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Electromagnetic Interferences between Power Systems and Pipelines. Field Vs. Circuit Theory based Models

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ABSTRACT

The simulation of the electromagnetic interferences between power lines and pipelines at power frequency (50 or 60 Hz) is today a topic of great interest. The reason why this interest is related to the increasing number of situations of interference, but also to the increasing interference effects due to the more performing covering used in modern pipelines.
The theory related to the electromagnetic interferences phenomenon is directly derived from Maxwell equations and it is well known. The soil reaction can be calculated using the Sommerfeld integrals, a set of equations developed about 100 years ago but still not very well known and difficult to manage.
Anyway, Maxwell equations and Sommerfeld integrals can be used for the calculation of the electromagnetic interferences in practical cases only using numerical methods implemented in computer programs.
The numerical methods suitable for electromagnetic interferences simulations can be divided in two classes; field theory based and circuit theory based.
The methods based on field theory are general and rigorous but also time consuming in the modelling stage. On the other side, the methods based on the circuit theory in some case are easier in the modelling stage but their accuracy it is not always adequate.
This document gives an overview and a comparison between field and circuit based models suitable for electromagnetic interferences simulations.

Keywords: Electromagnetic Interferences, Computer Modelling, PEEC, Phase Component Method

INTRODUCTION

This document gives an overview about numerical models suitable for electromagnetic interferences simulations.
The models described in this document are implemented in the XGSLab™ simulation environment [13], [14] and in particular in the modules XGSA_FD™ (based on the field theory model) and NETS™ (based on the circuit theory model).

The first part gives a synthetic description of the reference theory (Maxwell equations and Sommerfeld integrals).
The second part gives a short description of the numerical methods PEEC (Partial Element Equivalent Circuit) and PCM (Phase Component Method).
The third part compares results from models based on field and circuit theory in some particular cases.

THEORY

The electromagnetic interferences are governed by the Maxwell equations. The Maxwell equations in differential form and in the frequency domain taking into account the constitutive relations are the following:

$$rot\mathbf{H} = \mathbf{J} + j\omega\dot{\varepsilon}\mathbf{E} \tag{1}$$

$$rot\mathbf{E} = -j\omega\mu\mathbf{H} \tag{2}$$

$$div\left(\dot{\varepsilon}\mathbf{E}\right) = q \tag{3}$$

$$div\left(\mu\mathbf{H}\right) = 0 \tag{4}$$

where H indicates the magnetic field, J the current density, E the electric field and q the charge density.

A first important consequence of the Maxwell equations is the charge conservation law that links charge to current density:

$$div\mathbf{J} = -j\omega q \tag{5}$$

The properties of the propagation medium can be essentially described by the conductivity σ (or the resistivity ρ=1/σ), the permittivity ε and permeability μ. The complex permittivity, conductivity and resistivity are linked by the following equations:

$$\dot{\varepsilon} = \varepsilon + \frac{\sigma}{j\omega} = \frac{\dot{\sigma}}{j\omega} = \frac{1}{j\omega\dot{\rho}} \tag{6}$$

The permeability of the propagation media involved in electromagnetic interferences between power system and pipelines, i.e. air and soil, can be considered uniform and equal to the free space permeability.

The Maxwell equations can be expressed also in an alternative form using the vector potential A and the scalar potential U. This approach reduces the unknowns of the problem from six (E_x, E_y E_z, H_x, H_y H_z) to four (A_x, A_y, A_z, U).

The vector potential can be defined as follows:

$$\mathbf{H} = \frac{1}{\mu} rot\mathbf{A} \tag{7}$$

Using (2) it follows:

$$rot(\mathbf{E} + j\omega\mathbf{A}) = 0 \tag{8}$$

An irrotational vector can be expressed as gradient of a scalar potential.

Using the scalar potential U it follows:

$$\mathbf{E} = -gradU - j\omega\mathbf{A} \tag{9}$$

However, A and U are not yet uniquely determined. It is possible to impose an extra condition using the Lorentz gauge condition:

$$U = -\frac{1}{\mu\dot{\sigma}} div\mathbf{A} = -\frac{\dot{\rho}}{\mu} div\mathbf{A} \tag{10}$$

Using (10), U can be derived from A and is not strictly necessary to calculate it separately.

Using A, U and the Lorentz gauge condition, the Maxwell equations can be rewritten according to the following two inhomogeneous and decoupled wave equations also called Helmholtz equations:

$$\Delta\mathbf{A} - \gamma^2\mathbf{A} = -\mu\mathbf{J} \tag{11}$$

$$\Delta U - \gamma^2 U = -\frac{q}{\dot{\varepsilon}} \tag{12}$$

In previous equations, Δ indicates the Laplace operator (Δ=div grad), and γ indicates the coefficient of propagation of the medium:

$$\gamma = \sqrt{j\omega\mu(\sigma + j\omega\varepsilon)} \tag{13}$$

The Helmholtz equations indicate that A is related only to currents while U is related only to charges. The solutions of the Helmholz equations for an unbounded uniform medium are given by the following two integrals:

$$\mathbf{A} = \frac{\mu}{4\pi}\int_{V_J} \mathbf{J}\frac{e^{-\gamma r}}{r}dv \tag{14}$$

$$U = \frac{1}{4\pi\varepsilon}\int_{V_q} q\frac{e^{-\gamma r}}{r}dv \tag{15}$$

were V_J and V_q are respectively the space regions where currents and charges density distributions are present.
If currents and charges are bordered in thin conductors, previous integrals on volumes can be replaced by the following integrals along the conductor axis L:

$$\mathbf{A} = \frac{\mu}{4\pi}\int_{L} I\frac{e^{-\gamma r}}{r}dl\hat{\mathbf{l}} \tag{16}$$

$$U = \frac{1}{4\pi\dot{\varepsilon}}\int_{L} q\frac{e^{-\gamma r}}{r}dl \tag{17}$$

In previous equations, l is the length variable along the conductor axis L, and r represents the distance from a source point along the conductor axis and the field point.
According to (5), the charge density distribution q can be replaced with the leakage current density distribution –dI/dl, and (17) can be then replaced with the follows:

$$U = -\frac{1}{4\pi\dot{\sigma}}\int_{L} \frac{dI}{dl}\frac{e^{-\gamma r}}{r}dl \tag{18}$$

The equations (16) and (18) are the base for numerical integral methods. Some methods like MoM (Method of Moments) use equations (16) and (10), other methods like PEEC use equations (16) and (18).

At low frequency, it is usually possible to apply the quasi static approximation. In such case, the coefficient of propagation effects can be neglected and (16) and (18) became:

$$\mathbf{A} = \frac{\mu}{4\pi}\int_{L} I\frac{1}{r}dl\hat{\mathbf{l}} \tag{19}$$

$$U = -\frac{1}{4\pi\dot{\sigma}}\int_{L} \frac{dI}{dl}\frac{1}{r}dl \tag{20}$$

This assumption simplify the calculations but can be used only if the size r of the system composed by sources and victims of the electromagnetic interference is small if compared to the wavelength of the electromagnetic field λ and then if:

$$r << \lambda = \frac{2\pi}{\sqrt{\pi f \mu_0 \sigma}} \cong 3162\sqrt{\frac{\rho}{f}} \qquad (21)$$

At power frequency, this condition is generally fulfilled but it must be checked in case of large system size or small soil resistivity.

So far the propagation medium has been supposed uniform and extended to the infinite.
In the reality, many systems used in the practice lie in the air on in the soil but anyway close to the soil surface and then, close to the interface between two propagation media with very different properties. In the range of the frequencies of interest, the air can be consider a dielectric medium, and the soil can be considered a conductive medium but unfortunately not a perfect conductor, which would greatly simplify the treatment.
The electromagnetic fields and the scalar and vector potentials are affect by the presence of these different media. If the two media can be represented as two half spaces divided by an unbounded and flat surface, the problem can be approached using the Sommerfeld integrals. The Sommerfeld integrals allow to calculate the vector potential in the surrounding of an infinitesimal Hertz's dipole placed horizontally or vertically close to the interface that divides two linear and isotropic half spaces. In other words, Sommerfeld integrals represent the exact solution of the Maxwell equations related to an infinitesimal Hertz's dipole in the presence of a lossy half space, taking into account the continuity conditions at the half space interface.

The components A_x and A_z of an horizontal dipole are the following:

$$A_x = \frac{\mu}{4\pi}\left(G - G_i + U\right) Idl \qquad (22)$$

$$A_z = \frac{\mu}{4\pi}\frac{\partial W}{\partial x} Idl \qquad (23)$$

The component A_z of a vertical dipole is the following:

$$A_z = \frac{\mu}{4\pi}\left(G - G_i + V\right) Idl \qquad (24)$$

A dipole with an arbitrary inclination can be represented as a combination of an horizontal and a vertical dipole.

In previous equations:

$$G = \frac{e^{-\gamma_e r}}{r} \quad r = \sqrt{a^2 + h^2} \quad h = s - z \qquad (25)$$

$$G_i = \frac{e^{-\gamma_e r_i}}{r_i} \quad r_i = \sqrt{a^2 + h_i^2} \quad h_i = s + z \qquad (26)$$

$$U = \int_0^\infty \frac{2\lambda e^{-\alpha_e (s+z)}}{\alpha_e + \alpha_a} J_0\left(\lambda a\right) d\lambda \qquad (27)$$

$$V = \int_0^\infty \frac{2\lambda \dot{\sigma}_a e^{-\alpha_e (s+z)}}{\alpha_e \dot{\sigma}_a + \alpha_a \dot{\sigma}_e} J_0\left(\lambda a\right) d\lambda \qquad (28)$$

$$W = \int_0^\infty \frac{2\lambda \left(\dot{\sigma}_a - \dot{\sigma}_e\right) e^{-\alpha_e (s+z)}}{\left(\alpha_e + \alpha_a\right)\left(\alpha_e \dot{\sigma}_a + \alpha_a \dot{\sigma}_e\right)} J_0\left(\lambda a\right) d\lambda \qquad (29)$$

$$\alpha_e = \sqrt{\lambda^2 + \gamma_e{}^2} \tag{30}$$

$$\alpha_a = \sqrt{\lambda^2 + \gamma_a{}^2} \tag{31}$$

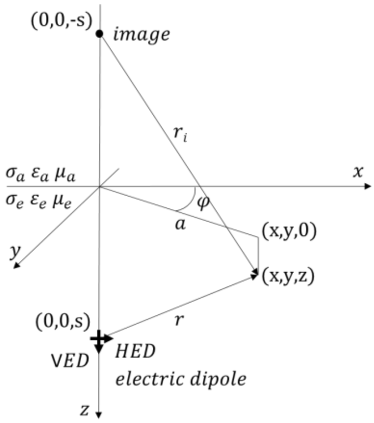

Figure 1 - Reference system for Sommerfeld integrals

In (27), (28) and (29), J_0 indicates the Bessel functions of first kind and zero order.
The discussion about the Sommerfeld integrals is clearly out of the scope of this document and the reader can find any detail in [1].

Eexcept for a few special cases, the Sommerfeld integrals cannot be calculated analytically. Also the Numerical Quadrature of the Sommerfeld integrals poses difficulties related to the slow decaying, oscillatory behaviour and poles of the integrand and requires special techniques using the zeros of the Bessel function and accelerating convergence algorithm. The Numerical Quadrature of Sommerfeld integrals is anyway a time consuming task.
An interesting option to calculate the Sommerfeld integrals is based on the finitely conducting earth image theory proposed by Bannister and Dube [5]. This approximation can be obtained by means of mathematical manipulations of the Sommerfeld integrals. The basic idea is to approximate the Sommerfel integrals with the effects of only a few spherical wave functions with closed form.

Anyway it is clear Maxwell equations and Sommerfeld integrals in general can be calculated only using numerical methods.

NUMERICAL METHODS

Numerical methods suitable for solving Maxwell equations and Sommerfeld integrals in general conditions have been developed starting on the last decades of previous century and the development of computer technology and numerical technique have made a decisive contribution to their progress and diffusion.
Numerical methods can consider electrodes with an arbitrary shape and size, and can consider the effects of self and mutual impedances, propagation, ionization …, but anyway, for engineering applications, they require some approximation with regard to soil modelling. The use of approximate soil models such as the multilayer or multizone model is commonly adopted ad accepted.

The numerical methods suitable for electromagnetic interference belonging to the so-called Numerical Electromagnetic Analysis (NEA) methods used to study electromagnetic transients in power systems. There is not a general consensus in the classification of NEA methods and these short notes will not be able to clarify the differences and peculiarities of all the various available methods.
In general it is clear that the accuracy and the application range of a method is more extensive as the approximations introduced with respect to the Maxwell equations and Sommerfeld integrals are smaller. In this sense, a first distinction is between: 1) full-wave, 2) quasi-static and 3) static methods.

The methods able to solve the complete set of Maxwell equations without simplifying assumptions are classified as full-wave methods. These methods can be applied in general.
In some conditions, essentially at low frequency, the quasi-static assumption can be used. In these conditions, the Maxwell equations can be simplified, the fields are assumed time-invariant / frequency-independent. The numerical approach is simplified and the calculation is faster.

Another simple and effective classification of the suitable numerical methods can be the following [10]:

- Circuit theory and transmission line based methods: these methods are based on equivalent circuits with lumped or distributed elements respectively. Both methods require a discretization of the system into electromagnetically coupling small sections. Each section is represented with lumped or distributed resistance, inductance or capacitance often calculated with analytical formulas. The calculation of distributed parameters is usually related to assumption of a quasi TEM propagation. Kirchhoff laws are used to assemble elements impedance and field sources in a single complete model. Usually these methods can be applied in a limited frequency range
- Electromagnetic Field Differential methods: these methods solve the Maxwell equations written in differential form in the space of interest partitioned in elements. Due to limitations in memory, only a finite space domain is considered in simulation, and appropriate boundary conditions are used in order to represent the space extension to infinite. These methods could be very accurate and can consider very realistic scenarios and arbitrary inhomogeneity of the propagation medium but usually they require considerable hardware resources and do not allow to represent large systems as they are in reality. The most diffused methods based on this approach are the finite difference time domain (FDTD) method and the finite element method (FEM)
- Electromagnetic Field Integral methods: these methods solve the Maxwell equations written in integral form. In this case, the discretization is applied not to the propagation medium but to the surface of the field sources. This reduces significantly the problem dimension in open space problems, the usual condition for engineering applications. The most diffused methods based on this approach are the MoM and PEEC methods

Taking into account the difficulty with open space problems of the methods based on the differential form of the Maxwell equations, the most interesting methods for electromagnetic interference analysis are essentially the MoM and PEEC methods.

The PEEC method was developed after 1990 and is then more recent than the MoM, and moreover it offers the important advantage of not requesting post process calculations to obtain potentials rises along the conductors.
The PEEC is the method used in the commercial software considered in this document.

In some conditions and in particular at low frequencies, methods based on the circuit theory

can offer a good option to the methods based on the field theory.
This document will compare results calculated using field and circuit theory in some particular cases.

The PEEC Method
In the following, the PEEC formulation is limited to thin structures with currents and charges constrained along conductor axes.
The PEEC method for thin structures is based on the continuity of the tangent axial component of the total electric field on the conductor surface.
If the conductor is real with an internal impedance per unit length z_i, and the current flowing along the conductor is I, the total electric field on his surface can have tangent components equal to the internal voltage drop per unit length along the conductor axes and continuity condition is:

$$E = \left(z_i + z_c \right) I - E_e \tag{32}$$

Outside the conductor, the electric field E is related to scalar potential U and vector potential A resulting from charges and currents distributions along the conductor axes according to the following general equation:

$$E = -\frac{\partial U}{\partial l} - j\omega A \tag{33}$$

Combining (32) and (33), it is immediate to obtain the following general differential equation:

$$\left(z_i + z_c \right) I + j\omega A + \frac{\partial U}{\partial l} = E_e \tag{34}$$

Equation (34) is valid in full-wave conditions with the only assumption of thin wire structures.
The vector and scalar potential in a generic point of the propagation medium associated to the current and charge or leakage current distributions along the conductor axis L can be expressed using (16) and (18) in case of uniform medium and using Sommerfeld integrals in the presence of a conducting half space.

In order to implement previous equations in a numerical model, the system of conductors is preliminarily partitioned in short elements composed of current and potential (or charge) cells (see Figure 2). The distribution of currents, leakage currents and potentials along the conductor axis are both approximated with pulse functions. Current and potential cells are interleaved each other. In each current cell, longitudinal current is uniform. The same, in each potential cell, the leakage current density (or charge density) and the potential are uniform. The current and potential values are assumed as the average values along the cell. Using these simple discernments is possible to convert previous differential equation in a linear system.

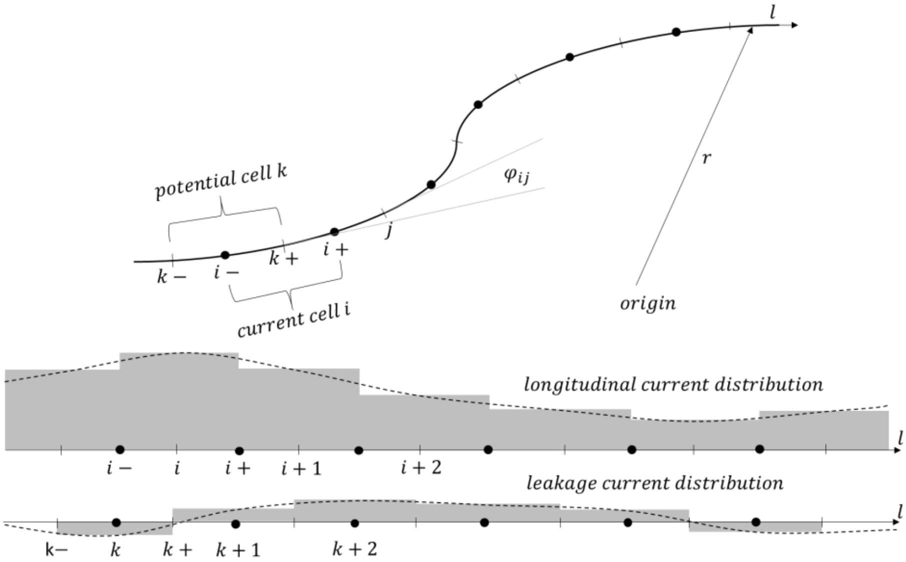

Figure 2 - Interleaved current and potential cells

Let us consider a generic current cell i with length li and end points i- and i+.
With the above assumptions on current distributions, the integral of (34) along the cell i can be rewritten as follows:

$$Z_{si} I_i + \sum_{j \neq i} Z_{mij} I_j + \sum_k W_{i_+ k} J_k - \sum_k W_{i\_k} J_k = E_{ei} \qquad (35)$$

The meanings of previous parameters are shortly the following:

- $Z_{s\,i}$ represents the self impedance of an element, that is the sum of internal, coating and external impedance
- $Z_{m\,I,j}$ represents the mutual inductive coupling between two elements
- $W_{i,i}$ represents the self coefficient of potential of an element
- $W_{i,j}$ represent the mutual conductive and capacitive coupling between two elements

The calculation of previous parameters are out of the scope of this document. Of course, the evaluation of such parameters is crucial, as anticipated, the PEEC method is full-wave but its application range depends on the accuracy in the calculation of its parameters.

Previous equations are related to the equivalent circuit of a PECC current cell as illustrated in the Figure 3.

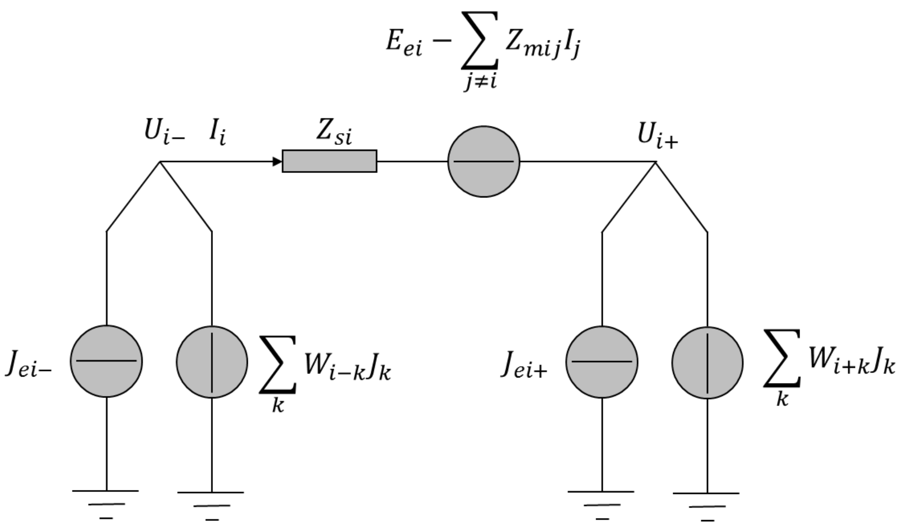

Figure 3 - Equivalent circuit of a PEEC current cell i

With the previous formulations, the Maxwell equations have been rewritten in a linear equation where the unknowns are currents and leakage currents.

In general, the system of conductors will be fragmented in N cells also called elements or segments. Each cell introduces two unknowns, the longitudinal current and the leakage current in cell. The total number of unknowns is anyway 2N. In order to have a determined linear system is then necessary to have 2N independent linear equations.
Equation (35) provides N equations. The missing N equations can be obtained by applying the first Kirchhoff to each cell, eventually taking into account also a forced injection current J_e.
For the potential cell k it follows:

$$I_{k_+} + J_{ek} - I_{k_-} - J_k = 0 \qquad (36)$$

The 2N equations can be assembled in a complete model in a single determined linear system.
The system of conductors can be energized with voltage generators, with current generators or with induced electromotive force or potentials due to inductive, capacitive or conductive couplings as already seen.
At the end, the solution of the linear system gives the distribution of longitudinal current, leakage current and potentials along the system of conductors.
With a post processing calculation is then possible to calculate the distribution of potential, electric and magnetic fields in each point of the propagation medium.
The calculation of these quantities can be performed as superposition effects of each single cell. This is possible if the system is linear, which is a fundamental requirement.

The PEEC approach in the frequency domain can be extended to the time domain using Fourier direct and inverse transforms.

The PCM

Using the PEEC method, the Maxwell equations have been rewritten in a linear system of equations where the unknowns are currents and leakage currents. A similar system of equation can be obtained also directly by using the circuit theory. The two systems will be different, but in some conditions, results can be substantially equivalent.
As known, the analysis of electrical networks can be done using the graphs theory and essentially using the following two methods:

- SCM (Sequence or Symmetrical Components Method)

- PCM (Phase Components Method)

The SCM is based on the Kirchhoff laws and the Fortescue technique and in some conditions is rigorous, in other conditions acceptable, in other conditions not applicable. Essentially, the SCM cannot be used in case of multiple grounded systems or in case of problems that involve currents to earth. This is typically the situation involved in electromagnetic interference condition.

The PCM is based only in the Kirchhoff laws and is for general applications with balanced or unbalanced systems and with symmetrical and unsymmetrical systems. The PCM works in multi-conductor mode, so it increases the size of the linear system involved with the problem and requires considerable memory resources and computing power.
But this is not a problem with modern computers.

In order to apply the PCM, the electrical network is divided in cells connected through buses.
A cell indicates a multi-port cell with one or more group of ports as represented in Figure 4.

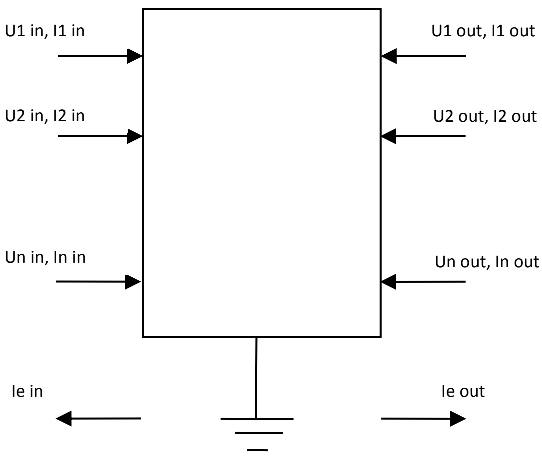

Figure 4 - Generic two sides cell

A bus can be represented as a multi-port connector as indicated in Figure 5.

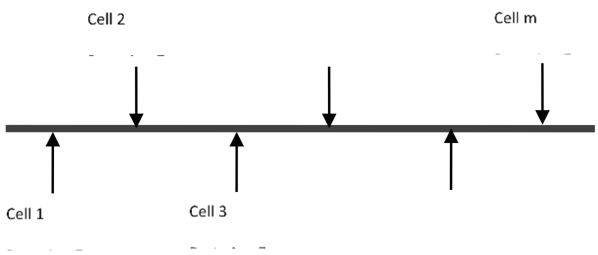

Figure 5 - Generic bus

If Ii and U_i indicate currents and potentials at port i, and p indicates the number of ports of the cell, using the Kirchhoff equations inside the cell it is possible to obtain the system of equation:

$$\left[A_{p\times 2p}\right]\begin{Bmatrix}\{\dot{I}_p\}\\ \{\dot{U}_p\}\end{Bmatrix}=\{N_p\} \tag{37}$$

For all cells, if P indicates the total number of ports, the system is:

$$\left[A_{P\times 2P}\right]\begin{Bmatrix}\{\dot{I}_P\}\\ \{\dot{U}_P\}\end{Bmatrix}=\{N_P\} \tag{38}$$

The missing P equations can be calculated at the bus connections and then from the network topology. For all cells and buses, the final system is:

$$\begin{bmatrix}\left[A_{P\times 2P}\right]\\ \left[B_{P\times 2P}\right]\end{bmatrix}\begin{Bmatrix}\{\dot{I}_P\}\\ \{\dot{U}_P\}\end{Bmatrix}=\begin{Bmatrix}\{N_P\}\\ \{0_P\}\end{Bmatrix} \tag{39}$$

The matrix of the linear system (39) is usually strongly sparse and can be stored and solved using specific numerical routines.
With a limited number of cells (Sources, Longitudinal and Transverse Impedances, Lines, Cables, Conductors, Transformers …) it is possible to represent any kind of network.

Again, at the end, the solution of (39) gives currents and potentials at each port. The module used, includes a special cell (called Hybrid) where it is possible to mix cables, lines and conductors like pipelines, railroads ... This cell has been developed also for the calculation of electromagnetic interferences between power lines and pipelines when they lie parallel or can be represented as series of parallel conditions using the approach in [7].

It is important to remember that the PEEC method considers the ends effects related to the use of short conductors. The PCM is based on the assumption of a quasi TEM propagation and uses equations based on the assumption of conductors infinite long, parallel and horizontal and the ends effects are not taken into account.
This, together with the difference in fragmentation can imply differences in results.

Infinite Conductor Modelling

In order to represent the extension to infinite of a conductor, it is possible to use its characteristic impedance:

$$Z_0=\sqrt{\frac{z}{y}} \tag{40}$$

where:

Z_0 (Ω) = characteristic impedance

z (Ω/m) = self impedance

y (S/m) = admittance to earth

If the conductor is a long pipeline, tacking into account that pipelines are usually coated, self-impedance and transverse admittance can be calculated using the following equations:

$$z=z_{\text{int}}+z_{coat}+z_{ext} \tag{41}$$

$$z_{\text{int}} = \sqrt{j\omega \frac{\rho_m \mu_m}{\pi^2 d^2}} \tag{42}$$

$$z_{coat} = j\omega \frac{\mu_0}{2\pi} \ln \frac{d + 2t_c}{d} \tag{43}$$

$$z_{ext} = j\omega \frac{\mu_0}{2\pi} \left(\ln \frac{4}{1.78\dot{\gamma}_e d} + \frac{1}{2} - \frac{4}{3} \dot{\gamma}_e h \right) \tag{44}$$

$$\gamma_e \cong \sqrt{j\omega \frac{\mu_0}{\rho_e}} \tag{45}$$

$$y = 2\pi \left(\frac{1}{\rho_c} + j\omega\varepsilon_c \right) \frac{1}{\ln \frac{d + 2t_c}{d}} \tag{46}$$

where:

$\omega = 2\pi f$ (rad/s) = angular frequency

z_{int} (Ω/m) = internal impedance

z_{coat} (Ω/m) = coating impedance

z_{ext} (Ω/m) = external impedance of an infinite long conductor

ρ_m (Ωm) = resistivity of the pipeline wall

μ_m (H/m) = permeability of the pipeline wall

d (m) = pipeline outer diameter coating excluded

t_c (m) = pipeline coating thickness

γ_e (1/m) = earth propagation constant

ρ_e (Ωm) = earth propagation resistivity

h (m) = pipeline depth referred to the pipe axis

ρ_c (Ωm) = resistivity of the pipeline coating

ε_c (H/m) = permittivity of the pipeline coating

COMPARISON BETWEEN FIELD AND CIRCUIT BASED MODELS

The methods based on field theory are general and rigorous but also time consuming in the modelling stage. On the other side, the methods based on the circuit theory is some case are easier in the modelling stage but their accuracy it is not always adequate.

In the following the comparison between these methods is limited to two cases and to final results. i.e. the induced current and potential from a power system to a pipeline.

The first case is related to an interference scenario where power system and pipeline are parallel (near and far). This scenario can be found in case of share corridors or in railways.
The second case is related to an interference scenario where power system and pipeline are not parallel.

Power System and Pipeline Parallel
In this first case, power system and pipeline are considered parallel.
Power System main data:
- Rated voltage: 220 kV
- Frequency: 50 Hz
- Average span: 400 m
- Tower foot resistance to earth: 10 Ω
- Phase conductor: ACSR, diameter 31.5 mm
- Sky wire: Al, diameter 11.5 mm
- Single phase to earth current: 10 kA

Pipeline main data:
- Outer diameter: 300 mm
- Wall: Steel, thickness 9.5 mm
- Covering: PE 20 years, thickness 2.5 mm
- Axis depth: 1 m
- Characteristic impedance: 0.964 + j 0.751 Ω

Other data:
- Interference length: 10 km
- Horizontal distance from tower and pipeline axes: 20 m
- Soil resistivity: 100 Ωm
- Layout: see Figure 6

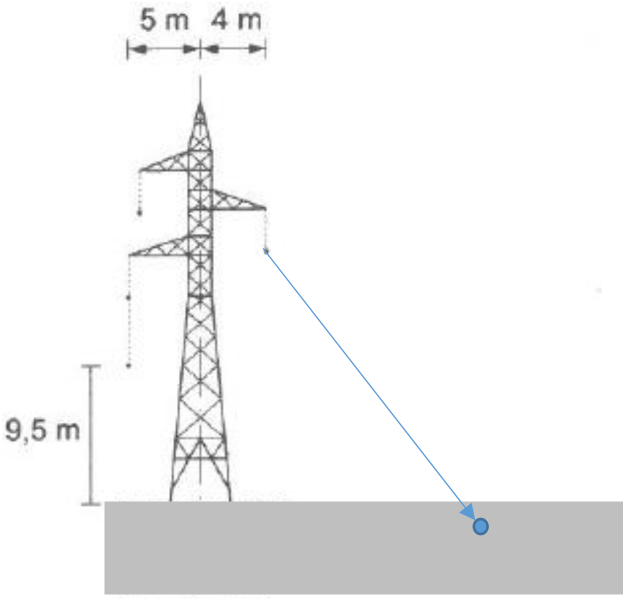

Figure 6 – Power system and pipeline

In following figures the distribution of induced current and potential calculated with field and circuit theory respectively.

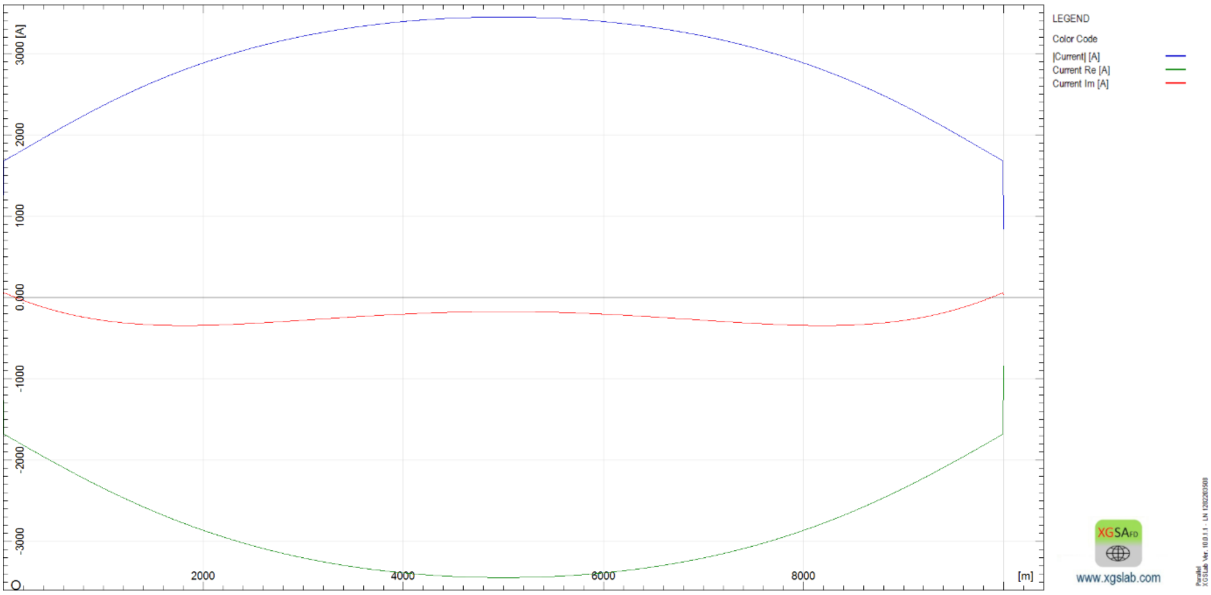

Figure 7 – Induced current distribution on pipeline - Field theory 20 m

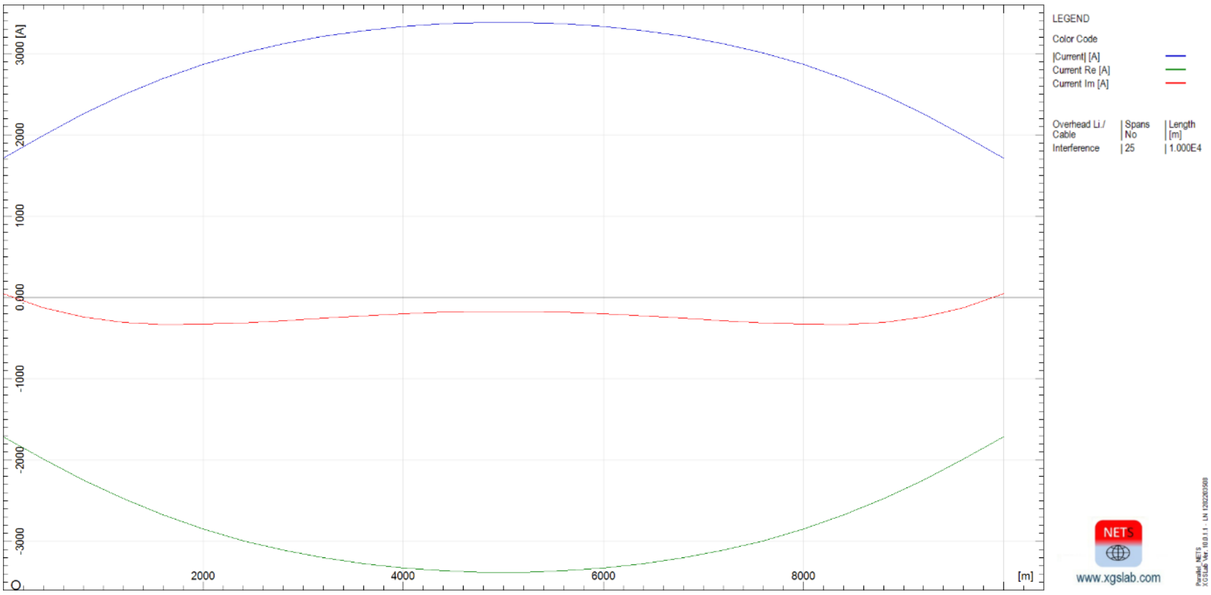

Figure 8 – Induced current distribution on pipeline - Circuit theory 20 m

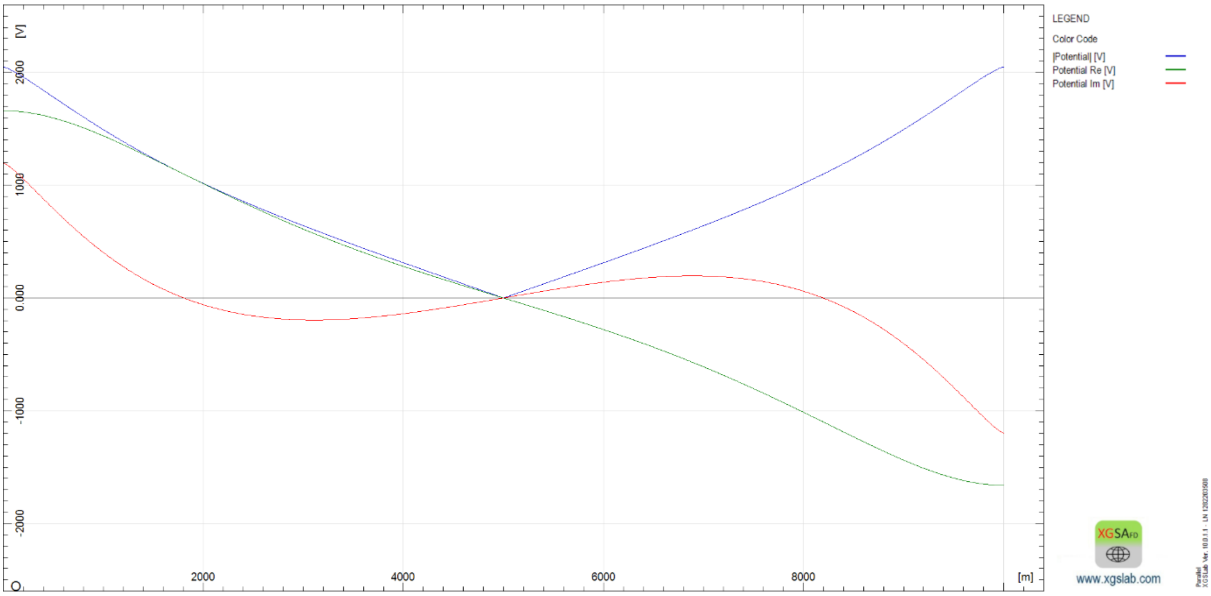

Figure 9 – Induced potential distribution on pipeline - Field theory 20 m

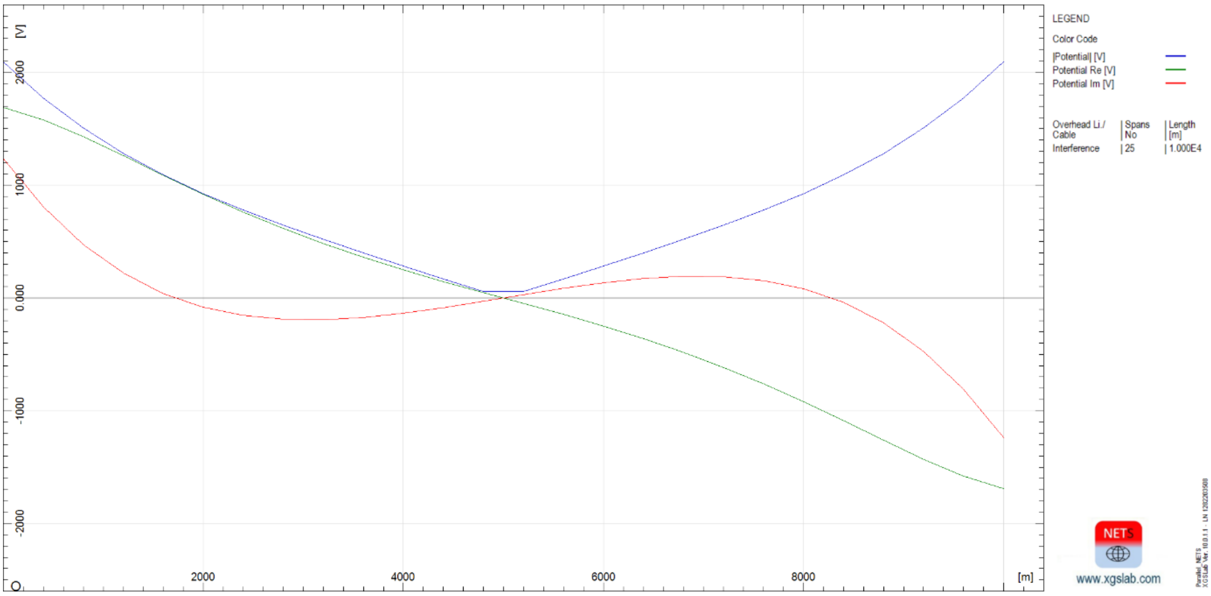

Figure 10 – Induced potential distribution on pipeline - Circuit theory 20 m

The agreement between results calculated using field and circuit theory is excellent.
The only visible differences are related to the induced potential distribution at the pipeline ends. This can be related to the end effects and it was expected.

In following figures the same results but with an horizontal distance from tower and pipeline axes 500 m.

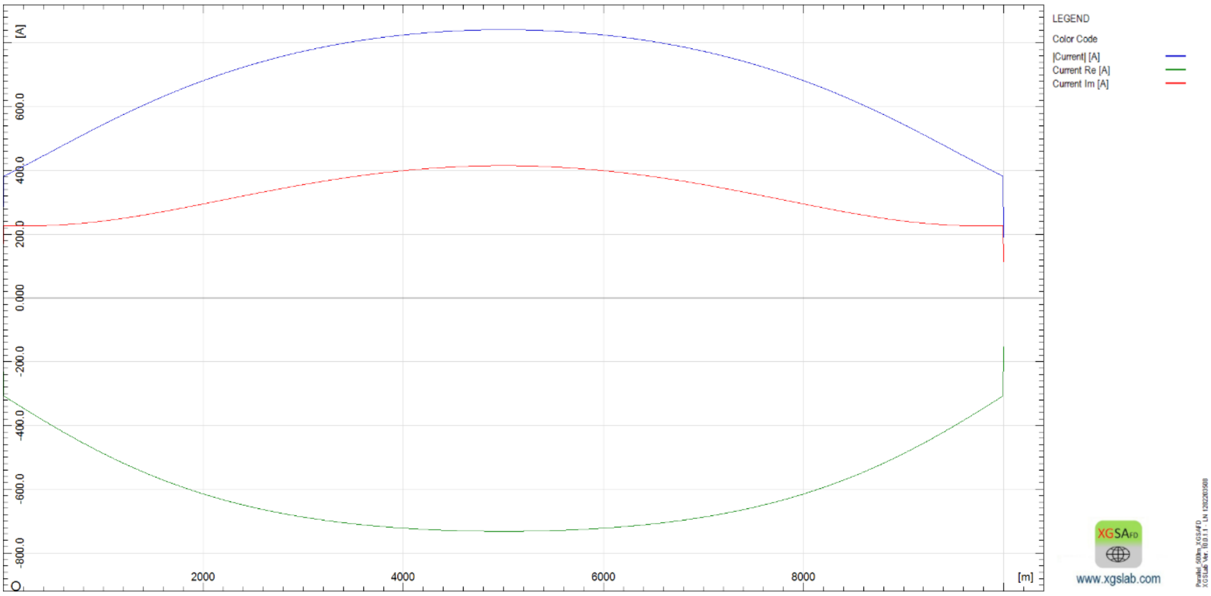

Figure 11 – Induced current distribution on pipeline - Field theory 500 m

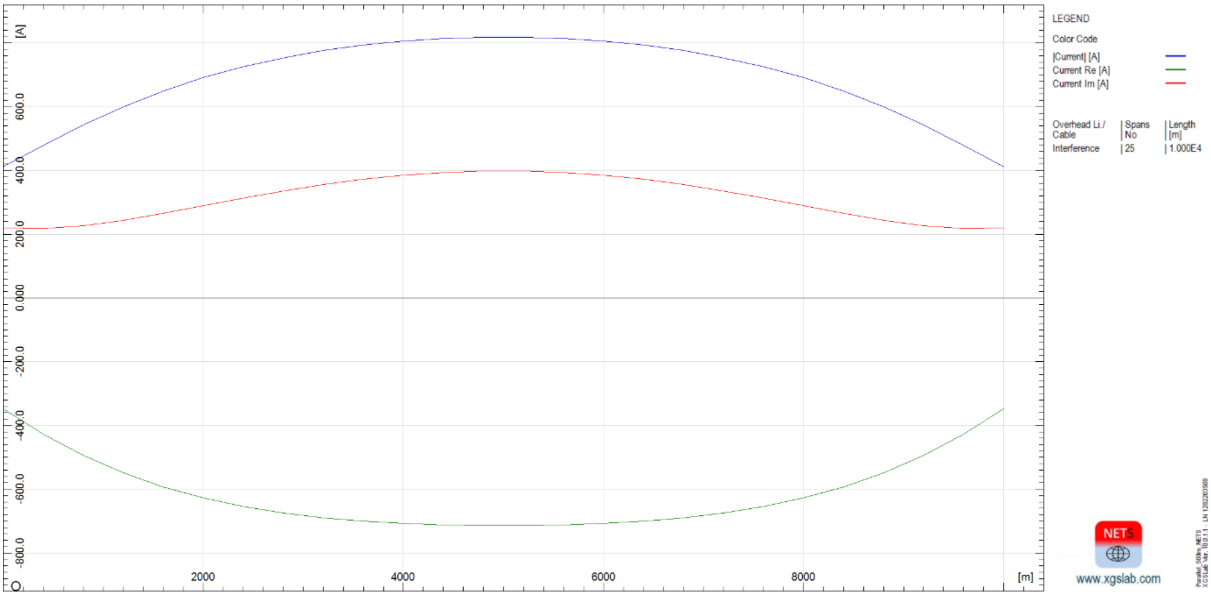

Figure 12 – Induced current distribution on pipeline - Circuit theory 500 m

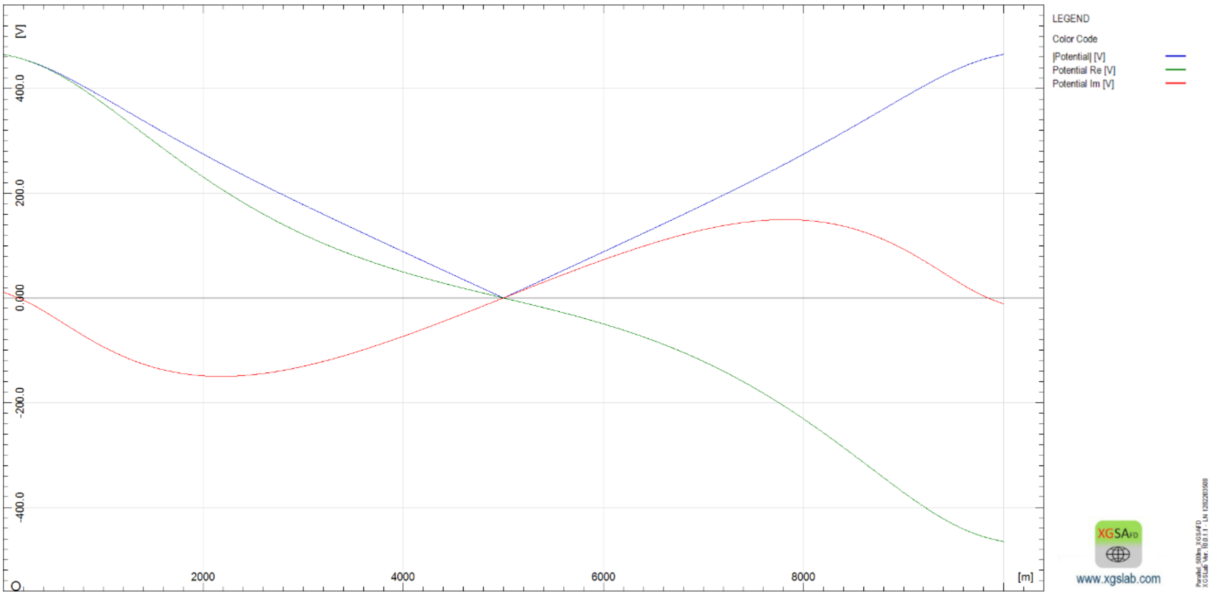

Figure 13 – Induced potential distribution on pipeline - Field theory 500 m

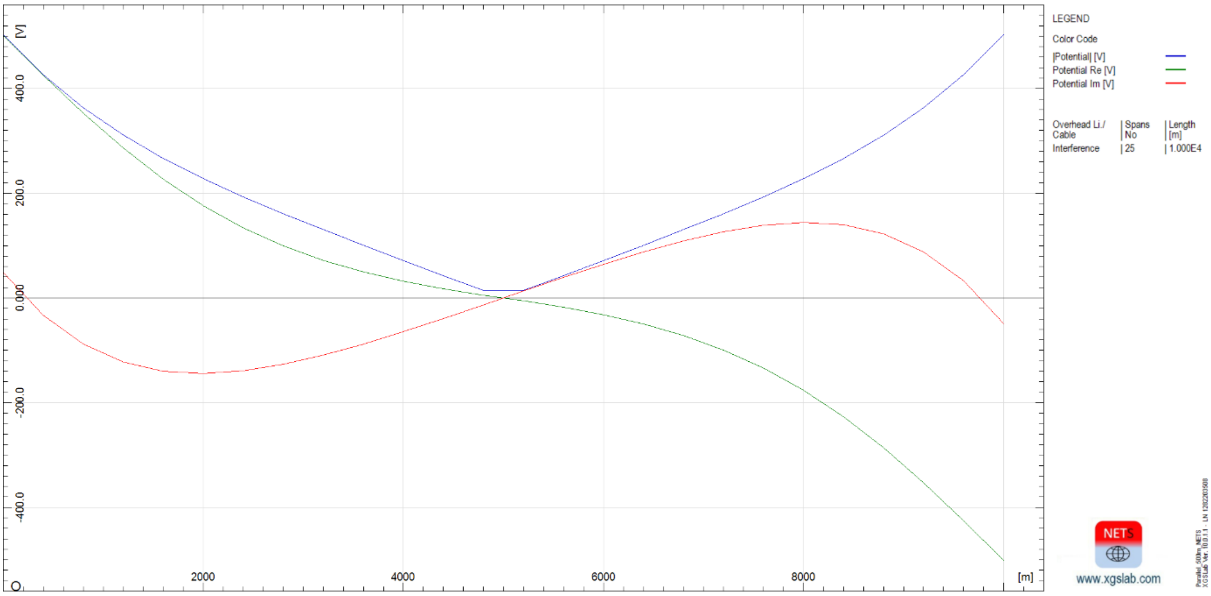

Figure 14 – Induced potential distribution on pipeline - Circuit theory 500 m

The agreement between results calculated using field and circuit theory is now good but not excellent.
The differences related to the end effects are now more evident.
In general, these differences grow with the ratio between interference distance and length.
In such conditions the equations used in the circuit theory approach, based on infinite long and parallel conductors gradually lose their validity.

Power System and Pipeline Not Parallel
In this second case, power system and pipeline are not parallel.
Power system and pipeline main data are as in previous case.

Other data as in previous case and moreover:
- Power System length: 10 km

- Power System route: straight, see Figure 15
- Pipeline length: 11.2 km
- Pipeline route: see Figure 15

The maximum distance between power system and pipeline in Figure 15 is at the starting point and is 2927 m.

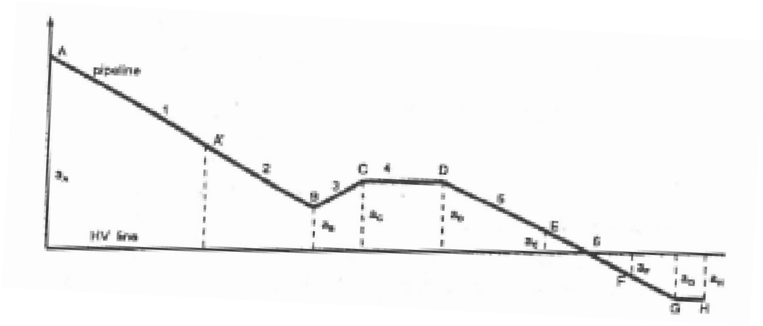

Figure 15 – Power system and pipeline

The interference scenario in Figure 15 is reduced to a series of parallel sections by partitioning power system and pipeline using the rules in [7] Appendix C 1.2.

In each section, the number of spans "n" is set as:

$$n = round\left(\frac{l}{s}\right) \quad (47)$$

where:

l (m) = section length

s (m) = span length

This assumption introduces unavoidable approximations in results.

Another problem in the application of the circuit theory approach is the definition of a reference length. Each section is reduced to an equivalent parallel section with an equivalent distance and the reference length related to the power line. This means information along pipeline can be evaluated only as orthogonal projection to the related power line. This is evident in the following figures, where pipeline length is 11.2 km using field theory (the true length) and 10 km using circuit theory (the projection on the power line).

Finally, in the specific case, the time in the modelling stage is similar for field and circuit theory.

In following figures, the distribution of induced current and potential calculated with field and circuit theory respectively.

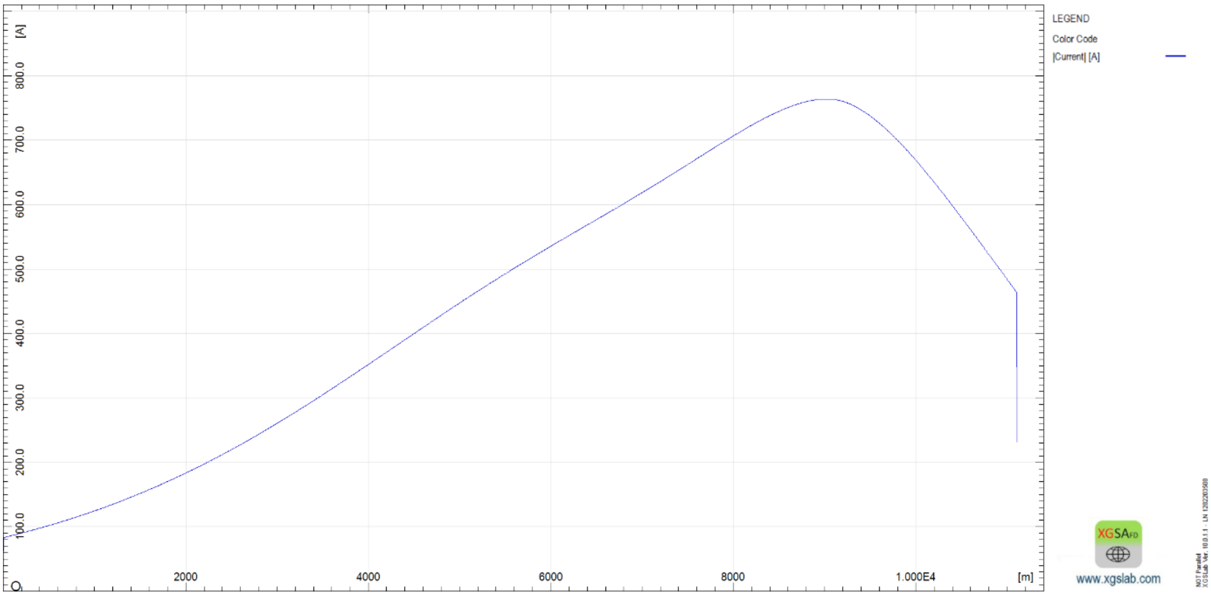

Figure 16 – Induced current distribution on pipeline - Field theory

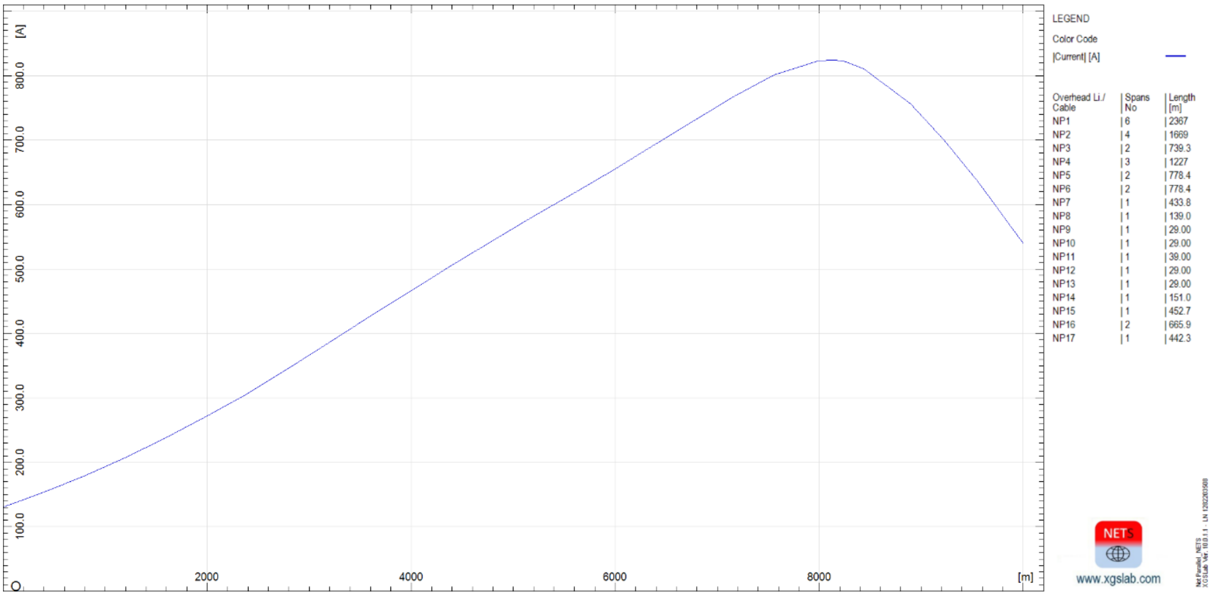

Figure 17 – Induced current distribution on pipeline - Circuit theory

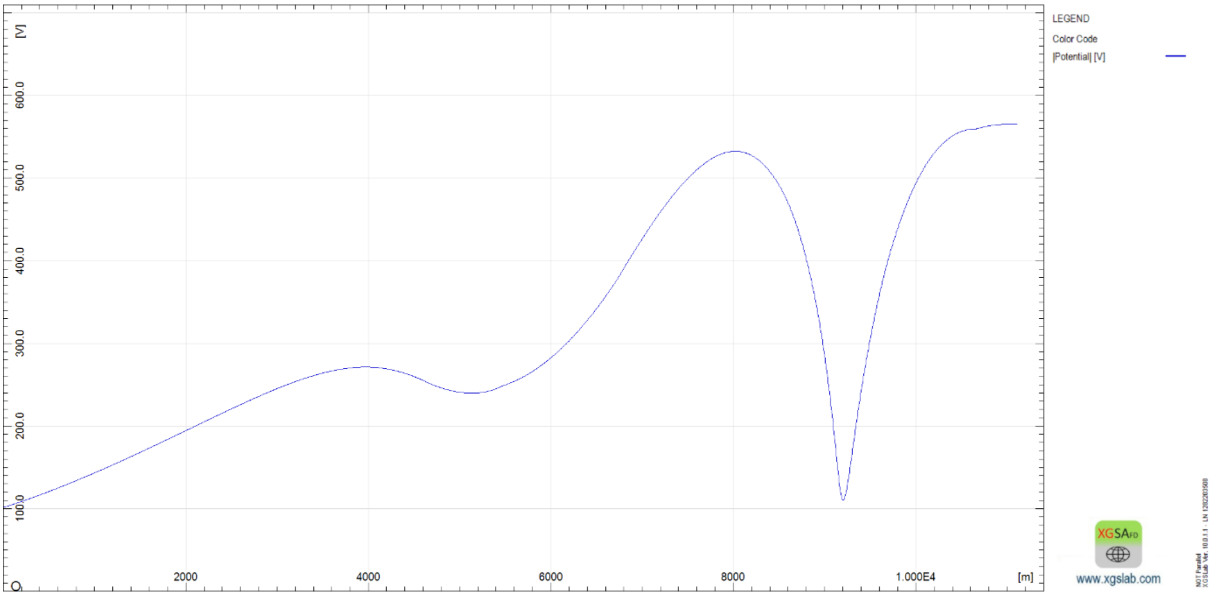

Figure 18 – Induced potential distribution on pipeline - Field theory

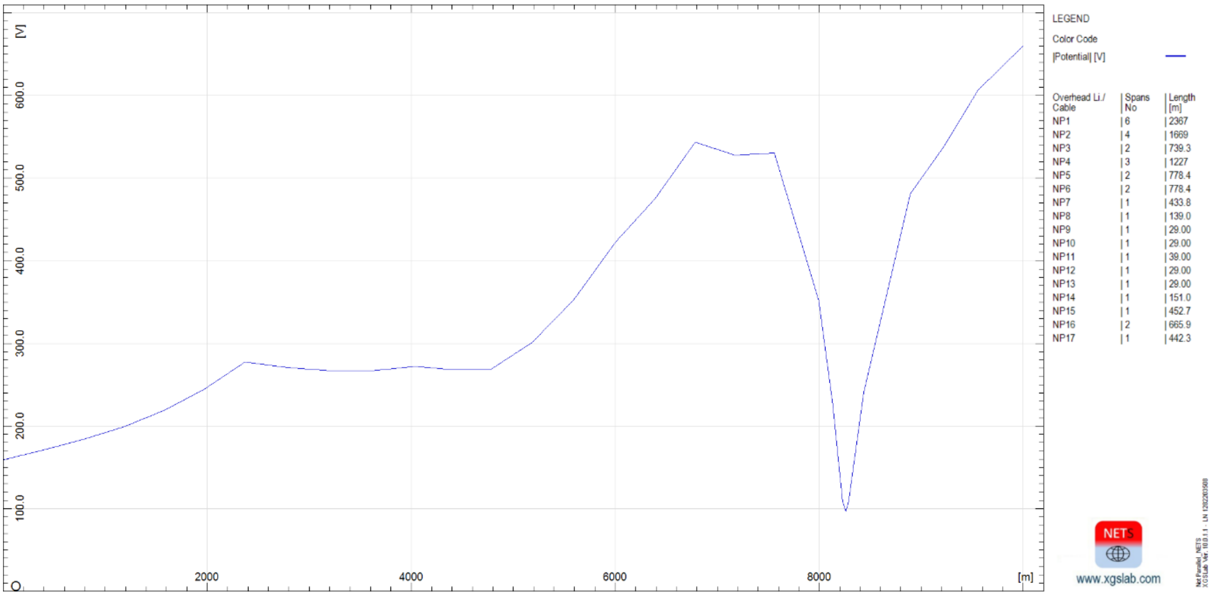

Figure 19 – Induced potential distribution on pipeline - Circuit theory

The agreement between results calculated using field and circuit theory is acceptable only for a preliminary calculation.
The difference in peak values is about 8% in current and 15% in potential.
These differences are related mainly to the following reasons:

- The division of the interference scenario in sections
- The method used for the reduction of sections to equivalent parallel sections
- The different used equations (Sommerfeld Vs. Carson)
- The end effects

CONCLUSIONS

This document describes the reference theory and two numerical models suitable for simulation of electromagnetic interferences between power lines and pipelines:

- The model based on the field theory and in particular on the PEEC method

- The model based on the circuit theory and in particular on the PCM method

The models based on field theory are general and rigorous and can be applied in all conditions but are usually time consuming in the modelling stage. These models are irreplaceable in case of complex 3D scenarios.

The models based on circuit theory approach are easier in the modelling stage, but only in case of simple scenarios, for instance in parallel conditions. In case of complex scenarios, the time spent in the modelling stage is similar to the time spent with a field theory approach.

The accuracy of the models based on circuit theory is good only in case of parallel conditions. In such cases the accuracy is excellent in case of small ratio between interference distance and interference length.

In case of complex 3D scenarios, the circuit theory is in general suitable only for preliminary evaluations.

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