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Transmission line grounding arrangement that overcomes the effective length issue

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***Abstract* — Obtaining a low value for the transmission line grounding impedance is an important issue when dealing with backflashover performance. Usually, for high resistivity soils, increasing the grounding grid dimensions does not lead to low impedance due to the effective length issue. In this work, a special arrangement of ground electrodes is proposed in order to overcome the effective length problem in high resistivity soil. The transient voltage response of this low impedance ground arrangement is determined numerically using parametric modeling approach. Additionally, comparisons of numerical simulations results and measurements from a reduced model study are presented for validation purpose. Regarding the calculation, the grounding arrangement behavior is analyzed considering the frequency dependence of ground electrical parameters.**

Keywords-Tranmission line performance, time-domain response, grounding electrode, grounding impedance, high resistiviy soil.

I. INTRODUCTION

Several efforts have been made to compute the transient behavior of the grounding electrodes [1] and important advances were achieved recently [2-7]. Ground electrodes arrangements with low impedance values are important to consider when dealing with the lightning performance of aerial transmission lines. In this paper, a special ground electrode arrangement is proposed and its response is analyzed. The main purpose is to obtain a low impedance value even for high resistivity soil.

The performance of grounding electrodes are strongly influenced by the lightning stroke current, electrodes geometry and soil resistivity and permittivity values. Considering the stroke current, the important parameters are the peak value and waveform. The soil ionization around the electrodes depends on the peak value and the waveform determines the transient response. The soil ionization phenomena are not treated in this study. In this study, the soil electric parameters are considered both frequency invariant and frequency dependent. This study uses the transmission line theory to calculate the ground electrode response with line parameters calculated using Sunde´s equations [1]. The corresponding time-domain response is obtained using the parametric modeling approach described in [7] and [8]. It was used to compute the horizontal electric field, due to lightning, in the border earth-air. The details of the special grounding arrangement is presented and its performance is validated through comparisons between calculations and measurements from a reduced model study.

The proposed arrangement is aimed to very high resistivity soil, as the case of the State of Minas Gerais, Brazil, where the median apparent resistivity is 1700 Ωm and the average is 2400 Ωm [9]. The proposed innovative arrangement, first analyzed and presented in [10], permits the use of grounding arrangements where wire lengths are greater than the effective length while producing a reduction in the impedance value.

II. LOW IMPEDANCE GROUND ELECTRODE CONFIGURATION

The IEEE Guide for Improving the Lightning Performance of Transmission Lines [12] states the use of additional guy wires on transmission towers improve the transmission line lightning performance: *This treatment should also improve lightning performance in two ways. First, each new guy anchor will behave as an additional ground electrode. The anchors may be grounded with low-resistivity material such as concrete, and bonded to any existing counterpoise or structure, to maximize the benefit. Second, the guy wires will mitigate the tower surge response. Four widely separated guy wires may reduce the impedance of a tower from 100 Ω to 50 Ω. This factor alone may reduce the outage rate of a tall line by 30%.*

Using the basic concept proposed in the IEEE Guide a simple and innovative idea to reduce the value of the impedance of a transmission tower ground electrode is sketched in Fig. 1.

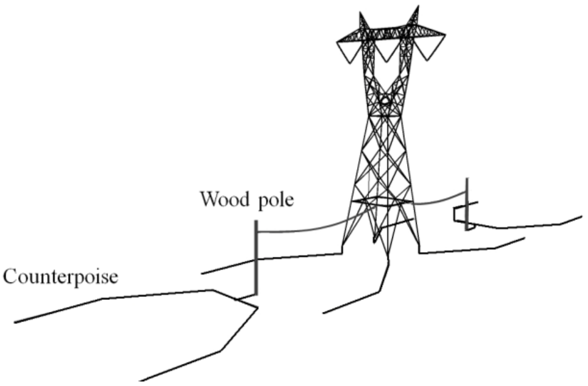

Figure 1. Skecth of the proposed grounding arrangment with low impedance ground electrode.

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The proposed concept is ease to implement and provides a technique that overcomes the effective length problem. It uses an aerial line to connect the tower basis to an extra set of counterpoise which provides the impedance value reduction. In terms of cost, it will increase about 20% in our estimate, mainly due to the pole and the aerial line, since the original buried conductor is split in two portions.

III. NUMERICAL SIMULATIONS

Since the main objective is studying the grounding arrangement performance, the coupling between the phase conductors and the aerial part of the proposed arrangement is not considered. However, if the coupling was considered, probably, a better line performance would be achieved because the aerial part of the arrangement acts like an extra shielding wire.

The classical current waveform of 1.2 x 50 μs is used in simulations and the current peak value is equal to 1 kA. The ground parameters considered are resistivity of 5000 Ωm and relative permittivity of 10. The buried cables, 90 m long, are modeled as a transmission line with parameters calculated according to Sunde [1]. The transient calculation is done based on the methodology depicted in [11]. The cases showed from Fig. 2 to Fig. 4 are used to determine the performance of the arrangement showed in Fig. 1. The arrangement showed in Fig. 2 is a classical design. Usually in the State of Minas Gerais, the power utilities do not use counterpoises longer than 90 m [9]. The simulation performed according Fig. 3 denotes the effective-length problem. The proposed grounding arrangement is shown in Fig. 4. In all the cases the ground potential rise (GPR) is calculated.

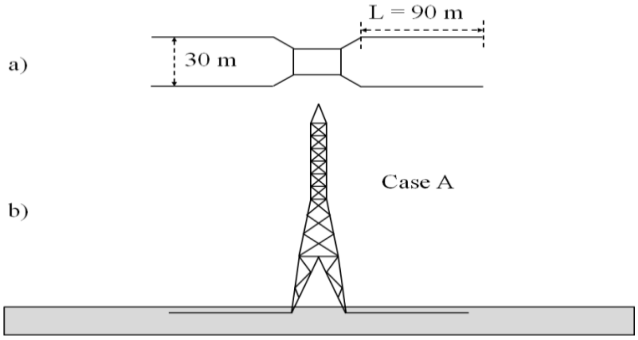

Figure 2. Grounding arrangement (case A). a) top view and b) side view.

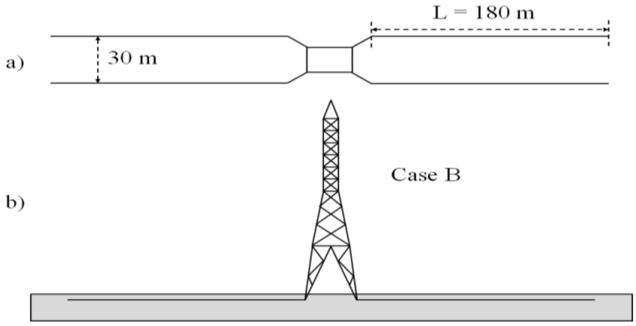

Figure 3. Grounding arrangement (case B). a) top view and b) side view.

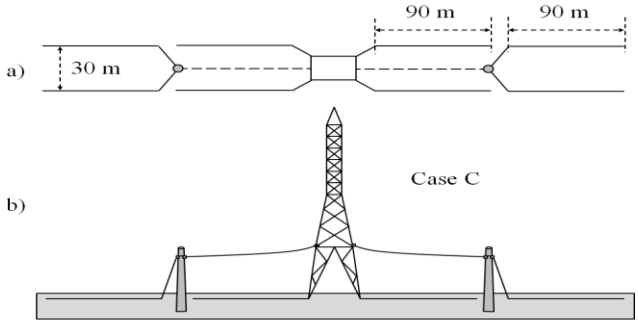

Figure 4. Grounding arrangement (case C). a) top view and b) side view.

The calculated GPR for cases A and B are presented in Fig. 5. The arrangement of case B only reduces the GPR for times greater than 1.5 μs and characterizes the effective-length problem.

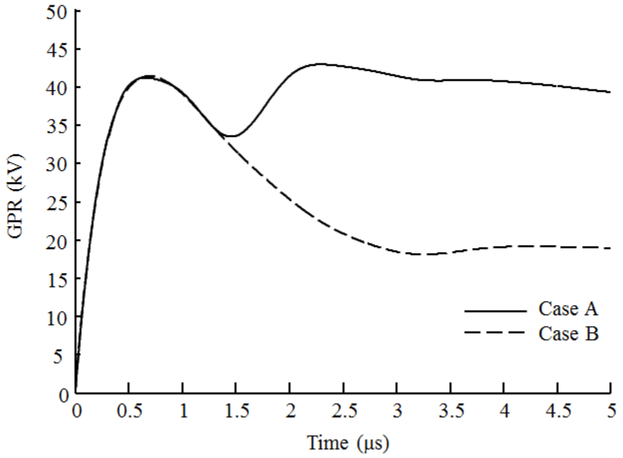

Figure 5. Ground potential rise, Cases A and B.

The GPR for cases A, B and C are compared in Fig. 6. The proposed arrangement (case C) provides an average reduction of about 30% when compared to case A, in the interval of ~0.5 to ~1.5 μs.

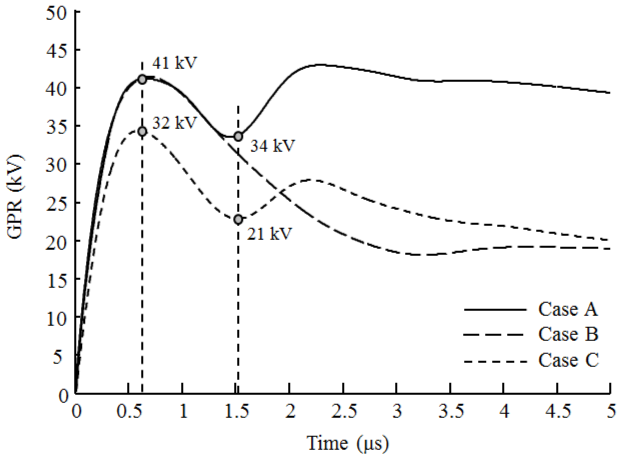

Figure 6. Ground potential rise, Cases A, B and C.

To clarify the effect of the extra counterpoises of the proposed grounding arrangement (case C), in relation to case A, the case showed in Fig. 7 is analyzed. In Case A_1 a continuous wire is installed connecting adjacent towers. It was considered that the adjacent towers are far so that reflected waves may be disregarded.

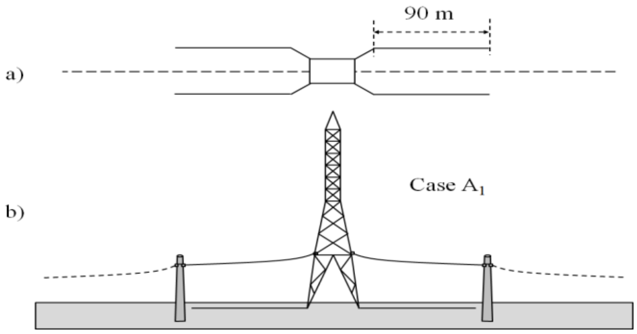

Figure 7. Continuous aerial wire connecting adjacent towers, Case A1, a) top view and b) side view.

The simulation result of Case A_1 together with the results of cases A and C are showed in Fig. 8. The curve of Fig. 8, for Case A_1 shows a reduction on the GPR when compared to Case A. This reduction occurs because the surge impedance of the aerial cable is in parallel with the impedance of the ground electrode. With the proposed arrangement, in addition to contribution of the aerial cable, the negative reflection in the extra counterpoises of the proposed arrangement provides a more pronounced reduction in GPR for times greater than 0.5 μs.

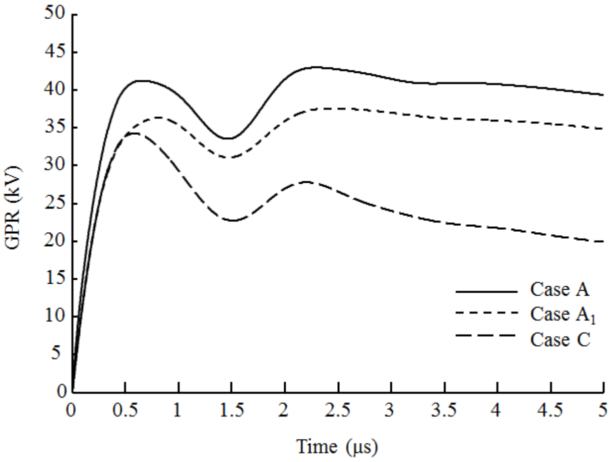

Figure 8. Ground potential rise, Cases A, C and A_1.

The transient impedance, $z(t)$, is defined as the ratio between the GPR and the current, as follows:

$$z(t) = \frac{GPR(t)}{i(t)} . \quad (1)$$

The transient impedance of Cases A and C are showed in Fig. 9.

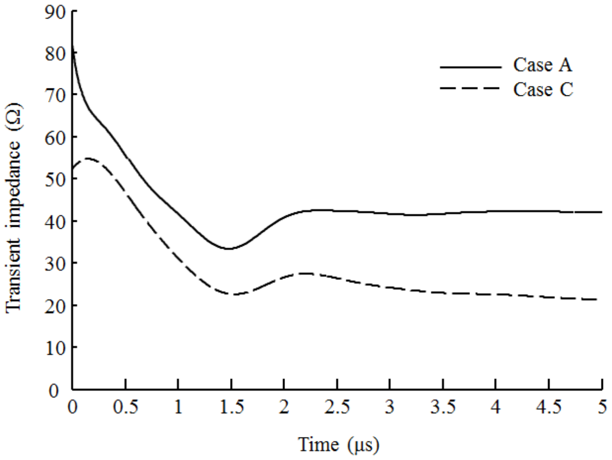

Figure 9. Transient impedance, Cases A and C.

IV. REDUCED MODEL STUDY

The obtained numerical results are validated through comparisons with a reduced model study measurements. The simulated lightning current is injected in the grounding arrangement using a low propagation velocity transmission line, the LIA, presented in [5]. This kind of transmission line was already used in lightning studies using reduced model in [13] and [14]. In [5] the LIA was used in a horizontal position, but in this study, due to the little diameter of the used hemispherical tank, the LIA was used in a vertical position. The LIA in vertical position is closer to the real phenomena and, according to [15], the position of excitation wire, in our case the LIA position, causes little influence on the measured values. This vertical transmission line is made with a thin insulated wire wrapped around a non-conductive polyvinyl chloride (PVC) pipe. The propagation velocity can be adjusted controlling the number of turns per unit length. For this study a propagation velocity of 24 m/μs was used. Using this transmission line and a portable impulse generator with a peak value of 1 kV and current peak value around 250 mA, a front time of 130 ns was achieved. The used arrangement is show in Fig. 10 and the obtained current waveform is shown in Fig. 11. The current peak value is almost independent of the grounding electrode impedance because of the vertical transmission line surge impedance is high, about 3 kΩ [5].

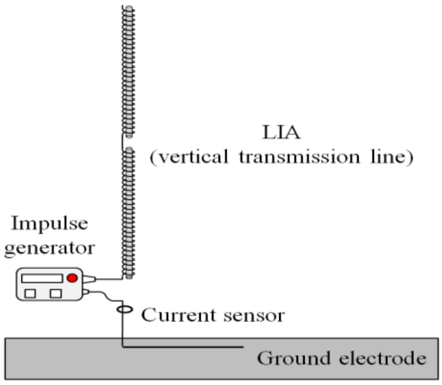

Figure 10. Arrangement used to simulate a stroke channel.

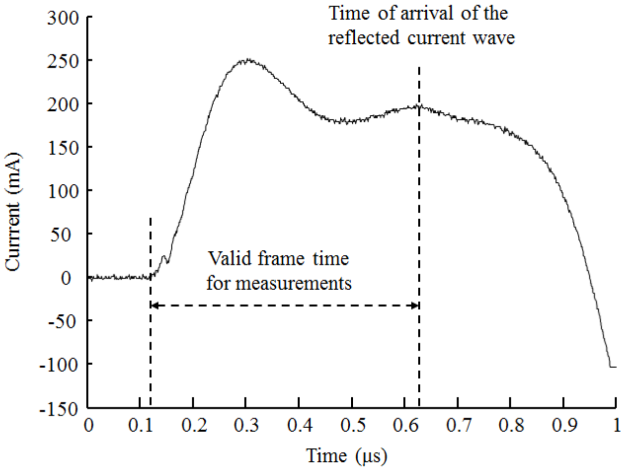

Figure 11. Current wave shape shown the reflected wave in the vertical transmission line upper end.

Figure 12. Hemispherical steel tank full of wet sand.

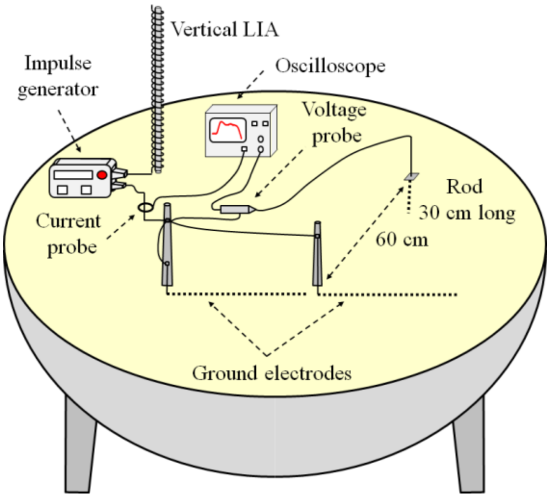

Figure 13. Picture of the experimental set.

The grounding electrode was simulated by a 2 copper pipes, 10 mm of diameter and 1 m long each. The ground was simulated by a hemispherical steel tank full of wet sand (see Fig. 12) similar to that used in [16]. To reduce the sand resistivity, a solution of water and salt (NaCl) was added. It is important to control the sand resistivity value, the current front time and the grounding electrode length in such a way the effective-length problem shows in the measurements. A value of about 10 Ωm was estimated for the sand resistivity. The overall scale factor is estimated to be 50, which corresponds to a real grounding electrodes of 50 to 100 m long buried in a soil of 500 Ωm and excited by a current with front time of 6.5 μs.

A schematic of the arrangement used in the experiment is shown in Fig.13. The GPR was measured in a same way used in [5]. Photographs of the experimental set are shown from Fig. 14 to Fig. 16.

Figure 14. Photograph of the vertical transmission line used to simulate the lightining channel.

Figure 15. Photograph of cooper pipes used to simulate ground electrodes.

Figure 16. Photograph of the aerial line used to connect the ground electrodes.

The three studied cases are shown in Figs. 17, 18 and 19.

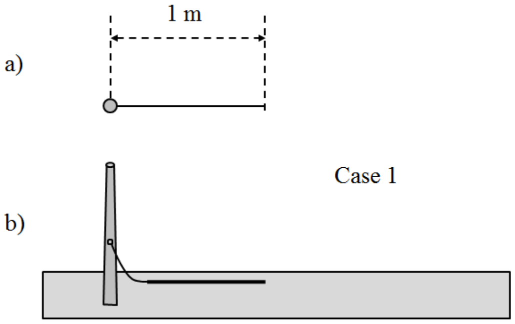

Figure 17. Case 1, horizontal ground electrode, 1m long. a) Top view, b) side view.

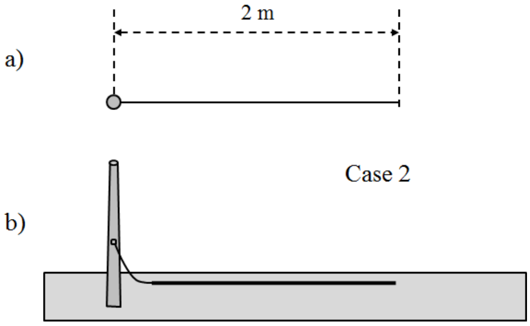

Figure 18. Case 2, horizontal ground electrode, 2m long. a) Top view, b) side view.

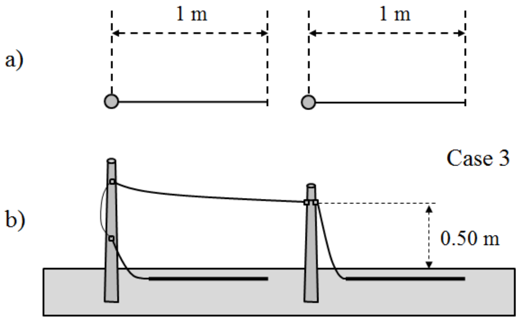

Figure 19. Case 3, two horizontal ground electrodes, 1m long each, connected by an aerial line 1m long. a) Top view, b) side view.

The measured GPR for the three cases are presented in Fig. 20, where the effective-length problem can be easily identified as well as the effectiveness of the proposed grounding electrode arrangement.

The measured values were compared with simulated results. Fig. 21 shows a comparison between the measured and the simulated current waveform used in calculation. The simulated current was obtained with two Heidler functions [17]. Moreover, as the sand was very wet, its relative permittivity was considered to be as the pure water ($\varepsilon_r = 80$) in simulations.

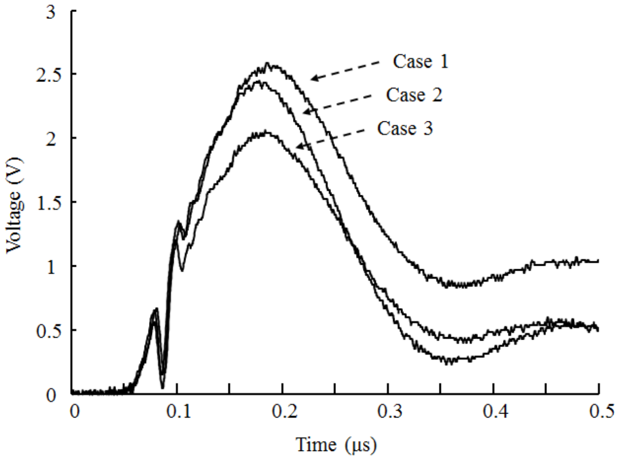

Figure 20. Measured GPR for the three studied cases.

The measured values were compared with simulated results. Fig. 21 shows a comparison between the measured and the simulated current waveform used in calculation. The simulated current was obtained with two Heidler functions [17]. Moreover, as the sand was very wet, its relative permittivity was considered to be as the pure water ($\varepsilon_r = 80$) in simulations.

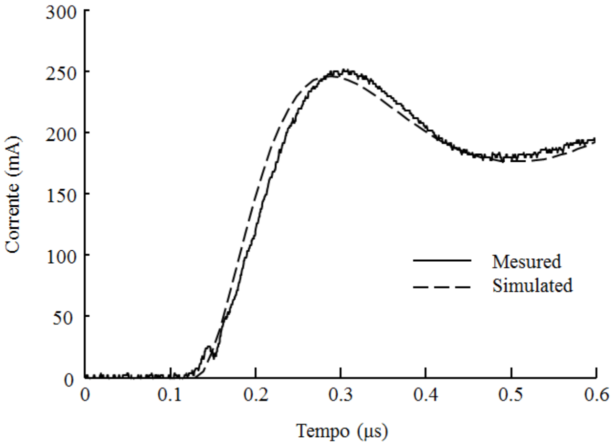

Figure 21. Measured and simulated current waveform.

Fig. 22 shows the calculated GPR for the three cases. The results are similar to those shown in Fig. 20. Aiming a better comparison, each one of the cases was compared separately in Figs. 23, 24 and 25 showing the wave front and the peak values very close, while the tails of the calculated voltages are higher than the measured ones. Reference [18] presents a study about the lightning-induced current in a cable buried in the first layer of a two-layer ground which shows that the effect of the second layer with low resistivity value is to reduce the tail of the induced current. It seems that something similar is occurring in the experimental set used in this study.

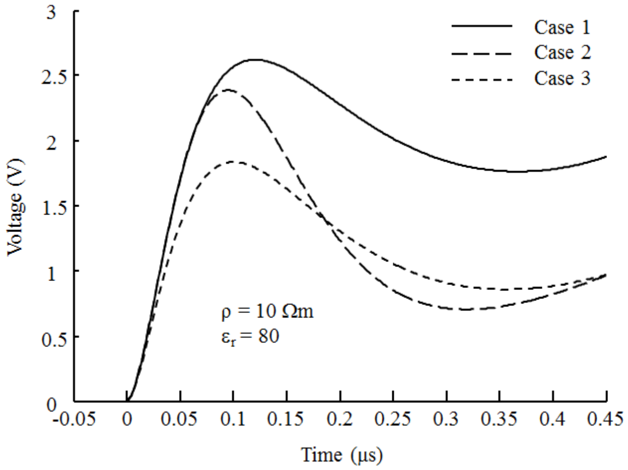

Figure 22. Calculated GPR for the three studied cases.

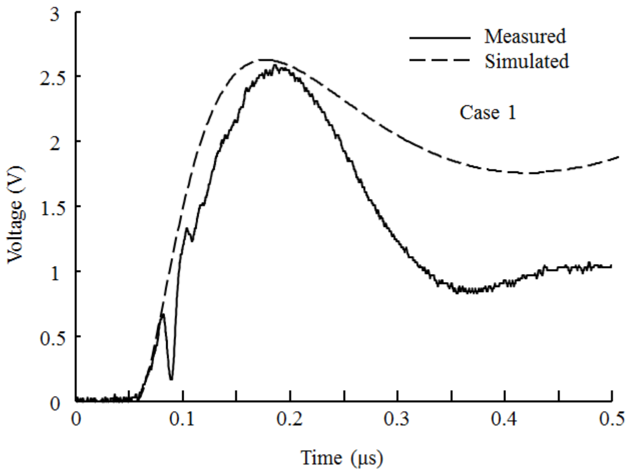

Figure 23. Calculated GPR for Case 1.

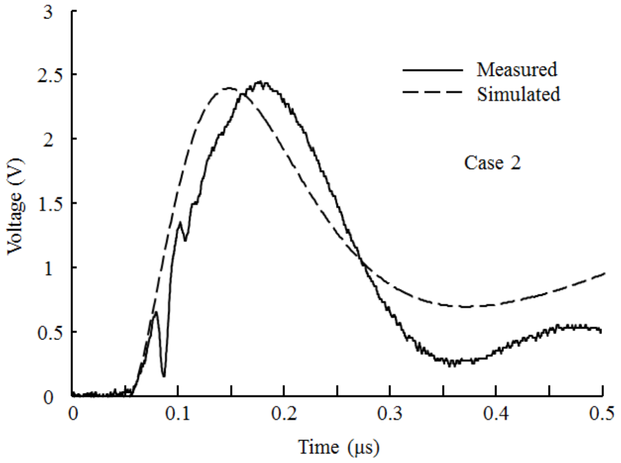

Figure 24. Calculated GPR for Case 2.

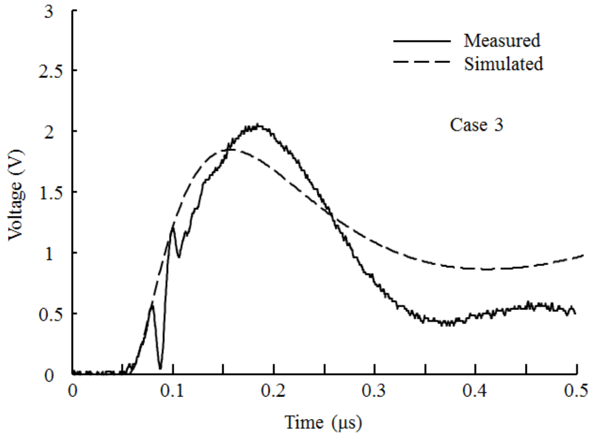

Figure 25. Calculated GPR for Case 3.

V. INFLUENCE OF THE FREQUENCY DEPENDENCY OF SOIL ELECTRICAL PARAMETERS

In order to represent the frequency dependency of the ground electrical parameters, this study use the universal model proposed by Longmire and Smith [19] which uses the experimental data of Scott [20]. The GPR for cases A, B and C were calculated using the Longmire and Smith model and results are shown in Fig. 26. It is clear that the behavior is similar to that one showed in Fig. 5 and Fig. 6 where constant parameters were used. The GPR values are about 30% lower if the frequency dependency is considered.

A second model to represent the frequency dependency of the ground electric parameters is the one proposed by Alipio and Visacro [21]. Fig. 27 shows a comparison of the GPR calculated for case C using the Longmire-Smith and the Alipio-Visacro models. The results are similar, but the second one presents lower values.

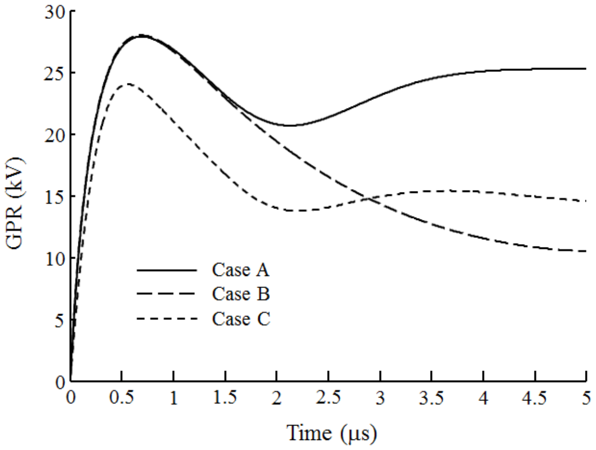

Figure 26. Parametric modeling approach, Cases A, B and C. Ground electric parameters considered frequency dependent, using Longmire and Smith model.

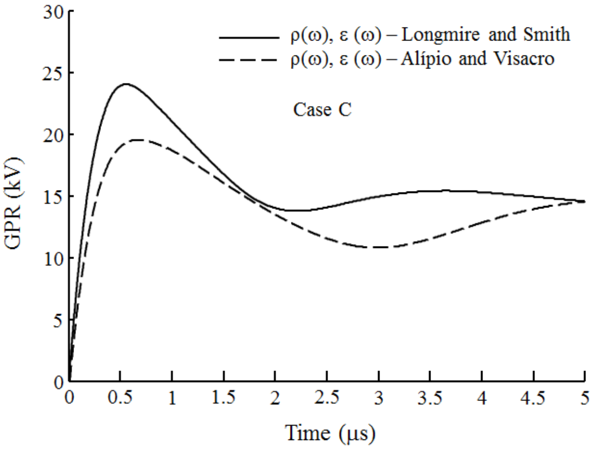

Figure 27. GPR calculated for case C considering the frequency dependency of the ground electric parameters.

The transient impedance of case C is shown in Fig. 28 considering the ground electrical parameters in both condition, as constant and varying (frequency dependency).

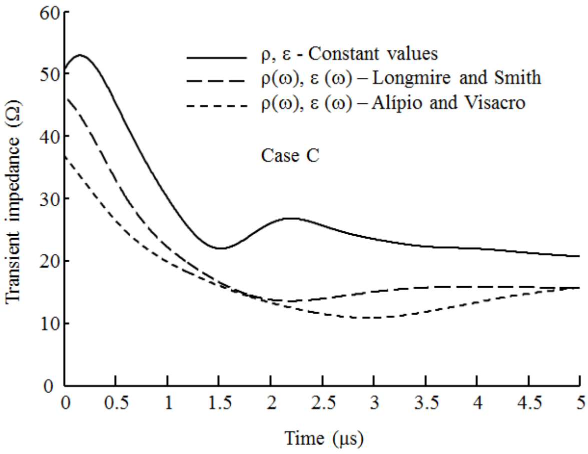

Figure 28. Transient impedance, Case C. Groud parameters considered as constant values and frequency dependent using Alípio and Visacro model and also Longmire and Smith model.

VI. DISCUSSION

In Fig. 5, it was shown that the increase in the wire length from 90 m to 180 m (cases A and B) implies in a voltage reduction of about 50% for the instant of time greater than 3 μs (long times). For the times lower than 1.5 μs the voltage reduction is zero, i.e., the values are the same for both cases.

For long times ($t \geq 3$ μs), case C is similar to case B. However, for the first few microseconds the GPR values are about 78% of the case A ($t \geq 0.5$ μs, approximately) and 62% ($t \geq 1.5$ μs, approximately), as verified in Fig. 8.

The better performance verified in case C is due to the effectiveness of the proposed arrangement in overcoming the effective-length problem using an aerial line (where the propagation velocity is higher than the velocity for the buried wires) connecting the two grounding electrodes. This aerial line connection makes the two ground arrangements works almost as they were in parallel leading to an equivalent average impedance value around 70% of case A in the range time from 0.5 to 1.5 μs.

The obtained experimental results using reduced model techniques are consistent with the numerical simulation results. The consideration of the steel tank, as a second layer of a two layer stratified soil improves the comparison.

For the case of frequency dependent soil electric parameters, the results showed in Fig. 26 presented a similar behavior to the cases with constant soil parameters.

If the tower does not sustain the aerial cable of the proposed arrangement, due to mechanical constraints, a pole can be installed near the tower as illustrated in Fig. 29.

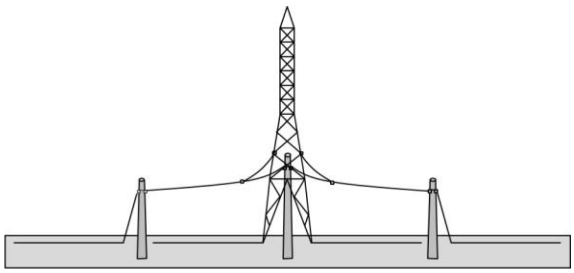

Figure 29. Practical implementation of the proposed solution.

VII. CONCLUSIONS

This paper presented a special grounding arrangement to overcome the effective-length problem in transmission line towers installed in high resistivity soil. Numerical and measurements from reduced model study was presented and discussed.

The proposed transmission line grounding arrangement is a low cost and simple solution that can be adopted in rural areas in places that exhibit very high soil resistivity values.

The numerical simulations results exhibit a very good agreement with that obtained in reduced model experiments.

Usually, in the State of Minas Gerais the power utilities do not use counterpoises longer than 90 m and in very high resistivity soils it does not provide adequate low values for grounding impedance. Consequently, the desirable lightning performance of the transmission lines is not achieved.

For soils with resistivity values of about 5000 Ωm the proposed grounding arrangement works well providing an average reduction around 30% in the impedance values in the time range between 0.5 and 1.5 μs and when compared with the classical solution (counterpoises shorter or equal to 90 m).

The transient impedance of the proposed solution in a 5000 Ωm soil varies from 46 Ω to 30 Ω, approximately, in the time interval of 0.5 to 1.5 μs, considering the soil electric parameters as constant. If the frequency dependency is considered, the transient impedance varies in a range of 30 Ω to 20 Ω, approximately, in the same time interval.

The next stage of this research project is to perform measurements in a real transmission line using the proposed arrangement, which the authors expect to report soon.

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