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A Vertical Grounding Arrangement that Diminishes Impulse Coefficient in a Two-Layered Soil

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***Abstract*—This paper presents a vertical grounding mesh to transmission line (TL) towers for use in two-layered soils, where the second-layer has a lower resistivity compared to the first. To a better knowing about its behavior, a comparison with horizontal arrangement composed by counterpoise cables, for critical soils from a 230 kV TL, is realized focusing in impulse coefficient parameter. A first analysis of the procedure based on TL-theory with electromagnetic (EM) method is made and an evaluation of homogenous soil for the arrangements is realized. The results indicate a lower grounding resistance and impulsive impedance for the proposed vertical option compared to horizontal arrangement, using much less conductor material and presenting a margin to reduce such parameters due to the distance to effective length.**

***Keywords*— Grounding impulse coefficient, impulsive impedance, lightning,.**

I. Introduction

Tropical areas usually present soils with high resistivities, especially when compared to that from temperate zones. Furthermore, a greater lightning incidence occur in such regions, which only turns harder the protection project of transmission lines (TL) [1]. Increase TL performance for lightning almost always require an improvement of grounding from their towers [2], which derives in a research for arrangements with lower costs and a dimension that is supported by right-of-way limits.

Vertical arrangements are presented by [3,4] as an alternative for meshes composed by counterpoise cable, which are typical from TL towers. Considering two-layered soils, such configurations can be a good choice when the second-layer presents a lower electric resistivity compared to first-layer, i.e., $\rho_2 < \rho_1$. Thus, an electrode that reaches the second layer region can diminishes ground resistance and ground impedance with lower conductor material compared to horizontal option.

Recently, using the median two-layer soil parameters from Minas Gerais state, Brazil [5], a four-vertical electrode mesh was compared to the longest typical four-counterpoise cables option available for grounding and presented a notable characteristic [4]. For unitary current pulses with front time varying from 0.5 to 10 μs, the vertical arrangement presented lower GPR peaks than that from horizontal alternative, which derived in a much more planar impulsive response. Such characteristic would be very welcome in conditions similar to those from Minas Gerais median soil: with $\rho_2 < \rho_1$.

As [4] uses TL-theory to estimate harmonic grounding impedance and knowing that such approach may present significative errors in certain conditions of conductor length and resistivity soil evaluated [6], a comparison with a rigorous electromagnetic (EM) model is necessary to support the previous conclusion. Also, if validated, a wider number of soils with $\rho_2 < \rho_1$ would be analysed to verify if the same behaviour is observed for other conditions.

This work presents a comparative study about impulse coefficient I_C, given by the ratio:

$$I_C = Z_P / R_{LF} \, , \tag{1}$$

where Z_P is the impulsive impedance and R_{LF} is grounding low-frequency resistance, for a four vertical electrode and a counterpoise cable arrangement. Two-layered soils with $\rho_2 < \rho_1$, presented in some towers from a 230 kV TL [7], are analyzed and their I_C evaluated to comprehend if the same characteristic shown in [4] are maintained and/or how they change with other ρ_1, ρ_2 and h_1 values, where h_1 is the thickness of the first-layer soil.

II. Theoretical Review and Tooling Used

A. A procedure based on TL theory for horizontal grounding arrangement composed by counterpoise cables

A TL technique to compute harmonic grounding impedance for arrangement composed by counterpoise cables can be adapted from [8], which presents a formulation for a single horizontal electrode. The resistive, capacitive and inductive elements are described, respectively, by [9]:

$$R = \frac{\rho_{eq}}{\pi L_e}\left[\ln\left(\frac{2L_e}{\sqrt{2rd_e}} \right) - 1 \right], \tag{2}$$

$$C = \rho_{eq}\varepsilon_0\varepsilon_r / R, \tag{3}$$

$$L = \frac{\mu_0 L_e}{2\pi}\left[\ln\left(\frac{2L_e}{r} \right) - 1 \right], \tag{4}$$

where ρ_{eq} is the soil resistivity, L_e is the conductor length, d_e and r its depth and radius, ε_0 is vacuum electric permittivity, ε_r the relative electric permittivity and μ_0 is vacuum magnetic permeability.

Such elements are calculated by per-unit length and applied to Z_{in} to compute harmonic grounding impedance for a single horizontal electrode:

$$Z_{in} = Z_C \coth(\gamma L_e), \tag{5}$$

$$Z_C = \sqrt{\frac{j\omega L'}{G' + j\omega C'}}, \tag{6}$$

$$\gamma = \sqrt{j\omega L'(G' + j\omega C')}, \tag{7}$$

where Z_C is the characteristic impedance, γ the propagation constant, ω the angular frequency and L', G' and C', respectively, the per-unit length inductance, conductance and capacitance.

Using the same procedure presented by [10] for typical counterpoise cables arrangement, an equivalent circuit is approximated for the problem and the final harmonic grounding impedance is computed by:

$$Z_{in} = \left(\frac{Z_C + Z_M}{4}\right)\coth(\gamma L_e), \tag{8}$$

$$Z_M = \sqrt{\frac{j\omega L_M^{'}}{G_M^{'} + j\omega C_M^{'}}}, \tag{9}$$

where Z_M is the characteristic impedance referred to mutual per-unit length parameters.

A procedure to calculate an apparent resistivity ρ_{eq} of a uniform soil for a two-layered medium is used, such as that proposed by Endrenyi [11]. Parameters, such as dimension and arrangement position inside the soil, are used to estimate ρ_{eq}.

B. A procedure based on TL theory for a multiple vertical electrodes grounding arrangement

As indicated by Tagg [12], a single vertical rod immersed in a two-layer soil has an apparent resistivity ρ_{eq} given by:

$$\rho_{eq} = \frac{L_e \rho_1 \rho_2}{\rho_2 h + \rho_1 (L_e - h_1)}(1+B), \tag{10}$$

where ρ_1 is the first-layer and ρ_2 the second-layer electric resistivity of the soil, h_1 is the first-layer thickness and B is a factor described by:

$$B = \left[\ln\left(\frac{4L_e}{r}\right) - 1\right]^{-1} \left\{\sum_{n=1}^{\infty} k^n \ln\left[\frac{2nh_1 + L_e}{(2n-2)h_1 + L_e}\right]\right\}, \tag{11}$$

and k is the reflection factor:

$$k = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}. \tag{12}$$

Blattner's formula is a simplification of (10), when B is considered null [13]. As a consequence, the final resistance of a vertical rod can be estimated by two independent resistors that represent each soil layer.

For harmonic grounding impedance, such procedure is used to compute the parameter. An equivalent TL-circuit has their parameters estimated by [9]:

$$R_i = \frac{\rho_i}{2\pi L_{ei}}\left[\ln\left(\frac{4L_{ei}}{r}\right) - 1\right],\ G_i^{'} = (R_i L_{ei})^{-1}, \tag{13}$$

$$C_i = \rho_i \varepsilon_0 \varepsilon_{ri} / R_i,\ C_i^{'} = C_i / L_{ei}, \tag{14}$$

$$L_i = \frac{\mu_0 L_{ei}}{2\pi}\left[\ln\left(\frac{2L_{ei}}{r}\right) - 1\right],\ L_i^{'} = L_i / L_{ei}, \tag{15}$$

where G'_i, C'_i and L'_i are the per-unit length conductive, capacitive and inductive elements for each i-layer.

If we cascade the TL-circuit, the harmonic grounding impedance can be reach, for a two-layer soil (i = 2), using:

$$Z_{in} = Z_1 \frac{Z_{L2} + Z_1 \tanh(\gamma_1 L_{e1})}{Z_1 + Z_{L2} \tanh(\gamma_1 L_{e1})}, \tag{16}$$

$$Z_1 = \sqrt{\frac{j\omega L_1^{'}}{G_1^{'} + j\omega C_1^{'}}}, \tag{17}$$

$$\gamma_1 = \sqrt{j\omega L_1^{'}(G_1^{'} + j\omega C_1^{'})}, \tag{18}$$

$$Z_{L2} = Z_2 \coth(\gamma_2 L_{e2}),\ Z_2 = \sqrt{\frac{j\omega L_2^{'}}{G_2^{'} + j\omega C_2^{'}}}. \tag{19}$$

A formula that incorporates the full-form of Tagg's formula for harmonic grounding impedance of a vertical rod is presented by [14]. It also shows that Blattner's expression seems to be useful for cases where $\rho_2 < \rho_1$, which is the main focus of this work, i.e., although is a simplification, can be applied without significative errors for these soil conditions.

Multiple vertical electrodes are estimated using an equivalent radius r_{eq} from the self-radius and each conductor distance [9], i.e.:

$$r_{eq} = \left[Nr(D/2)^{N-1}\right]^{1/N},\ D << L_e, \tag{20}$$

for N electrodes and a half-distance D between the electrodes.

The final harmonic grounding impedance will be calculated by (16) using r_{eq} from (20) for (13)-(15) [4].

C. Impulse coefficient comparison of horizontal and vertical arrangements based on EM and TL procedures

To illustrate the conditions evaluated by EM and TL procedures, Fig. 1 shows the vertical and horizontal electrodes arrangements considered in this work.

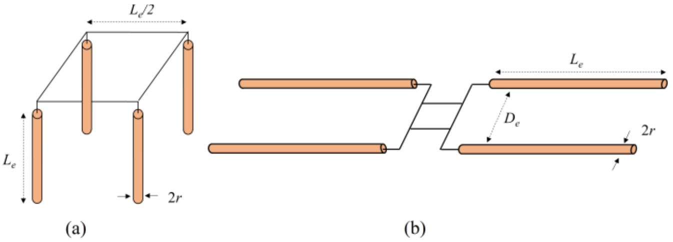


Fig. 1. Grounding (a) vertical and (b) horizontal arrangements used in this work [4].

Unitary current pulses, with front time t_f varying from 0.5 to 10 µs, which can englobe t_f from first and subsequent strokes, are applied for each arrangement. The vertical mesh has 27 m length and a side of $L_e/2$ = 13.5 m, which forms a square on soil surface. Using the same radius from vertical option, r = 4.37 mm, the horizontal arrangement has L_e = 90 m and a distance between the counterpoise cables D_e of 30 m.

Considering the median two-layer soil parameters from Minas Gerais state, i.e., ρ_1 = 2100 Ωm, h_1 = 5 m and ρ_2 = 900 Ωm, Endrenyi's approach for horizontal arrangement indicates an equivalent resistivity of 1804 Ωm [11]. The ground potential rise (GPR) of each condition is presented in Fig. 2, while Table I shows I_C calculated for each current wave using (1), where Z_P is described by [15]:

$$Z_P = \frac{\max(\mathrm{GPR})}{\max(I)}, \tag{21}$$

where I = 1 A for a unitary current pulse. All soils evaluated in this work have ε_r = 10 and a relative magnetic permeability μ_r = 1.

A much more planar response is observed for vertical arrangement option, especially for fast transients such as that with t_f lower than 4 µs. For a first stroke with t_f = 5 µs, a reduction of 17.1% in I_C is observed, while for a subsequent stroke with t_f = 1 µs reaches 48.8%, a remarkable result.

Despite these interesting characteristics observed for a vertical arrangement, an EM analysis for the same conditions is necessary to validate the curves, which are presented in Fig. 3 and Table II. Using HFSS as the EM software, a condition with two-layer soil for horizontal arrangement is also analyzed to know if the Endrenyi's procedure applied for TL method and TL technique maintain the order of the values estimated for I_C.

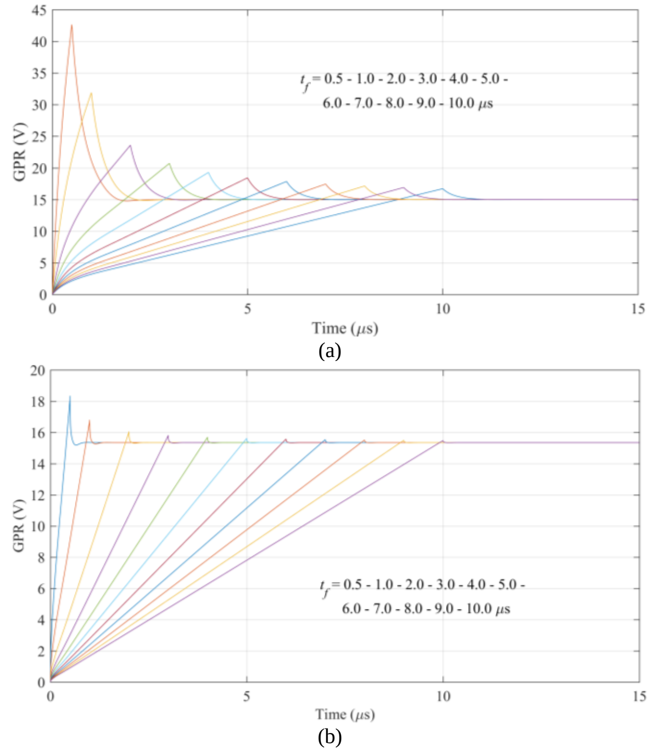


Fig. 2. GPR curves for grounding arrangement composed by four: (a) horizontal counterpoise cables (ρ_{eq} = 1804 Ωm) and (b) vertical electrodes (ρ_1 = 2100 Ωm, h_1 = 5 m and ρ_2 = 900 Ωm) – using TL procedure [4].

TABLE I. IMPULSE COEFFICIENTS I_C FOR HORIZONTAL AND VERTICAL ARRANGEMENTS USING TL PROCEDURE – ADAPTED FROM [4]

t_f (µs)	*I_C for horizontal arrangement* (ρ_{eq} = 1804 Ωm, R_{LF} = 15.00 Ω)	*I_C for vertical arrangement* (ρ_1 = 2100 Ωm, h_1 = 5 m, ρ_2 = 900 Ωm, R_{LF} = 15.35 Ω)	*I_C difference between vertical and horizontal meshes*
0.5	2.84	1.20	- 57.7%
1.0	2.13	1.09	- 48.8%
2.0	1.57	1.05	- 33.1%
3.0	1.38	1.03	- 25.4%
4.0	1.29	1.02	- 20.9%
5.0	1.23	1.02	- 17.1%
6.0	1.19	1.01	- 15.1%
7.0	1.16	1.01	- 12.9%
8.0	1.14	1.01	- 11.4%
9.0	1.13	1.01	- 10.6%
10.0	1.11	1.01	- 9.01%

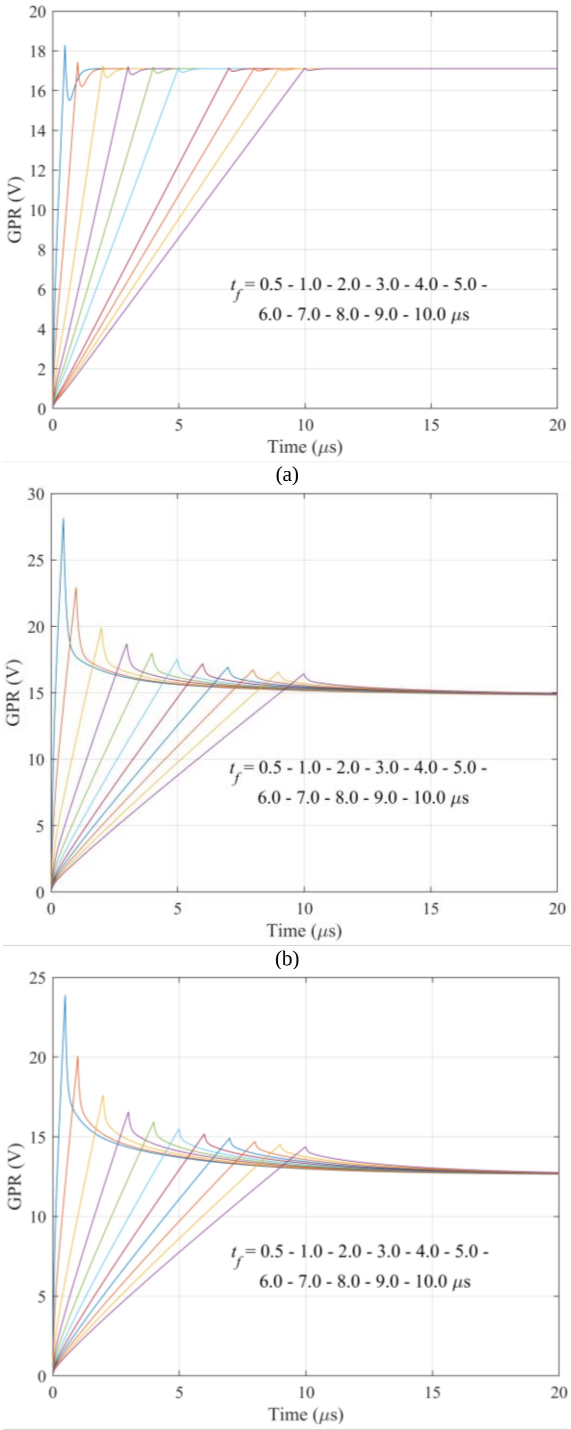


Fig. 3. GPR curves for grounding arrangement composed by four: (a) vertical electrodes (ρ_1 = 2100 Ωm, h_1 = 5 m and ρ_2 = 900 Ωm), (b) horizontal counterpoise cables with Endrenyi's approximation (ρ_{eq} = 1804 Ωm) and (c) the original stratified soil (ρ_1 = 2100 Ωm, h_1 = 5 m and ρ_2 = 900 Ωm) – using HFSS.

HFSS results show a similar behavior for the vertical arrangement, with I_C differences a bit slower than that showed by TL procedure. For a first stroke with t_f = 5 μs, we note a reduction of 16.1% of I_C and, for a subsequent stroke with t_f = 1 μs, 34.9% considering an equivalent homogenous soil. If

TABLE II. IMPULSE COEFFICIENTS I_C FOR HORIZONTAL AND VERTICAL ARRANGEMENTS USING HFSS PROCEDURE

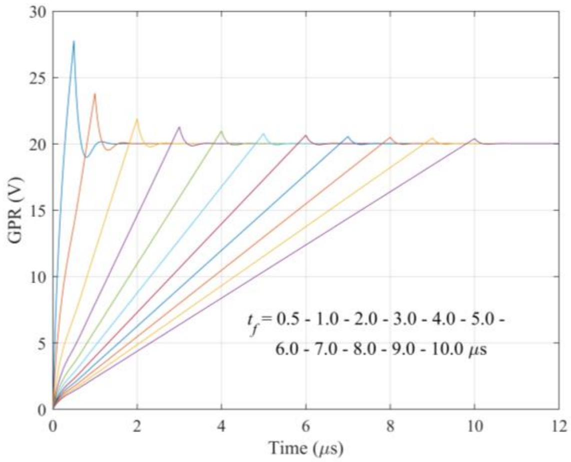
t_f (μs)	***I_C for horizontal arrangement*** (ρ_1 = 2100 Ωm, h_1 = 5 m, ρ_2 = 900 Ωm, R_{LF} = 12.60 Ω) / (ρ_{eq} = 1804 Ωm, R_{LF} = 14.66 Ω)	***I_C for vertical arrangement*** (ρ_1 = 2100 Ωm, h_1 = 5 m, ρ_2 = 900 Ωm, R_{LF} = 17.11 Ω)	***I_C difference between vertical and horizontal meshes***
0.5	1.90 / 1.92	1.07	- 43.6% / - 44.3%
1.0	1.59 / 1.56	1.02	-36.0% / - 34.9%
2.0	1.40 / 1.36	1.01	- 27.8% / - 25.7%
3.0	1.31 / 1.27	1.01	- 23.5% / - 21.1%
4.0	1.27 / 1.23	1.00	- 20.6% / - 18.2%
5.0	1.23 / 1.20	1.00	- 18.5% / - 16.1%
6.0	1.20 / 1.17	1.00	- 16.8% / - 14.5%
7.0	1.18 / 1.16	1.00	- 15.4% / - 13.3%
8.0	1.17 / 1.14	1.00	- 14.1% / - 12.2%
9.0	1.15 / 1.13	1.00	- 13.1% / - 11.4%
10.0	1.14 / 1.12	1.00	- 12.2% / - 10.6%

the original two-layered soil is considered, such I_C differences reach 36.0% and 18.5% for the same comparison. Such results indicate an overestimation of I_C considering TL method, notably for current pulses with t_f lower than 2 μs, i.e., first strokes tend to be well represented by their approximations, but some subsequent requires caution in their use. Another assumption by using this TL procedure, in addition with transverse electromagnetic (TEM) mode hypothesis, is that $D = L_e/2$ is much lower than L_e, which allows to use (20) – another approach that adds error to technique. Nevertheless, the I_C differences shown in Table I and II are not very different, so the comparison can be made using TL at least to estimate the order of I_C values for current waves with $t_f < 2$ μs.

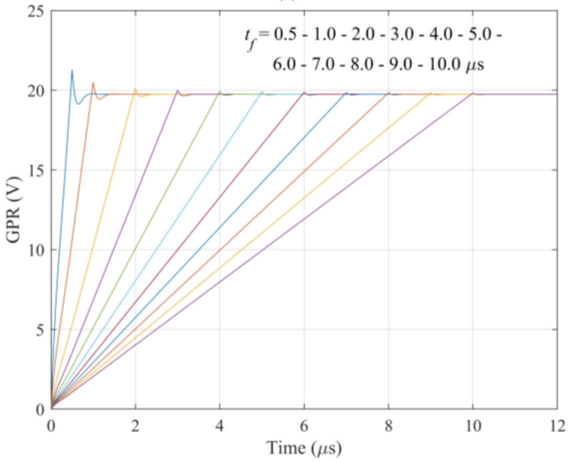
The main result of this comparison is that even EM method supports the conclusion that the multiple vertical electrode can be a good alternative to a typical horizontal option, at least for conditions when $\rho_2 < \rho_1$, such as that typical two-layer soil from Minas Gerais state. Apparently, this characteristic is due to the vertical electrodes touching the second-layer from soil with lower resistivity.

To support the last affirmative, an analysis using TL method is made for a 1000 Ωm uniform soil. The horizontal arrangement has L_e = 30 m and a distance between the conductors of 15 m, while the vertical option has 22 m length and a side of $L_e/2$ = 11 m. The chosen geometrical dimensions for the meshes tends to be lower than the effective length, as can be seen from the values showed by [15] for a horizontal electrode in a 1000 Ωm soil and a current wave with t_f = 1.2 μs: 34 m. GPR curves and I_C comparison are presented, respectively, in Fig. 4 and Table III.

As present in Fig. 4 and Table III, the vertical arrangement compared to a horizontal option with a similar grounding resistance R_{LF} doesn't have very significant differences for I_C



(a)



(b)

Fig. 4. GPR curves for grounding arrangement composed by four: (a) horizontal counterpoise cables (ρ = 1000 Ωm) and (b) vertical electrodes (ρ = 1000 Ωm) – using TL procedure.

TABLE III. IMPULSE COEFFICIENTS I_C FOR HORIZONTAL AND VERTICAL ARRANGEMENTS FOR A 1000 ΩM UNIFORM SOIL USING TL PROCEDURE

t_f (µs)	I_C *for horizontal arrangement* (ρ = 1000 Ωm, R_{LF} = 20.03 Ω)	I_C *for vertical arrangement* (ρ = 1000 Ωm, R_{LF} = 19.75 Ω)	I_C *difference between vertical and horizontal meshes*
0.5	1.39	1.08	- 22.3%
1.0	1.19	1.04	- 12.7%
2.0	1.09	1.02	- 6.91%
3.0	1.06	1.01	- 4.73%
4.0	1.05	1.01	- 3.61%
5.0	1.04	1.01	- 2.92%
6.0	1.03	1.01	- 2.41%
7.0	1.03	1.01	- 2.08%
8.0	1.02	1.00	- 1.85%
9.0	1.02	1.00	- 1.66%
10.0	1.02	1.00	- 1.46%

values in a uniform soil. For the condition evaluated, a difference of 12.7% and 2.92% is noted, respectively, for a current wave with a t_f = 1 and 5 µs, which are very lower than observed from stratified soil condition. The homogenous soil case evaluated, although indicating lower I_C for fast surges, is not so remarkable than that from a two-layer condition, which has more appeal to be an alternative for critical cases that horizontal arrangements usually can't reach a desired low Z_P.

III. EVALUATING IMPULSE COEFFICIENT FOR CRITICAL SOILS OF A 230 KV TL

A. Preliminary considerations

From measurements obtained from 230 kV TL Irapé-Araçuaí 2 [16], four critical soil conditions are analyzed using arrangements composed by counterpoise cables and vertical electrodes. All horizontal arrangements have 90 m length, a distance of 30 m between the conductors and 4.37 mm radius, while the vertical alternative uses electrodes with a length L_e with a square side $D_e = L_e/2$, such as that illustrated by Fig. 1.

A similar R_{LF} for vertical arrangement compared to the horizontal mesh was used to define L_e and D_e values. Table IV presents the evaluated soils, the equivalent ρ_{eq}, obtained using [11], for the grounding horizontal arrangement and the L_e applied to the grounding vertical mesh. All responses are derived from TL methods described in Section II.

TABLE IV. CONSIDERED PARAMETERS FOR SOIL AND THE EVALUATED GROUNDING ARRANGEMENTS TO ANALYSE MEASUREMENTS FROM 230 KV TL IRAPÉ-ARAÇUAÍ 2 [16]

Case	ρ_1 (Ω)	h_1 (m)	ρ_2 (Ω)	ρ_{eq} (Ω) [11]	L_e (m)
1	4496	5.8	1040	3020	21
2	10194	3.4	1377	5833	15
3	12551	4.6	2839	8144	21
4	5711	7.3	2052	4268	27

B. Results

All cases showed in Table IV have their results presented in Table V to VIII, which contain a column to indicate the I_C values for each simulation. To illustrate some simulations, Fig, 5 and 6 show GPR curves for cases 2 and 4.

As shown in Fig. 5 and 6 and I_C values from Tables V to VIII, the vertical arrangement has a response practically resistive for all conditions evaluated. The meshes composed by counterpoise cables presents, at least for fast surges up to t_f = 1 µs, some overshoot in GPR curves that results in higher I_C values compared to the vertical option.

From [15], we can infer, considering surges with $t_f \leq 1$ µs for cases 2 and 4 and some with $t_f > 1$ µs for case 1, that the 90 m length horizontal meshes evaluated can pass the effective length for such ρ_{eq} analyzed, which affects I_C due to a stabilization of Z_P while R_{LF} continues to decrease. Even with this hypothesis, the results suggest an advantage for vertical arrangement due to the capacity to obtain lower Z_P especially for fast surges, such as subsequent strokes, with a much lower total conductor length used for their implementation – this characteristic derives in a

TABLE V. IMPULSE COEFFICIENTS I_C FOR HORIZONTAL (90 M LENGTH) AND VERTICAL (21 M LENGTH) ARRANGEMENTS FOR CASE 1 USING TL PROCEDURE

t_f (µs)	I_C for horizontal arrangement (ρ_{eq} = 3020 Ωm, R_{LF} = 25.11 Ω)	I_C for vertical arrangement (ρ_1 = 4496 Ωm, h_1 = 5.8 m, ρ_2 = 1040 Ωm, R_{LF} = 24.77 Ω)	I_C difference between vertical and horizontal meshes
0.5	2.03	1.00	- 50.7%
1.0	1.59	1.00	- 36.9%
2.0	1.25	1.00	- 20.1%
3.0	1.17	1.00	- 14.6%
4.0	1.13	1.00	- 11.3%
5.0	1.10	1.00	- 9.28%
6.0	1.09	1.00	- 7.85%
7.0	1.07	1.00	- 6.79%
8.0	1.06	1.00	- 5.99%
9.0	1.06	1.00	- 5.35%
10.0	1.05	1.00	- 4.85%

TABLE VI. IMPULSE COEFFICIENTS I_C FOR HORIZONTAL (90 M LENGTH) AND VERTICAL (15 M LENGTH) ARRANGEMENTS FOR CASE 2 USING TL PROCEDURE

t_f (µs)	I_C for horizontal arrangement (ρ_{eq} = 5833 Ωm, R_{LF} = 48.46 Ω)	I_C for vertical arrangement (ρ_1 = 10194 Ωm, h_1 = 3.4 m, ρ_2 = 1377 Ωm, R_{LF} = 45.92 Ω)	I_C difference between vertical and horizontal meshes
0.5	1.24	1.00	- 19.3%
1.0	1.04	1.00	- 4.17%
2.0	1.01	1.00	- 1.34%
3.0	1.01	1.00	- 1.06%
4.0	1.01	1.00	- 0.78%
5.0	1.01	1.00	- 0.64%
6.0	1.01	1.00	- 0.53%
7.0	1.00	1.00	- 0.47%
8.0	1.00	1.00	- 0.41%
9.0	1.00	1.00	- 0.37%
10.0	1.00	1.00	- 0.35%

better performance, considering Z_P and R_{LF}, for vertical meshes compared to horizontal arrangements using a conductor length equal to the effective length. For situations, such as those shown in Table IV with $\rho_2 < \rho_1$, this can be very welcomed to reach desired Z_P values that don't result, for example, in a LT disconnection by backflashover in insulator chains from an incidence of first and/or subsequent strokes.

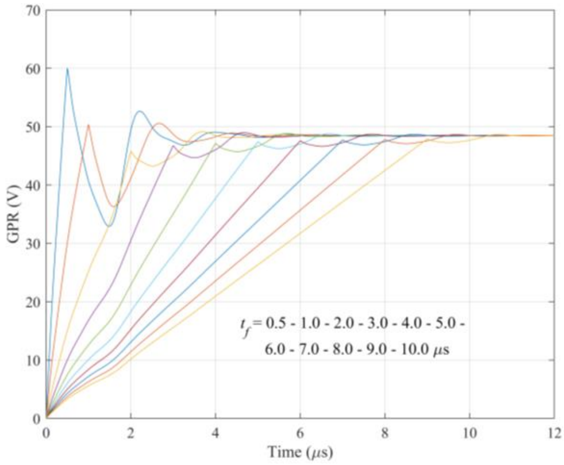
TABLE VII. IMPULSE COEFFICIENTS I_C FOR HORIZONTAL (90 M LENGTH) AND VERTICAL (21 M LENGTH) ARRANGEMENTS FOR CASE 3 USING TL PROCEDURE

t_f (µs)	I_C for horizontal arrangement (ρ_{eq} = 8144 Ωm, R_{LF} = 67.70 Ω)	I_C for vertical arrangement (ρ_1 = 12551 Ωm, h_1 = 4.6 m, ρ_2 = 2839 Ωm, R_{LF} = 65.83 Ω)	I_C difference between vertical and horizontal meshes
0.5	1.07	1.00	- 6.18%
1.0	1.02	1.00	- 1.86%
2.0	1.00	1.00	- 0.29%
3.0	1.00	1.00	- 0.21%
4.0	1.00	1.00	- 0.16%
5.0	1.00	1.00	- 0.10%
6.0	1.00	1.00	- 0.10%
7.0	1.00	1.00	- 0.09%
8.0	1.00	1.00	- 0.07%
9.0	1.00	1.00	- 0.07%
10.0	1.00	1.00	- 0.06%

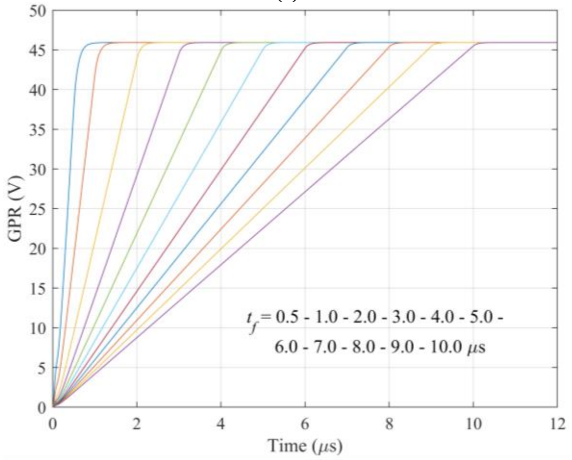
TABLE VIII. IMPULSE COEFFICIENTS I_C FOR HORIZONTAL (90 M LENGTH) AND VERTICAL (27 M LENGTH) ARRANGEMENTS FOR CASE 4 USING TL PROCEDURE

t_f (µs)	I_C for horizontal arrangement (ρ_{eq} = 4268 Ωm, R_{LF} = 35.48 Ω)	I_C for vertical arrangement (ρ_1 = 5711 Ωm, h_1 = 7.3 m, ρ_2 = 2052 Ωm, R_{LF} = 36.47 Ω)	I_C difference between vertical and horizontal meshes
0.5	1.58	1.00	- 36.6%
1.0	1.28	1.00	- 21.9%
2.0	1.08	1.00	- 7.53%
3.0	1.06	1.00	- 5.59%
4.0	1.04	1.00	- 4.16%
5.0	1.03	1.00	- 3.38%
6.0	1.03	1.00	- 2.82%
7.0	1.02	1.00	- 2.42%
8.0	1.02	1.00	- 2.12%
9.0	1.02	1.00	- 1.91%
10.0	1.02	1.00	- 1.72%

Case 3 perfectly illustrates such condition. For a 90 m length, a horizontal arrangement reaches R_{LF} = 67,70 Ω with, at best, Z_P = R_{LF}, which is probably insufficient to prevent a backflashover from a lightning direct incidence at TL ground wires or tower. Hypothetically, if the necessary Z_P was 30 Ω, a vertical grounding arrangement, such as that presented in Fig. 1, can reach this parameter value much more easily and without the requirement of special modifications in the evaluated critical tower.

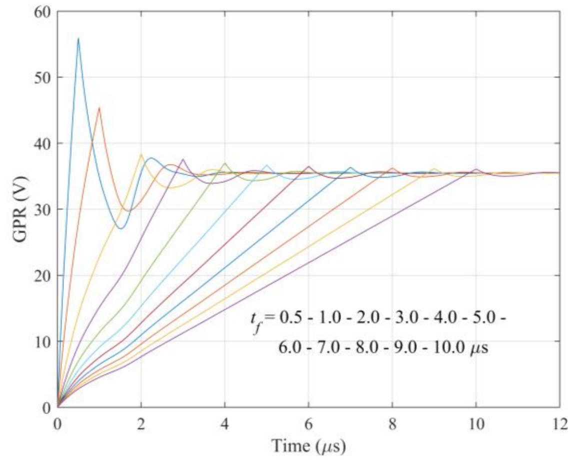


(a)

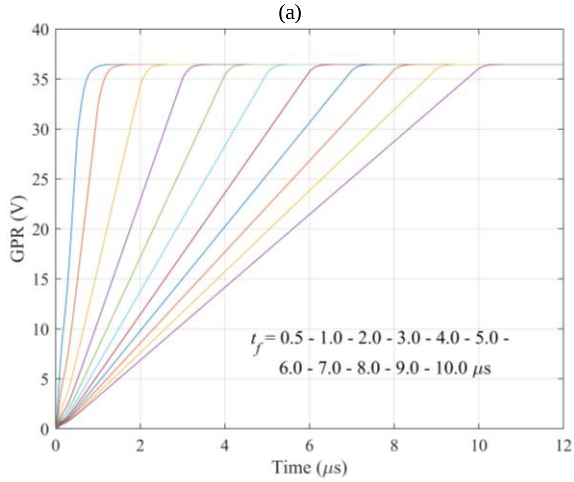


(b)

Fig. 5. GPR curves for case 2: grounding arrangement composed by four: (a) horizontal counterpoise cables (ρ_{eq} = 5833 Ωm) and (b) vertical electrodes (ρ_1 = 10194 Ωm, h_1 = 3.4 m and ρ_2 = 1377 Ωm) – using TL procedure.



(a)



(b)

Fig. 6. GPR curves for case 4: grounding arrangement composed by four: (a) horizontal counterpoise cables (ρ_{eq} = 4268 Ωm) and (b) vertical electrodes (ρ_1 = 5711 Ωm, h_1 = 7.3 m and ρ_2 = 2052 Ωm) – using TL procedure.

IV. CONCLUSIONS

This work presented a grounding vertical arrangement for TL towers as an alternative to that typical composed by counterpoise cables. For two-layered soils with $\rho_2 < \rho_1$, the proposed configuration would have a lower impulse coefficient compared to the typical grounding mesh, especially for fast surges such as subsequent strokes. An analysis aiming impulse coefficient value was made, with an initial comparison of TL and EM methods to solve the problem and comparative evaluations for the median two-layer soil from Minas Gerais state and some critical conditions related to towers from a 230 kV TL.

The results support the preliminary conclusions from [4]. Comparing with EM procedure, TL technique tends to overestimate the values from current waves with t_f < 2 μs, supporting its use for first strokes – subsequent strokes require some caution. Although, the proposed I_C comparison of vertical and horizontal grounding arrangements tends to be a reasonable approximation for surges with t_f < 2 μs.

The critical soils from 230 kV TL towers presented promising results using vertical meshes. For cases where the effective length probably was surpassed with a horizontal arrangement, vertical option can be a very good alternative due to the I_C values associated with its use. In addition, a margin to extend the electrodes length and still decrease R_{LF} and Z_P exists, which is an advantage compared to horizontal meshes for such critical soil conditions. From the homogenous soil evaluation, this characteristic appears to be due to reach the lower resistivity from second-layer soil and not due to vertical arrangement itself.

EM solutions for critical soil conditions and evaluations considering electrical resistivity and permittivity variable with frequency are being made, with experimental practices to support the obtained results planned to be realized.

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