# On the Effects of EMI and the Soil Structure on Transmission Line Parameters - Part I: Theoretical Model

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*Abstract*—**This paper presents a methodology for computing the electrical parameters of overhead transmission lines accounting for metallic pipeline interferences and soil stratification effects. The method is based on the closed-form analytical solution of the Carson's integral, which is used to calculate self and mutual line parameters. A wide variety of scenarios on a 230 kV/60 Hz transmission line 200 km long, considering a hypothetical case of interferences with a pipeline and soil stratifications based on resistivity measurements. Obtained results reveal that zero sequence impedance may be significantly affected by uncertainties due to pipeline interferences and soil layered structure, thereby a more robust line parameter calculation in practical applications is required to avoid errors in line design which uses zero sequence as fundamental parameters.**

*Keywords*—**ATP, electromagnetic interferences, line parameters, short circuit, transmission lines.**

## I. INTRODUCTION

The problem of mutual electromagnetic influences between transmission lines and other metallic structures (such as gas and oil pipelines, fences, railroads etc) still poses challenges to the scientific community. Due to the increasingly restrictive environmental regulations regarding the use of space, cases of interference in right of ways shared by lines and pipelines have become common, which has motivated researches in this area [1], [2].

A metallic pipeline when exposed to the energized conductors of a transmission line is subjected to a variety of phenomena, which results in the rise of metal potential along its path due to inductive, conductive and capacitive coupling mechanisms between the two structures, in both steady-state (normal operation) and transient (fault cases) regimes [1], [2]. As a consequence, some risks to the integrity of assets (facilities

involved) and people arise, such as: electrical shock caused by touch or step voltages, breakdown of the pipeline dielectric coating, metal electrochemical corrosion and damage due to current imposition to the metallic pipe and connected equipment [1].

It should be noted that the presence of a metallic pipeline in the vicinity of a given transmission line also may affect the calculation of its electrical parameters, leading to uncertainties in the model settings taken into account in various monitoring approaches, such as protection and fault location functions.

Another recognized source of error that may affect the calculation of line parameters is the uncertainty of the soil electrical resistivity [3]. Indeed, actual soils are anisotropic media, i.e. their properties vary with direction and depth [4]. Nevertheless, its influence on the classical coupling model is expressed in Carson's equation by an uniform parameter $\rho$ [5]. Besides, designers usually adopt typical values from soil tables, rather than actually having resistivity surveys and building accurate soil models [6].

Thus, this work presents an improved methodology for calculating transmission line parameters under interference conditions and accounting for the soil layered model. The obtained results reveal the performance of zero sequence impedance may be significantly affected if interferences and soil stratification are neglected.

## II. MATHEMATICAL MODEL

### A. Calculation of Overhead Transmission Line Parameters Under Interference Conditions

For the purposes of this paper, in which the wave propagation phenomenon is not the main concern, the nominal-$\pi$ model is sufficiently precise for representing the transmission line. Also, it is worthy to

emphasize that the methods proposed in this section remain valid, without loss of generality for the long line model (equivalent-$\pi$ model), by using the appropriate correction factors in terms of the propagation constant and line length, accordingly to the procedure extensively documented in the literature [7], [8]. Thus, the determination of the series impedances $Z$ and shunt admittances $Y$ for the transmission line model subject to interferences is required.

Fig. 1 shows a system comprised of phase conductors, designated by the subscripts $a$, $b$ and $c$, neutral wires, identified by the subscripts $n1...nN$ and an underground pipeline, followed by the $p$ subscript. The series impedance matrix of this system assumes the general form expressed in (1) [8]:

$$\mathbf{Z} = \begin{bmatrix} Z_{a,a} & Z_{a,b} & Z_{a,c} & Z_{a,n1} & \dots & Z_{a,nN} & Z_{a,p} \\ Z_{b,a} & Z_{b,b} & Z_{b,c} & Z_{b,n1} & \dots & Z_{b,nN} & Z_{b,p} \\ Z_{c,a} & Z_{c,b} & Z_{c,c} & Z_{c,n1} & \dots & Z_{c,nN} & Z_{c,p} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ Z_{nN,a} & Z_{nN,b} & Z_{nN,c} & Z_{nN,n1} & \dots & Z_{nN,nN} & Z_{nN,p} \\ Z_{p,a} & Z_{p,b} & Z_{p,c} & Z_{p,n1} & \dots & Z_{p,nN} & Z_{p,p} \end{bmatrix} \quad (1)$$

Elements $Z_{i,j}$ outside the main diagonal of the matrix $\mathbf{Z}$ correspond to the mutual impedances between conductors $i$ and $j$ with ground return path, computed in ohms per unit length using Carson's equation (2) [5]:

$$Z_{i,j} = Z_m = \frac{j\omega\mu_0}{2\pi} \ln\left(\frac{D'_{i,j}}{D_{i,j}}\right) + $$
$$\frac{j\omega\mu_0}{2\pi} \int_0^\infty \frac{2e^{-H\lambda}}{\lambda + \sqrt{\lambda^2 + j\frac{\omega\mu_0}{\rho} - \omega^2\mu_0\varepsilon_0\varepsilon_r}} \cos(\lambda D)\, d\lambda, \quad (2)$$

where $\mu_0 = 4\pi \times 10^{-7}$ H/m is the magnetic permeability constant in free space, $\varepsilon_0 \approx 8.85 \times 10^{-12}$ F/m is the vacuum electrical permittivity, $\rho$ is the local soil electrical resistivity, in $\Omega$.m, $\varepsilon_r$ is the local soil relative electrical permittivity, $H$, $D$, $D_{i,j}$ and $D'_{i,j}$ are the relative distances represented in Fig. 1, in meters, with: $H = y_i + y_j$, $D = x_j - x_i$, $D_{i,j} = \sqrt{(x_j - x_i)^2 + (y_i - y_j)^2}$ and $D'_{i,j} = \sqrt{(x_j - x_i)^2 + (y_i + y_j)^2}$, being $[x_q, y_q]$, $q = i,\, j, ...$ are the coordinates of $q$-th conductor/pipeline.

Elements $Z_{i,i}$ in the main diagonal are the self impedances of the aboveground conductors, calculated as in (3):

$$Z_{i,i} = Z_s = R_{AC} + \frac{j\omega\mu_0}{2\pi} \ln\left(\frac{2|y_j|}{GMR}\right) + $$
$$\frac{j\omega\mu_0}{2\pi} \int_0^\infty \frac{2e^{-2|y_j|\lambda}}{\lambda + \sqrt{\lambda^2 + j\frac{\omega\mu_0}{\rho} - \omega^2\mu_0\varepsilon_0\varepsilon_r}}\, d\lambda, \quad (3)$$

where $R_{AC}$ is the conductor AC ohmic resistance (supplied by the manufacturer) corrected to the operating temperature, given in ohms per unit length, and $GMR$
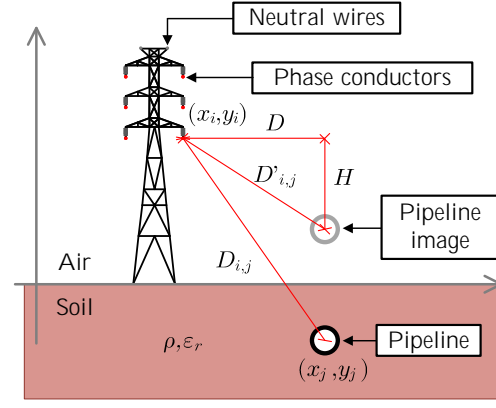


Figure 1: Phase conductors, neutral wires and pipeline.
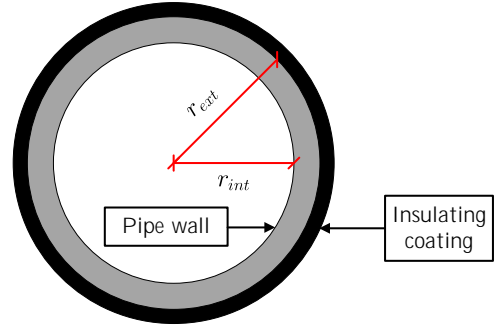


Figure 2: Cross section of a pipeline.

is the geometric mean radius of the conductor, as reported by the manufacturer or calculated according to the geometry of the cable bundle, expressed in meters. For the case of a tubular conductor, such as the pipeline depicted in Fig. 2, the geometric mean radius, denoted by $GMR_{TU}$ is determined using (4) [9]:

$$\ln(GMR_{TU}) = \ln(r_{ext}) - \frac{\frac{r_{ext}^4}{4} - r_{ext}^2 r_{int}^2}{(r_{ext}^2 - r_{int}^2)^2} + $$
$$\frac{r_{int}^4[\frac{3}{4} + ln(\frac{r_{int}}{r_{int}})]}{(r_{ext}^2 - r_{int}^2)^2}, \quad (4)$$

where $r_{ext}$ and $r_{int}$ express, respectively, the external and the internal radius of the tubular pipeline structure, in meters.

The first term in (2) and the second term in (3) correspond to the ground return impedance for a perfectly conductive soil. The improper integrals, known as Carson's integrals, represent the effects of the soil with finite resistivity, including losses caused by current return. The Carson's integral solution has been

assessed by several researchers using numerical techniques based on quadratures, power series expansion or deduction of simplified expressions, being worth mentioning the formulas derived by Carson-Clem, Deri, Lucca and Ametani [1], [10], [11], [12]. The use of simplified formulas is convenient, but may introduce significant errors if the particularities of the interference problem under study are not well understood. In general, these expressions produce satisfactory results for low frequencies and relatively small spacings between conductors, which imposes a limitation to the calculation model.

In [13], Theodoulidis shows that the Carson's integral can be evaluated analytically, with floating-point precision and without convergence problems, by means of a closed-form solution, i.e., expressed in terms of one or more functions whose behavior is well known. Indeed, the integrals in (2) and (3) can be written as (5) with the variable change expressed as shown in (6) and (7):

$$\int_0^\infty \frac{2e^{-H\lambda}}{\lambda + \sqrt{\lambda^2 + j\frac{\omega\mu_0}{\rho} - \omega^2\mu_0\varepsilon_0\varepsilon_r}} \cos\left(\lambda D\right) d\lambda =$$

$$\frac{\pi}{2u_1}[\widehat{H_1}(u_1) - \widehat{Y_1}(u_1)] - \frac{1}{u_1^2} + \frac{\pi}{2u_2}[\widehat{H_1}(u_2) - \widehat{Y_1}(u_2)] - \frac{1}{u_2^2}, \quad (5)$$

$$u_1 = (H - jD)\sqrt{j\frac{\omega\mu_0}{\rho} - \omega^2\mu_0\varepsilon_0\varepsilon_r}, \quad (6)$$

$$u_2 = (H + jD)\sqrt{j\frac{\omega\mu_0}{\rho} - \omega^2\mu_0\varepsilon_0\varepsilon_r}, \quad (7)$$

where $\widehat{H_1}$ is the Struve function and $\widehat{Y_1}$ is the Bessel function of the second type, both of first order [13].

Since the interfering pipeline is not energized by the power system, it can be treated in the same way as the neutral conductors in the calculation model. Therefore, nodes related to the neutral conductors and the pipeline can be eliminated from (1) using Kron reduction. For a 3-phase system, considering neutral conductors and the pipeline grounded on both extremities, one can write the following equivalent series impedance matrix:

$$\mathbf{Z_{EQ}} = \mathbf{Z_{FF}} - \mathbf{Z_{FG}} \cdot \mathbf{Z_{GG}}^{-1} \cdot \mathbf{Z_{GF}}, \quad (8)$$

being:

$$\mathbf{Z_{FF}} = \begin{bmatrix} Z_{a,a} & Z_{a,b} & Z_{a,c} \\ Z_{b,a} & Z_{b,b} & Z_{b,c} \\ Z_{c,a} & Z_{c,b} & Z_{c,c} \end{bmatrix}, \quad (9)$$

$$\mathbf{Z_{FG}} = \begin{bmatrix} Z_{a,n1} & \dots & Z_{a,nN} & Z_{a,p} \\ Z_{b,n1} & \dots & Z_{b,nN} & Z_{b,p} \\ Z_{c,n1} & \dots & Z_{c,nN} & Z_{c,p} \end{bmatrix}, \quad (10)$$

$$\mathbf{Z_{GG}} = \begin{bmatrix} Z_{n1,n1} & \dots & Z_{n1,nN} & Z_{n1,p} \\ \vdots & \ddots & \vdots & \vdots \\ Z_{nN,n1} & \dots & Z_{nN,nN} & Z_{nN,p} \\ Z_{p,n1} & \dots & Z_{p,nN} & Z_{p,p} \end{bmatrix}, \quad (11)$$

$$\mathbf{Z_{GF}} = \begin{bmatrix} Z_{n1,a} & \dots & Z_{nN,a} & Z_{p,a} \\ Z_{n1,b} & \dots & Z_{nN,b} & Z_{p,b} \\ Z_{n1,c} & \dots & Z_{nN,c} & Z_{p,c} \end{bmatrix}. \quad (12)$$

Assuming the transmission line is transposed, the matrix (8) is rewritten as:

$$\mathbf{Z_{EQ,T}} = \begin{bmatrix} Z_P & Z_M & Z_M \\ Z_M & Z_P & Z_M \\ Z_P & Z_M & Z_P \end{bmatrix}. \quad (13)$$

where $Z_P$ and $Z_M$ are computed using:

$$Z_P = \frac{\mathbf{Z_{EQ}}(1,1) + \mathbf{Z_{EQ}}(2,2) + \mathbf{Z_{EQ}}(3,3)}{3}, \quad (14)$$

$$Z_M = \frac{\mathbf{Z_{EQ}}(1,2) + \mathbf{Z_{EQ}}(2,3) + \mathbf{Z_{EQ}}(3,1)}{3}. \quad (15)$$

Finally, the sequence impedance matrix $\mathbf{Z_{012}}$ is obtained by applying the Fortescue transformation[1]:

$$\mathbf{Z_{012}} = \mathbf{T}^{-1} \cdot \mathbf{Z_{EQ,T}} \cdot \mathbf{T} \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix}, \quad (16)$$

being

$$\mathbf{T} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}, \text{ where } a = 1\angle 120°, \quad (17)$$

where $Z_0$, $Z_1$ and $Z_2$ are, respectively, the zero, positive and negative sequence impedances of the transmission line, in ohms per unit length.

A similar procedure is performed to determine the transmission line admittances. Referring again to the dimensions shown in Figs. 1 and 2, and using the same notation as in the calculations shown so far, the matrix $\mathbf{P}$ is formed with the Maxwell's potential coefficients defined in (19) and (20).

$$\mathbf{P} = \begin{bmatrix} P_{a,a} & P_{a,b} & P_{a,c} & P_{a,n1} & \dots & P_{a,nN} & P_{a,p} \\ P_{b,a} & P_{b,b} & P_{b,c} & P_{b,n1} & \dots & P_{b,nN} & P_{b,p} \\ P_{c,a} & P_{c,b} & P_{c,c} & P_{c,n1} & \dots & P_{c,nN} & P_{c,p} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ P_{nN,a} & P_{nN,b} & P_{nN,c} & P_{nN,n1} & \dots & P_{nN,nN} & P_{nN,p} \\ P_{p,a} & P_{p,b} & P_{p,c} & P_{p,n1} & \dots & P_{p,nN} & P_{p,p} \end{bmatrix} \quad (18)$$

$$P_{i,j} = \frac{1}{2\pi\varepsilon_0\varepsilon_r} \ln\left(\frac{D'_{i,j}}{D_{i,j}}\right). \quad (19)$$

$$P_{i,i} = \frac{1}{2\pi\varepsilon_0\varepsilon_r} \ln\left(\frac{D'_{i,i}}{r_{ext}}\right). \quad (20)$$

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[1]Equation (17) shows the Fostescue transformation matrix for an ABC system. For ACB systems, the matrix must be adapted.

By analyzing (19) and (20), which are valid for the 60 Hz frequency, it is observed that the transmission line shunt admittances are determined, essentially, by the configuration of the aboveground conductors and by the electrical permittivity of the medium. Therefore, no influences of interference with underground metallic pipes are expected, since they are immersed in a conductive medium (the ground), which is outside the electrostatic coupling region. Obviously, if interference occurs with metallic pipes above ground level, the transmission line admittances will be affected. Besides, for a low frequency scenario, Maxwell's potential coefficients are unaffected by the soil resistivity. In this section, further calculation steps of shunt admittances are omitted, since they are similar to those shown in (8)-(16).

### B. Accounting for the Soil Stratification in the Line Parameters Calculation Model

Fig. 1 depicts a case where the soil is perfectly uniform, with electrical resistivity $\rho$ for all $y \in (0, \infty)$, which is considered in Carson's equations (2)-(3). However, real soils are more complex structures, composed by solid, liquid and gaseous elements, whose electrical resistivity is dependent on the presence of water, particle porosity, type of electrolyte and temperature [4].

In practical situations, the soil electrical resistivity is commonly obtained by the Wenner's method, which consists of taking successive readings of an apparent electrical resistivity value from the surface of the soil in different locations and for several depths [14].

The process of deriving a layered soil model from the apparent resistivity measurements is known as soil stratification. Fig. 3 shows a real soil with several layers with different resistivities $\rho_i$ and thickness $h_i$, and its corresponding model.
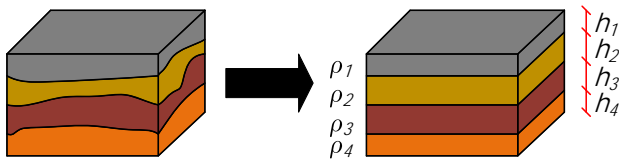


Figure 3: Real soil and stratified model.

The uniform soil model corresponds to the simple arithmetic mean of the apparent resistivity values. Modeling soils stratified in two or more layers requires more sophisticated numerical methods. The problem of soil stratification is well known in electrical grounding applications [4], as well as the uncertainties inherent to the uniform soil model [15].

The Finite Element method has been increasingly used in solving problems involving multi-layered soils.

Although this is a precise approach, it is also computationally expensive. An alternative strategy that has presented valid results in previous studies is to reduce the multi-layered model to a uniform equivalent and apply the classic coupling equations such as the Carson's ones [16].

A multi-layered soil, described by $N$ values of resistivity $[\rho_1, \rho_2, \rho_3, ..., \rho_N]$ and $N-1$ thickness values $[h_1, h_2, h_3, ..., h_{(N-1)}]$, can be reduced to a uniform equivalent as described in [17], whose effect is illustrated in Fig. 4.
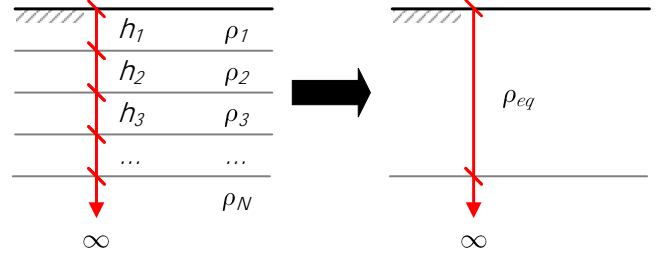


Figure 4: Stratified soil and its equivalent uniform model.

Considering $\sigma_N = 1/\rho_N$ and $f$ being the power system frequency, in hertz, the presence of multiple layers with different constitutive properties is accounted by replacing the uniform variable $\sigma$ in Carson equation by the equivalent parameter $\sigma_{eq}$, defined as in (21)-(23).

This approach has been proved to provide accurate results yielding a single real-valued parameter that can be readily used with the classic Carson equation (2), therefore being fully compatible with the native ATP routines that handle transmission line parameters [17].

### III. CASE STUDY

The transmission system is composed of a 200 km long power line which shares the right-of-way with a 8" diameter underground carbon steel pipeline installed at 1.5 m depth, which runs parallel to the transmission line axis along the entire course. Fig. 5 shows the geometry of the typical tower the transmission line, indicating the distance from the parallel pipeline, with dimensions in meters.

The specifications of the transmission line conductors and pipeline are given in Table I.

Table I: Specifications of conductors and pipeline

| Conductor | Description | Temperature |
|---|---|---|
| Phases | ACSR 636 MCM 27/7 (Peacock) | 50 °C |
| Neutral | Steel 3/8" HS | 50 °C |
| Pipe | 8" diameter Carbon-Steel | 50 °C |

$$\sigma_{N-1,N} = \sigma_{N-1} \left[ \frac{(\sqrt{\sigma_{N-1}} + \sqrt{\sigma_N}) - (\sqrt{\sigma_{N-1}} - \sqrt{\sigma_N})e^{-2h_{N-1}\sqrt{\pi f \mu_{N-1} \sigma_{N-1}}}}{(\sqrt{\sigma_{N-1}} + \sqrt{\sigma_N}) + (\sqrt{\sigma_{N-1}} - \sqrt{\sigma_N})e^{-2h_{N-1}\sqrt{\pi f \mu_{N-1} \sigma_{N-1}}}} \right]^2, \tag{21}$$

$$\vdots$$

$$\sigma_{m-1,m} = \sigma_{m-1} \left[ \frac{(\sqrt{\sigma_{m-1}} + \sqrt{\sigma_{m-1,m}}) - (\sqrt{\sigma_{m-1}} - \sqrt{\sigma_{m-1,m}})e^{-2h_{m-1}\sqrt{\pi f \mu_{m-1} \sigma_{m-1}}}}{(\sqrt{\sigma_{m-1}} + \sqrt{\sigma_{m-1,m}}) + (\sqrt{\sigma_{m-1}} - \sqrt{\sigma_{m-1,m}})e^{-2h_{m-1}\sqrt{\pi f \mu_{m-1} \sigma_{m-1}}}} \right]^2, \tag{22}$$

$$\sigma_{eq} = \sigma_1 \left[ \frac{(\sqrt{\sigma_1} + \sqrt{\sigma_{m-1,m}}) - (\sqrt{\sigma_1} - \sqrt{\sigma_{m-1,m}})e^{-2h_1\sqrt{\pi f \mu_1 \sigma_1}}}{(\sqrt{\sigma_1} + \sqrt{\sigma_{m-1,m}}) + (\sqrt{\sigma_1} - \sqrt{\sigma_{m-1,m}})e^{-2h_1\sqrt{\pi f \mu_1 \sigma_1}}} \right]^2, \, (1 \le m \le N-2). \tag{23}$$
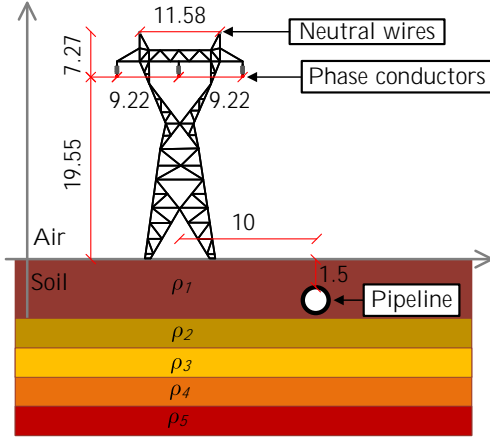


Figure 5: Geometry of the typical tower.

In order to exemplify the effect of the soil resistivity, it is used the apparent resistivity data available in Annex B.3 of the standard ABNT NBR 7117, which represent a soil model stratified in five layers, whose parameters are summarized in Fig. 6 [14].
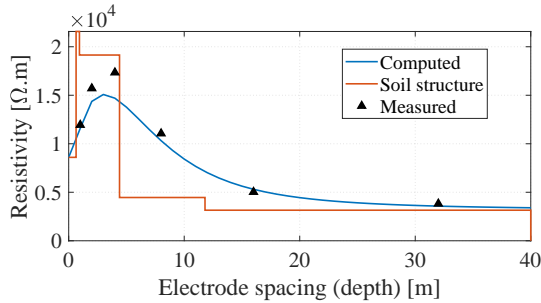


Figure 6: Five-layered soil model as in [14].

Table II contains a comparison between three different uniform soil models: 1) the equivalent uniform model, determined using (21)-(23) and the data presented in [14]; 2) the conventional uniform model, established under IEEE Std. 80 as the simple arithmetic

Table II: Resistivity values from uniform models

| Model | Resistivity [$\Omega$.m] |
|---|---|
| IEEE Std. 80 uniform | 10815 |
| RESAP uniform | 9401.48 |
| Equivalent uniform | 3160.89 |

mean of the apparent resistivity values [15]; and 3) the uniform model obtained using the RESAP module from software CDEGS, which is based on the curve-fitting technique reported in [18].

Applying (21)-(23) to the parameters of the stratified soil, a uniform equivalent soil model with resistivity 3160.89 $\Omega$.m is obtained, about 29% of the result for a uniform model obtained directly from the apparent resistivity measurements. It should also be noted that the uniform equivalent resistivity is very close to the value indicated for the deep soil resistivity, which confirms, numerically, reports in the literature that the deep soil resistivity is predominant in studies involving ground return path, and for calculations of mutual couplings in large systems, such as transmission line parameters, the use of the average values of the deep layers often yields satisfactory results for practical purposes [19].

In purpose to compare the three types of soil models and the influence of interference to calculate TL parameters, six scenarios are studied: 1) considering IEEE Std. 80 uniform soil and no interferences; 2) considering RESAP uniform soil and no interferences; 3) considering equivalent uniform soil and no interferences; 4) considering IEEE Std. 80 uniform soil and interference caused by a 10 m parallel pipeline; 5) considering RESAP uniform soil and interference caused by a 10 m parallel pipeline; and 6) considering equivalent uniform soil and interference caused by a 10 m parallel pipeline,

Finally, Table III shows the comparison between the scenarious of line parameters calculation.

Shunt admittances result in the same values for both calculation methods, with $Y_1$=3.1034j $\mu$S/km and

Table III: Line parameters of the case study for each scenario

| Cases | $Z_1$ [Ω/m] | $Z_0$ [Ω/m] |
|---|---|---|
| 1 | 0.1107 + j0.5337 | 0.5834+j1.8263 |
| 2 | 0.1107 + j0.5337 | 0.5775+j1.8146 |
| 3 | 0.1107 + j0.5337 | 0.5335+j1.722 |
| 4 | 0.1108 + j0.5336 | 0.3819+j1.3669 |
| 5 | 0.1108 + j0.5336 | 0.38+j1.3628 |
| 6 | 0.1108 + j0.5336 | 0.3648+j1.329 |

$Y_0$=2.2324j $\mu$S/km. This is explained by the fact that the capacitance is independent of the soil resistivity and that the interfering pipeline is buried beneath the ground, that is, immersed in a conductive medium and, consequently, absent of electrostatic couplings with the energized conductors of the transmission line. It is relevant to note that the positive sequence parameters do not present considerable differences, with an error of less than 1%. The soil models represents an insignificant influence in line parameters, which presents less than 3% of deviation in zero sequence. However, the zero sequence impedance is shown to be significantly influenced by interference conditions, in which a discrepancy of 30.81% is observed between the same soil models with different interference conditions.

## IV. CONCLUSIONS

Results discussed indicate that the zero sequence line parameters are sensitive to the soil model and the presence of interferences, presenting an error 30.809% smaller in relation to the calculation procedure in which these variables are ignored. The positive sequence parameters are little affected by the soil resistivity and the inductive coupling with other installations.

From the above, it is considered of fundamental importance that, in transmission line design, short-circuit studies, dimensioning and calibration of protection and fault location devices, precise numerical methods are used to calculate the electrical parameters. However, it is also necessary to ensure the quality of the field gathered information, especially soil resistivity measurements and the survey of interferences with other facilities.

In a companion paper, the effects on transmission line parameters due to interferences and different soil models are further investigated, with numerical analyses of short-circuits and fault location studies on a transmission system.

## References

[1] WG-36.02, "Publication n. 95 - Guide on the Influence of High Voltage AC Power Systems on Metallic Pipelines," Paris, pp. 1–135, 1995. [Online]. Available: http://www.e-cigre.org/Order/select.asp?ID=96

[2] G. C. Christoforidis, D. P. Labridis, and P. S. Dokopoulos, "A hybrid method for calculating the inductive interference caused by faulted power lines to nearby buried pipelines," *IEEE Transactions on Power Delivery*, vol. 20, no. 2, pp. 1465–1473, April 2005.

[3] S. Das, S. Santoso, A. Gaikwad, and M. Patel, "Impedance-based Fault Location in Transmission Networks: Theory and Application," *IEEE Access*, vol. 2, pp. 537–557, 2014.

[4] J. He, R. Zeng, and B. Zhang, *Methodology and Technology for Power System Grounding*, 2012.

[5] J. R. Carson, "Wave Propagation in Overhead Wires with Ground Return," *Bell Syst. Tech. J.*, vol. 5, pp. 539–554, 1926.

[6] E. Whelan, J.M; Hanratty, B.; Morgan, "Earth Resistivity in Ireland," in *CDEGS Users' Group*, Montreal, 2010, pp. 155–164.

[7] H. Saadat, *Power System Analysis*, 2nd ed., McGraw-Hill, Ed., 1999.

[8] J. J. Grainer and W. Stevenson, *Power System Analysis*, 1994. [Online]. Available: http://medcontent.metapress.com/index/A65RM03P4874243N.pdf

[9] H. L. Seneff, "Study of the Method of Geometric Mean Distances Used in Inductance Calculations," 1947.

[10] G. Deri, A., Tevan, "The Complex Ground Return Plane - A Simplified Model for Homogeneous and Multi-Layer Earth Return," no. August, pp. 31–32, 1981.

[11] G. Lucca, "Mutual Impedance between an Overhead and a Buried Line with Earth Return," in *Proc. Int. Electr. Eng. 9th Int. Conf. EMC*, no. 1, 1994, pp. 80–86.

[12] A. Ametani, T. Yoneda, Y. Baba, and N. Nagaoka, "An Investigation of Earth-Return Impedance Between Overhead and Underground Conductors and Its Approximation," *IEEE Transactions on Electromagnetic Compatibility*, vol. 51, no. 3, pp. 860–867, 2009. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=4914803

[13] T. Theodoulidis, "On the Closed-Form Expression of Carson's Integral," *Periodica Polytechnica, Electrical Engineering*, vol. 59, no. 1, pp. 26–29, 2015.

[14] ABNT, "NBR 7117 - Medição da Resistividade e Determinação da Estratificação do Solo," pp. 1–72, 2012.

[15] IEEE Std 80, "Guide for Safety In AC Substation Grounding," pp. 1–192, 2000.

[16] A. G. L. Furlan, "Estudo de Interferências Eletromagnéticas entre Linhas de Transmissão e Dutos Enterrados," Dissertação (Mestrado), Universidade Federal de Santa Catarina, 2015.

[17] A. G. Martins-Britto, F. V. Lopes, and S. R. M. J. Rondineau, "Multi-layer Earth Structure Approximation by a Homogeneous Conductivity Soil for Ground Return Impedance Calculations," *IEEE Transactions on Power Delivery*, vol. 8977, no. c, pp. 1–1, 2019.

[18] F. Dawalibi and C. Blattner, "Earth Resistivity Measurement Interpretation Techniques," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-103, no. 2, pp. 374–382, 1984. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=4112522

[19] R. Southey and F. Dawalibi, "Improving the Reliability of Power Systems with More Accurate Grounding System Resistance Estimates," *Proceedings. International Conference on Power System Technology*, vol. 4, pp. 98–105, 2005. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1053512