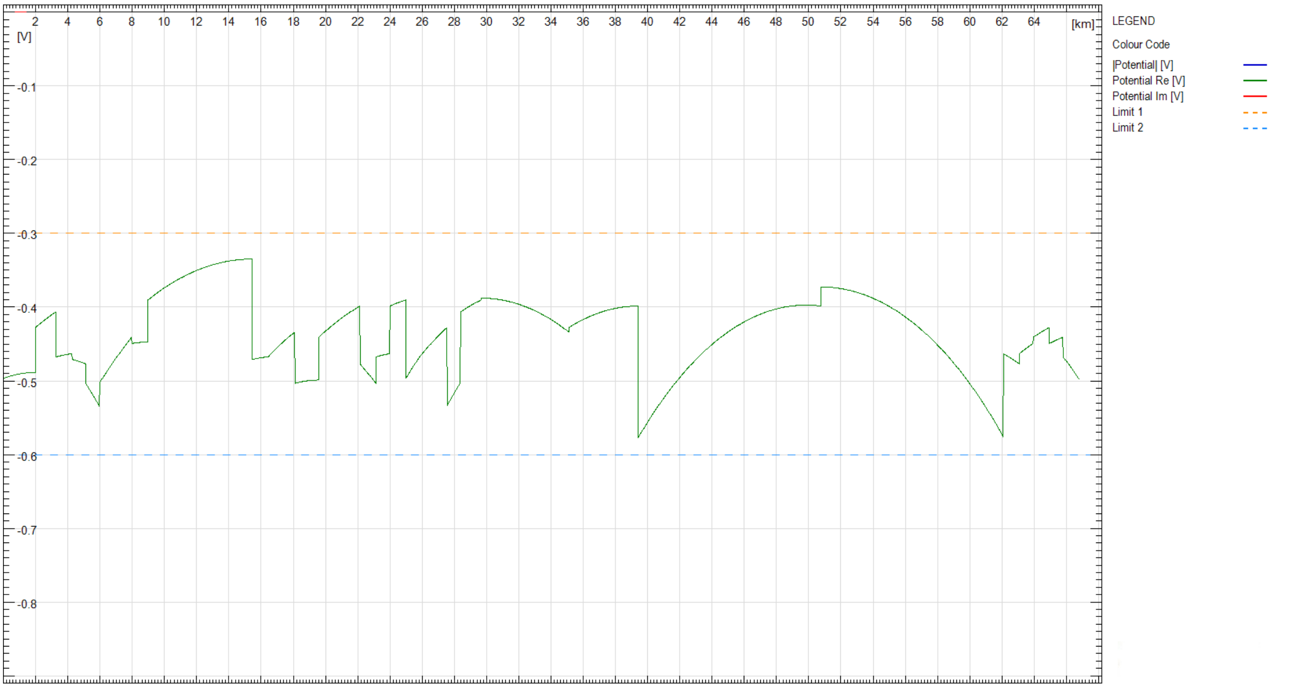

Figure 4.7: Potential distribution on pipeline to be protected

Figure 4.7 indicates that protection conditions are fulfilled everywhere.
Figure 4.8 represents the earth surface potential distribution in the pipeline area.
The sites where anodic groundbeds are placed are quite evident.

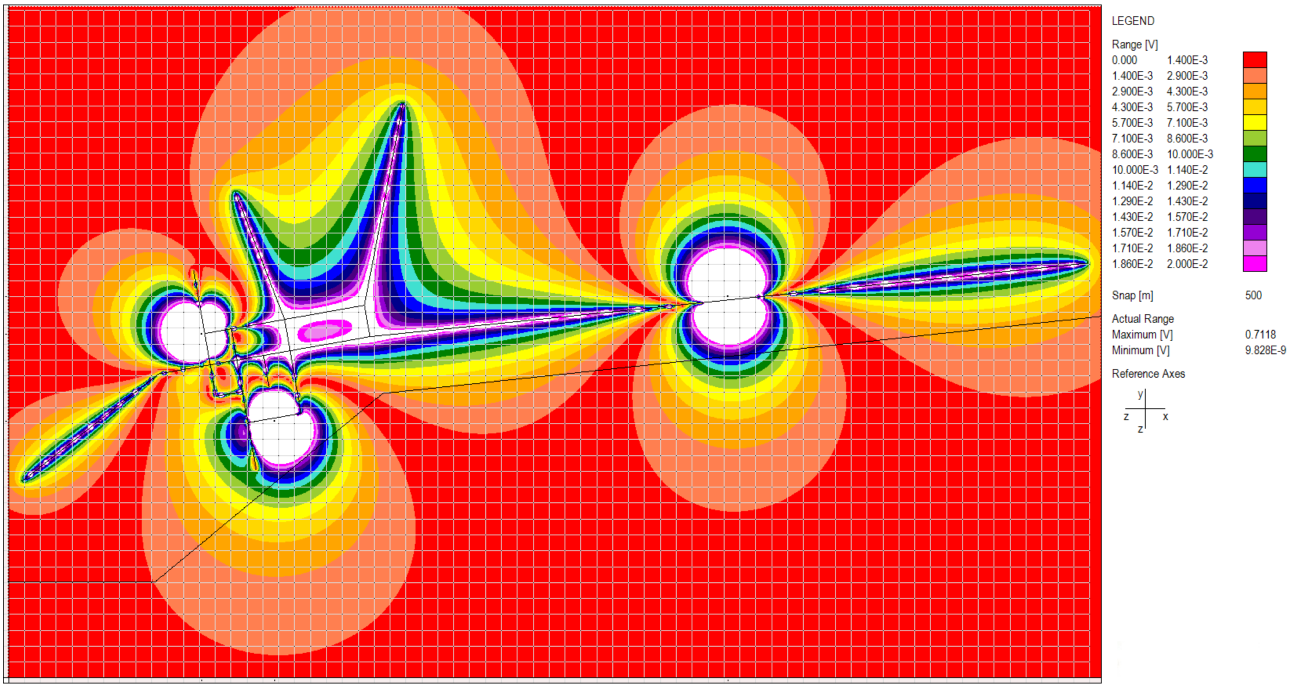

Figure 4.8: Earth surface potential distribution

The current density on MMO/Ti anodes with calcinated petroleum coke backfill has to be lower than 50 A/m^2.
It is easy to verify that this requirement is is widely fulfilled.

The voltage provided by each impressed current station can be calculated as follows:

$$V = V_A - V_C + R_{cable} I + \varphi^* \qquad (4.6)$$

where:
- V_A (V) = potential of Anode at the injection point given by the program
- V_C (V) = potential of Cathode at the injection point given by the program
- R_{cable} (Ω) = DC resistance of cables between A and C
- I (A) = protection current
- φ* (V) = sum of the electrode dissipative terms

In practical cases with titanium anodes:
- φ* = 2.2 – 2.9 V

Using copper conductor with cross section 50 mm^2 between A and C, taking into account a total cable length "l = 200 m" and considering φ* = 2.5 V, the voltage provided by the generators at the right side in Figure 4.8 is:
- V = 20.64 – 0.5473 + 0.0720 * 4 + 2.5 = 22.88 V

Nominal values of voltage and current of generators for cathodic protections should be double of the calculated values.
In the specific case generators with V = 50 V and I = 10 A should be considered.
In order to ensure safety condition for people and workers, it is appropriate that in all cases V < 50 V (rectifier output).

Regarding on the foreign pipeline, the condition is summed up in the following Figure.
A portion of the impressed currents of the cathodic protection plant is collected by the foreign pipeline.
Where the collected current leaves the pipeline and then where the leakage current is negative, there will be corrosion.

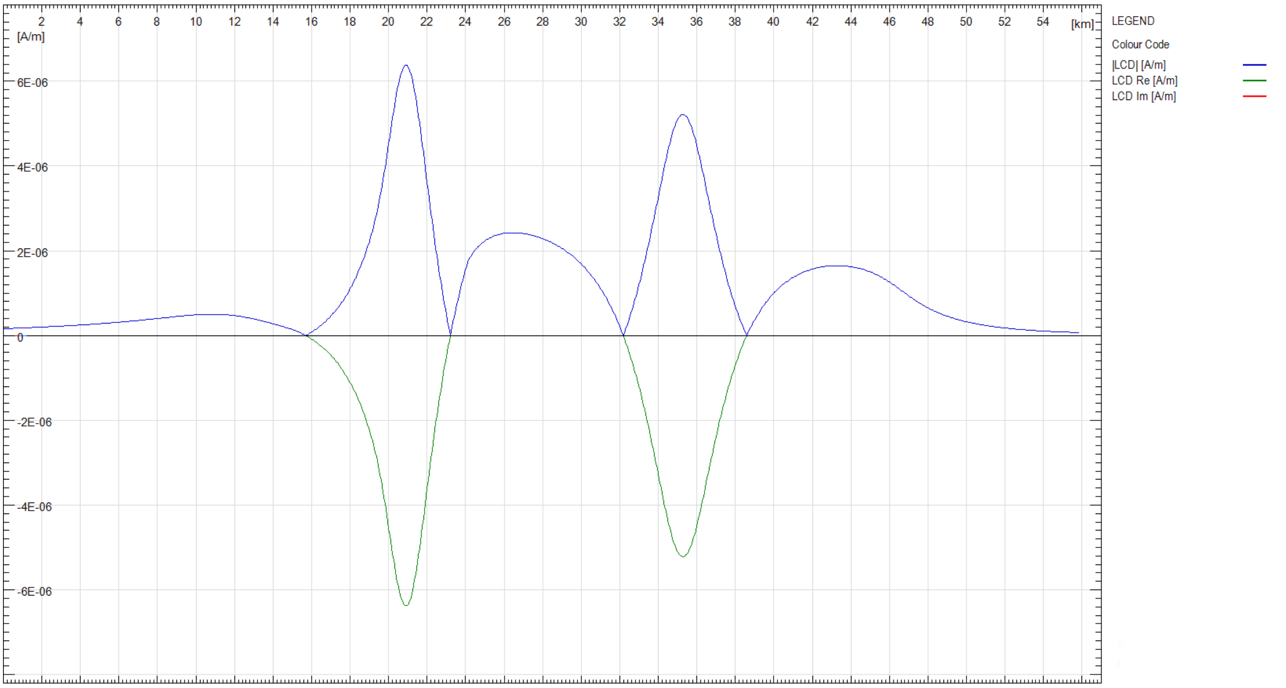

Figure 4.9: Leakage current density distribution along the foreign pipeline

5 – Electromagnetic Interferences

Cases of close proximity of substations or power lines and pipelines become more and more frequent and can give hazardous situation for people or damage to the pipeline or to the connected equipment.
The electromagnetic interference among substations or power lines and pipeline are due mainly to the conductive and inductive coupling respectively.
The electromagnetic interference causes an electromotive force along the pipeline and, as consequence, also longitudinal currents, leakage currents and potentials distributions.
As known, the conductive effects grow with the current to earth and with the soil resistivity and decrease with the distance between substations and pipeline.
Conductive effects appear only in case of fault to earth conditions.
The inductive effects grow with the power line current, with the length of the parallelism, with the soil resistivity and decrease with the distance between power line and pipeline [2].
Smaller inductive effects appear under steady state conditions while significant induced voltages appear under faulty conditions and in particular under single phase to earth fault condition. On the other hand, permissible induced voltages established by the standards are different for steady state and fault conditions. For these reasons, the electromagnetic interferences between power line and pipeline have to be evaluated in both steady state and faulty conditions.

As example, the electromagnetic interference between a distribution substation 220/20 kV and two overhead power lines 220 kV and an underground pipeline is evaluated.
In order to consider a more realistic case, a contemporary conductive and inductive interference is considered.
The main goal is to calculate the induced currents and voltages along the pipeline in faulty condition.
The general layout of the system of conductors is shown in Figure 5.1.

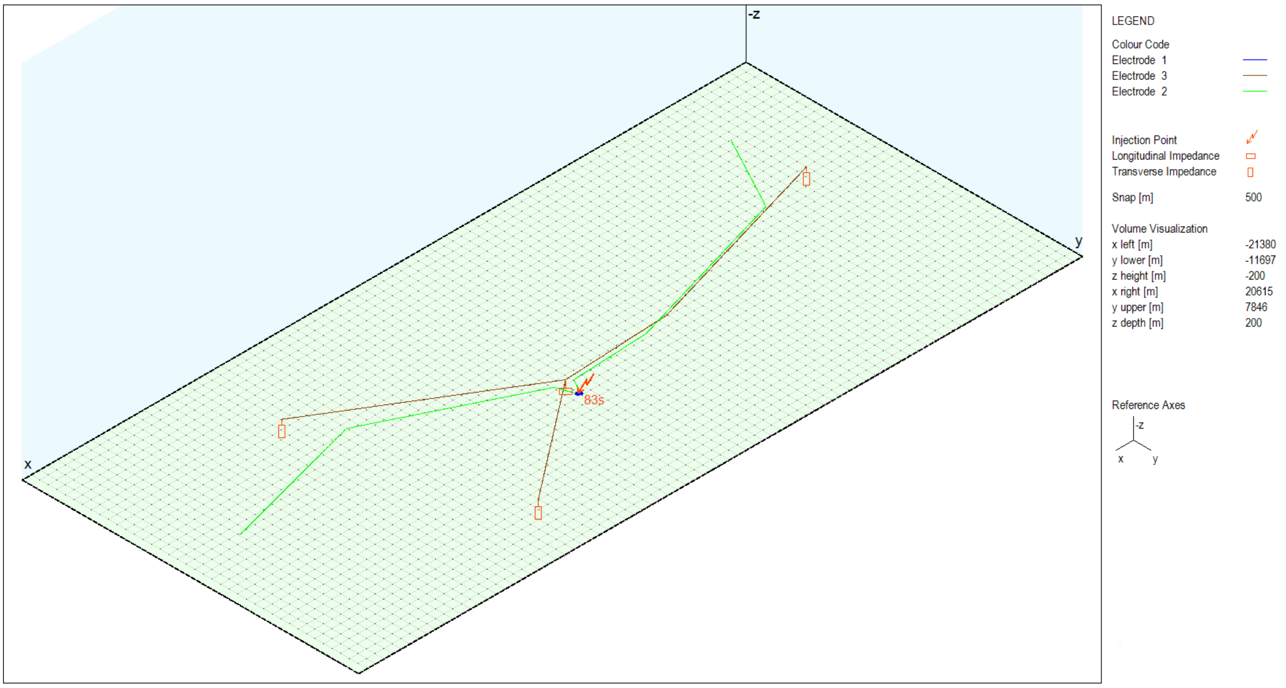

Figure 5.1: Layout of substation (blue), power lines (green) and pipeline (brown)

The soil model as in 3 will be considered.
Only the pipeline incoming the zone of influence of the power line is taken into account.
Based on [7], the width of the zone of influence can be calculated as follows:

$$d = 200\sqrt{\rho} \qquad (5.1)$$

where:
- ρ (Ωm) = resistivity of the bottom layer soil model

In the specific case:
- d = 1845 m

The substation representation is limited to its grounding system layout.
The overhead power line representation is simplified and takes into account only the phase conductor closest to the pipeline. The overhead earth wire screening effects are included in the calculation by applying a reduction factor "r" to the phase to earth fault current. The reduction factor depends on the number and self impedances of the overhead wires and on the mutual impedance between overhead wires and phase conductors and it is usually in the range 0.6 – 1.0.

$$r = \frac{I_e}{I_f} \qquad (5.2)$$

where:
- I_e (A) = current to earth
- I_f (A) = fault current

The model used in this case study is simplified but, in general conditions, it is possible to consider complex scenarios.
Other main data as in the following.

Power line:
- Layout: see Figure 5.1
- V = 220 kV
- f = 50 Hz
- h = 15 m (average height of the lowest phase conductor)
- I_f = 12.5 kA ∟0.0 deg (single phase to earth fault current)
- r = 0.8 (reduction factor)
- t_f = 0.35 s (clearance time)

The same data are used for both power lines connected to the substation.
The fault current direction in both cases are towards the substation.
The current to earth in the substation is then:

- I_e = 20 kA

Pipeline:

- Layout: see Figure 5.1 (infinite length in all directions and an insulating joint where indicate)
- The insulating joint is protected by a surge protection device with a low frequency discharge voltage 100 V
- Other data as for the pipeline to be protected in 4

Also in this case, the infinite length condition of the pipelines has been simulated with a transverse impedance corresponding to their characteristic impedances (this time referred to the frequency 50 Hz).

The potential distribution calculate along the pipeline has to be compared with the permissible voltage.
Usually Standards consider a permissible voltage for safety conditions of people and a different limit in order to avoid damage to the pipeline.
In fault conditions, Standard limits for safety conditions of people depend on the fault duration (for instance 1000 V if fault duration time is 0.35 s). This limits are referred to accessible metal parts.
The European standard limit (EN 50443 2012) in order to avoid damage to the pipeline in fault condition is 2000 V. This limit is referred to all parts.

The results of the interference are represented in the following Figures.
In the fists stage calculation, the surge protection device applied to the insulating joint is assumed not triggered. Figure 5.2 indicates that in this condition the difference between the potentials on the insulating join "V" is over the low frequency discharge voltage (100 V).

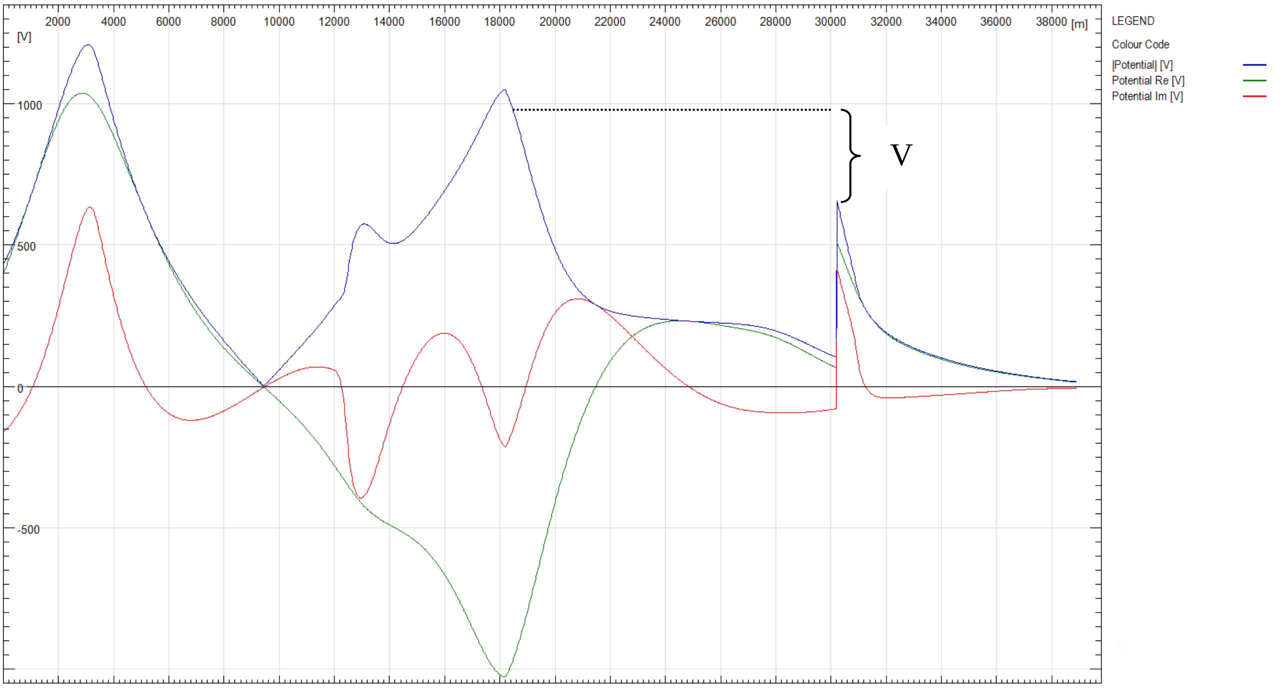

Figure 5.2: Potential distribution on pipeline with surge protection device not triggered

Figure 5.2 represents the potential distribution along a network of pipes and the discontinuities are related also to the kind of representation that appends all the pipes.
In the second stage calculation, the surge protection device is assumed triggered. Figure 5.3 indicates that the induced potentials are higher than the permissible values for safety conditions of people (1000 V).

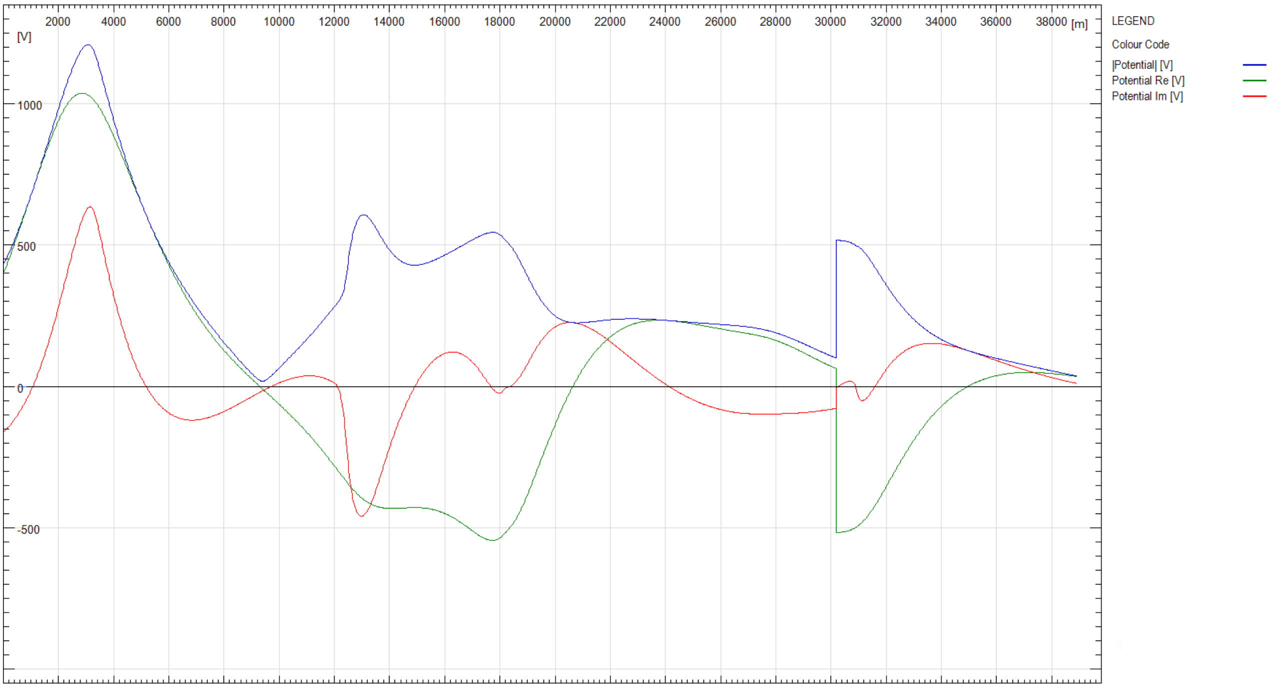

Figure 5.3: Potential distribution on pipeline with surge protection device triggered

As mitigation measure, two additional resistances to earth (2 Ω each) are applied to the pipeline in the spans around the highest potentials. These earth resistances in steady state condition are not active because connected to the pipeline via surge protection devices.

In the third stage calculation, the surge protection devices of insulating joint and of pipeline earthings are assumed triggered. Figure 5.5 indicates that the induced potentials are lower than the permissible values for safety conditions of people (1000 V), and then, also in order to avoid damage to the pipeline (2000 V).

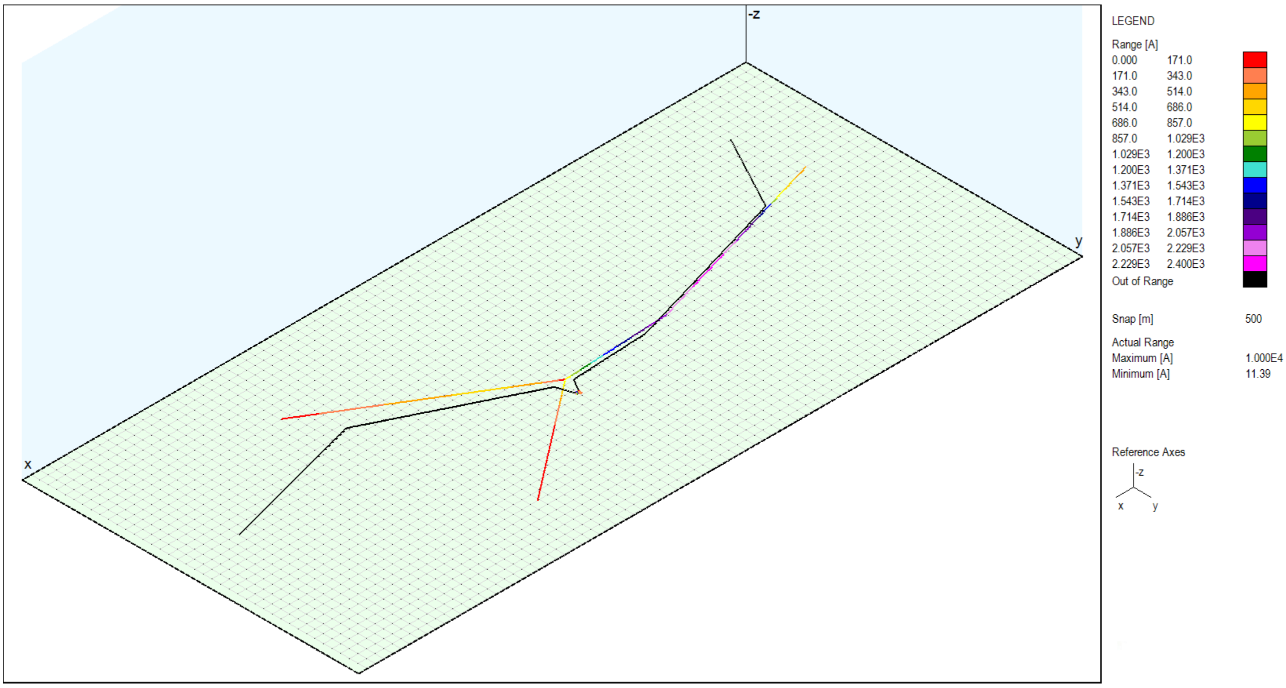

Figure 5.4: Current distribution on pipeline (magnitude)

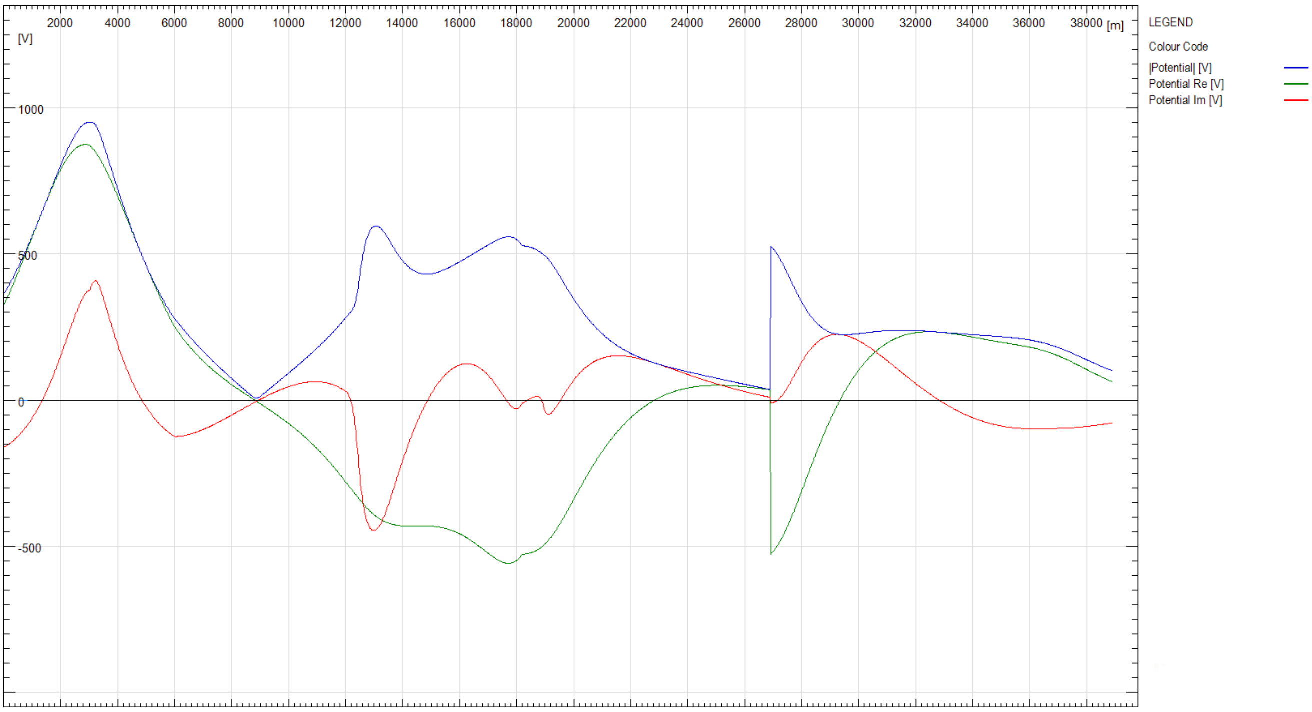

Figure 5.5: Potential distribution on pipeline with all surge protection devices triggered

Figure 5.6 represents the earth surface potential distribution in the interfering area.
The effects of the substation is quite evident.

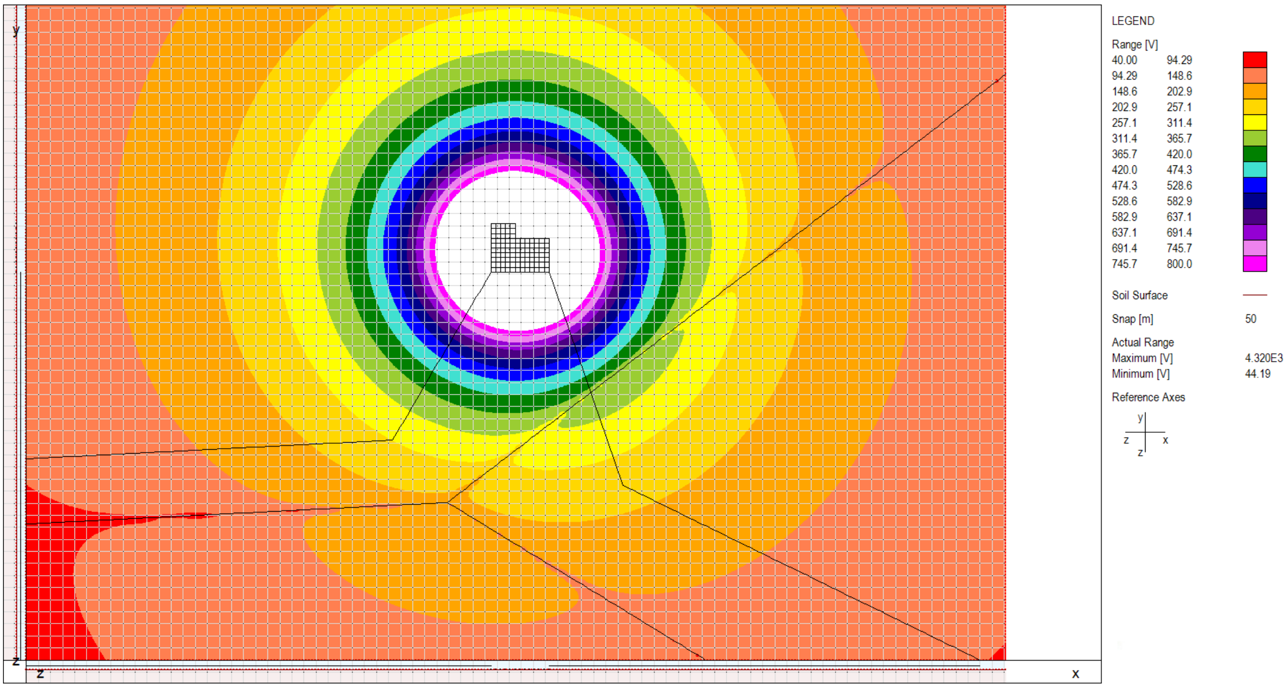

Figure 5.6: Earth surface potential distribution

6 – Conclusions

This paper describe the model implemented in a commercial software for electromagnetic simulations and two possible applications at low frequency.

In particular this paper describes the sizing of a cathodic protection with an impressed current system of a buried steel pipeline, and the evaluation of the electromagnetic interferences between a distribution substation and two overhead power line and a buried steel pipeline.

The cases study used in both applications are simplified, but it is easy to understand that in general conditions complex and realistic scenarios can be simulated. The system of conductors can include many conductors arranged and connected in an arbitrary way in the 3D space. The system of conductors can be energized both with current or electromotive force, or with voltages induced by conductive, capacitive or inductive coupling. Moreover the electric model of the system of conductors can include additional longitudinal or transversal impedance. The soil may be

represented with a layered or with a multizone model.
All these options are made possible by the used hybrid model, and the accuracy of the results make the used software a very interesting design tools.

References:

[1] XGSLab User's Guide and Tutorial, Rel. 6.4.2 (www.xgslab.com).

[2] E.D. Sunde, Earth Conduction Effects in Transmission Systems, first ed., D. Van Nostrand Company Inc., New York, 1949.

[3] S. Ramo, J.R. Whinnery, T. Van Duzer, Fields and Waves in Communication Electronics, first ed., Wiley International Edition, New York and London, 1965.

[4] L. Lazzari, P. Pedeferri, Protezione Catodica, second ed., CLUP, Milan, 1982 (in Italian).

[5] ITU / CCITT DIRECTIVES Volume III, Capacitive, inductive and conductive coupling: physical theory and calculation methods, Geneva (1989).

[6] F.P. Dawalibi, R.D. Southey, Analysis of Electrical Interference from Power Lines to Gas Pipelines – Part I: Computation Methods, IEEE Transactions on Power Delivery, Vol. 4, No. 3, July 1989, pp. 1840 – 1846.

[7] CIGRE WG 36.02 doc. 95 "Guide on Influence of High Voltage AC Power System an Metallic Pipelines" (1995).

[8] Electro Magnetic Transient Program Theory Book, Bonneville Power Administration, Portland, Oregon, 1995.

[9] L.D. Grcev, Computer analysis of Transient Voltages in Large Grounding Systems, IEEE Transactions on Power Delivery, Vol. 11, No. 2, April 1996, pp. 815 – 823.

[10] R. Andolfato, L. Bernardi, L. Fellin, Aerial and Grounding System Analysis by the Shifting Complex Images Method, IEEE Transactions on Power Delivery, Vol. 15, No. 3, July 2000, pp. 1001 – 1009.

[11] L.D. Grcev, V. Arnautovski Toseva, Grounding System Modeling for High Frequencies and Transient: Some Fundamental Considerations, IEEE Power Tech Conference Proceedings, Bologna (2003).

[12] CIGRE WG C4.501 doc. 543 "Guide for Numerical Electromagnetic Alaysist Method and its Appliction to Surge Phenomena" (June 2013).

[13] D. Cavka, N. Mora, F. Rachidi, A Comparison of Frequency Dependent Soil Models: Application to the Analysis of Grounding Systems, IEEE Transactions on Electromagnetic Compatibility, Vol. 56, No. 1, February 2014, pp. 177 – 187.