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Assessment of a Frequency Dependent Soil Model Impact on Lightning Overvoltages

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***Abstract*—A key aspect in the evaluation of the lightning performance of an overhead line is the tower grounding modeling approach. It affects the insulator string overvoltages and the ground potential rise (GPR). This work aims to assess the impact of the soil model i.e. using frequency independent and frequency dependent parameters. The developed grounding system model was implemented in the EMTP-ATP program. A RLC synthetized network is used instead of a constant lumped resistance. The RLC elements are derived from the rational approximation of the grounding system response obtained using a rigorous model based on the direct solution of Maxwell's equations in the frequency domain. An application example is presented, showing that the computed overvoltage is sensitive to the frequency dependence of the soil parameters. This effect is more pronounced for high resistivity soil.**

Keywords- lightning, overhead lines, grounding system, frequency depedent ground parameters

I. Introduction

The lightning response of an overhead line is amongst the most important phenomena related to its performance evaluation [1]. In the case of a direct incidence, it is assumed that it occurs in either phase conductors or shield wires. The associated overvoltage might be high enough to cause a flashover on string insulators leading to a short-circuit which in turn might cause the switching of the whole line. An indirect incidence, i.e., a lightning strike occurring nearby to a given overhead line might damage a distribution network due to induced voltages. According to statistical data, it is estimated that around 70% of unscheduled outages of transmission lines and more than 50% of distribution networks are attributed to the lightning incidence, [2] [3].

Given the difficulties related to observe a lightning overvoltage experimentally, it is customary to analyze it using computer simulations. In the technical literature there are, mainly, two main approaches. The first one is based on time-domain simulation using a electromagnetic transient (EMT)-type program such as ATP/EMTP, EMTP-RV or PSCAD [4]. The second one is based on developing dedicated program in the frequency domain with the time response obtained using either Fourier or Laplace Transform or their numerical counterparts [5][6]. While frequency domain based simulation can provide rather detailed tower grounding system including frequency dependent soil models [5]-[7], regardless of their formulation [7], [12]-[14].

EMT-type simulation commonly rely on a lumped resistance to represent the tower grounding [4]. Such approach leads to more severe results which do not correspond to values found experimentally [7][8][9]. A possibility to improve this scenario is to calculate the grounding system response in the frequency domain and then implement it using a rational approximation which leads to a state-space approximation. For instance, in [11] EMTP-RV was used to evaluate the lightning response of a tower grounding system modeled as a rational approximation and using a frequency dependent soil model based on [12].

In this work, we propose a similar approach but with some noticeable differences. First, the transmission system is modeled in ATP/EMTP and a RLC network is used to represent the tower grounding system instead of a state space realization. Second, we opt to use a distinct soil model, based on [13] which is also causal (see [15] for details regarding causality assessment of soil models). Third, the focus has been on both the ground potential rise and the overvoltage across insulator strings considering

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distinct lengths for the ground electrodes. The paper is organized as follows: section II describes the system configuration; the simulation results are presented in section III; and the main conclusions on this work are shown in section IV.

II. System Description

A distribution system of 138 kV was used for the evaluation of the lightning performance. The tower considered is depicted in Fig. 1 together with the coordinate of phase conductors and shield wire. The line span was assumed to be 400 m. Linnet cables were used for phase conductors (labeled as FA, FB and FC in Fig. 1), shield wire is a 3/8" HS cable (labeled as PR in Fig. 1).

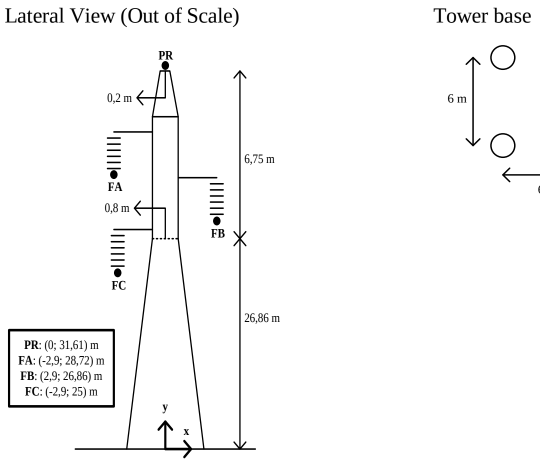


Figure 1. Tower configuration for 138 kV system.

The grounding consists of four counterpoise cables each of length L, buried at a depth of 0.5 m and connected to the metallic base of the tower, as shown in Fig. 2. In this work, we have considered 5 distinct lengths for the counterpoise, namely 10, 30 50, 70 and 90 m. Some different scenarios were considered for the ground parameters, a frequency dependent soil model with low frequency resistivity of 100 and 1000 Ω.m, and a constant parameter model using these two low frequency values and a relative ground permittivity of 15.

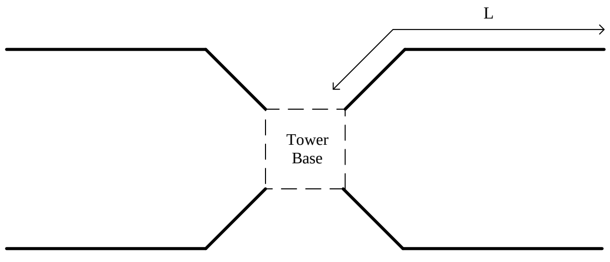


Figure 2. Tower grounding configuration.

The system considered two spans of 400 m and a single tower connected these spans. At end of each span there is a matching impedance to avoid unnecessary reflections. The injection current is made at the tower top. The adjacent towers and grounding influence are disregarded. This decision is not associated with any limitation of the developed modeling. In fact, it is based in order to focus the analysis on the investigation of the essence of influence of each parameter (tower, ground, soil resistivity, etc.) in overvoltage levels established in the system. As a reference, for spans not too long and time front current waves not too short, consideration of the adjacent towers and grounds implies a moderate reduction of the maximum overvoltage level at the tower top [16]. In other situations, the adjacent elements have influence only in the wave tail and little influence on the maximum overvoltage levels established. Therefore, this assumption can be considered as conservative.

The lightning strike is represented by a current injection given by the sum of Heidler functions [17] as shown below

$$i(t) = \sum_{k=1}^{n} \frac{I_k}{\eta_k} \frac{\left(\frac{t}{\tau_{1k}}\right)^{n_k}}{1 + \left(\frac{t}{\tau_{1k}}\right)^{n_k}} e^{-\frac{t}{\tau_{2k}}} \qquad (1)$$

where n =7, the others parameters in (1) can be found in [3][18][19]. The lightning current given by (1) reproduces median values of measurements made in the Morro do Cachimbo Station [3][18][19]. Fig. 3 depicts the current waveform used here, it is representative of a first return current, with an approximately peak of 45 kA.

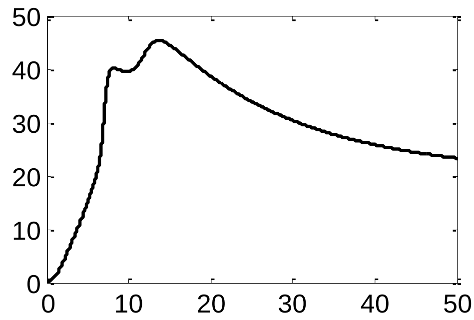


Figure 3. Current waveform obtained from Heidler functions for representation of the first return current (median) measured on the Morro do Cachimbo Station.

For the tower shown in Fig. 1, we have adopted the model depicted in Fig. 4. It consist to four lossless single-phase line with a propagation velocity equal to 80% of light [20], and surge impedance calculated as proposed in [21]-[23]. Table I presents the data for the tower model. These values were calculated using the revised Jordan's formula, which was extended in [21] to take into account vertical multiconductor systems. Four-level tower impedance model with highest impedance at the top and lowest in bottom section in Table I is similar to Wagner/Hileman cylinder model from 1960 [24].

The two-line span considered were represented assuming an untransposed frequency-dependent modal domain line model. In ATP/EMTP, this model is called the JMARTI model and uses a constant transformation matrix calculated at a user-defined frequency and a pole-residue realization of the characteristic impedance and propagation function, see [25] for details.

The tower grounding system is evaluated according to a comprehensive and elaborate electromagnetic modeling, based on the direct solution of Maxwell's equations in the frequency domain, by applying the Method of Moments, as described in [9] [10] [26][27][28].

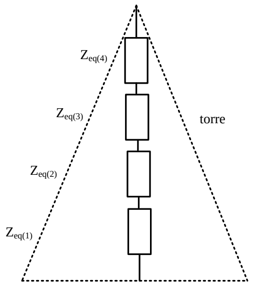


Figure 4. Tower model in ATP.

TABLE I. DATA FOR TOWER MODEL

TOWER SECTION K	SURGE IMPEDANCE (Ω)
1	130
2	182
3	235
4	290

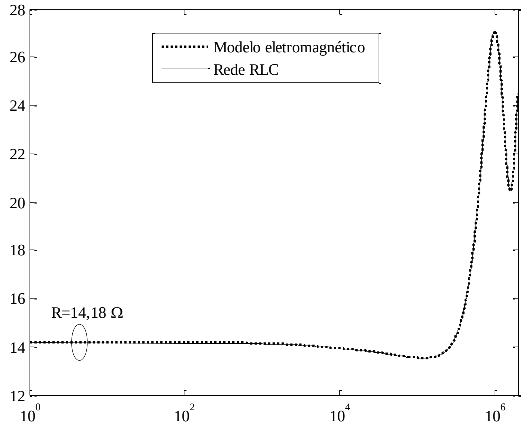
As mentioned before, some possibilities were considered for the behavior of the soil conductivity and permittivity. For the case of a frequency dependent soil model, we used the formulation in [13], which comprises experimental data obtained in several geological areas in Brazil and consider soil samples measured from 100 Hz up to 2 MHz. The value of the effective conductivity σ is expressed as a function of the low frequency conductivity σ_0 obtained from the measured 100 Hz soil resistivity.

$$\sigma + j\omega\varepsilon \approx \sigma_0 + \Delta i \left[\text{cotang}\left(\frac{\pi}{2}\alpha + j\right)\left(\frac{\omega}{2\pi \cdot 10^6}\right)^{\alpha}\right] \qquad (2)$$

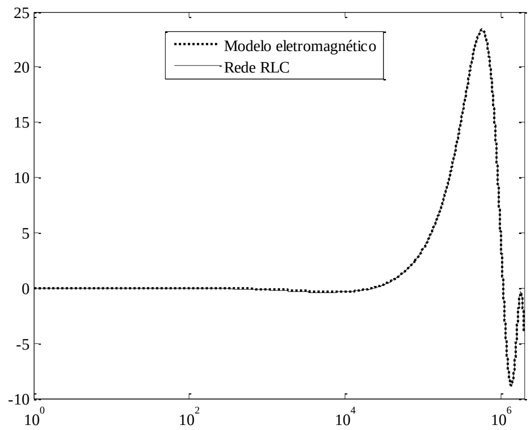
where ω is the angular frequency, $\sigma_0 = 1/\rho_0$ (where ρ_0 is the low frequency ground resistivity), Δi and α are statistical parameters, which express the frequency dependence of soil conductivity and permittivity. To evaluate the probability density functions associated with parameters Δi and α, Weibull distributions were adopted. As discussed in [13], for most cases of interest, it may be acceptable to consider median values for both Δi and α, which are 11.71 S/m and 0.706 respectively. From the frequency response of the grounding system, a rational approximation based on the vector fitting algorithm is obtained [29][30][31]. The pole-residue model is then converted to an equivalent RLC circuit allowing its direct use in ATP/EMTP. Figure 5 presents the tower grounding impedance as a function of frequency together with its rational approximation. The high frequency behavior of the tower grounding has a rather oscillatory behavior. The maximum value of the tower grounding impedance is more than two times higher than the low frequency value and a noticeable imaginary part. It can be seen that there is an excellent agreement between these two results. Only electrical grounding is modeled using fitting techniques by means of rational functions and represented directly in the time domain by equivalent RLC circuit.

III. SIMULATION RESULTS

For the time-domain responses, we consider a lightning striking at the tower top leading to currents propagating along the tower and through phase and shield wires. As mentioned, we consider the following scenarios: two cases considering a constant parameter model using only the low frequency ground resistivity and a relative ground permittivity of 15 and two considering frequency dependent soil models.



(a) Magnitude

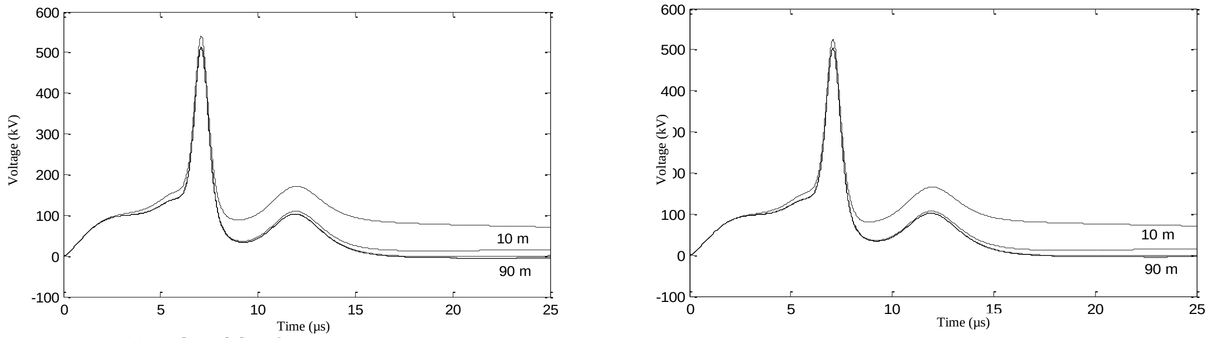


(b) argument

Figure 5. Tower Grounding impedance.

Figure 6 depicts the voltage at the lower string insulator considering a constant parameter soil model and a frequency dependent one for a low frequency soil resistivity of 100 Ω.m. In this case, the inclusion of frequency dependent soil parameter does not affect sensible the results. The reason for this lower impact lies in the fact that in this case the frequency where $\sigma \gg \omega\varepsilon$ in the ground is over around a few tenths of MHz. For the type of excitation considered here the harmonic content in the high frequency range is rather low. For a higher low frequency soil resistivity, the results are rather different as depicted in Fig. 7.

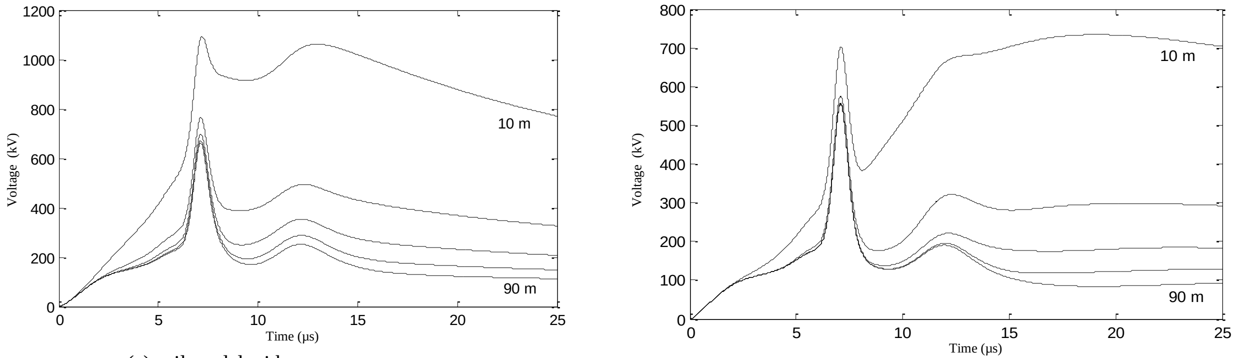
For longer ground electrodes it is found that the tail part of the voltage waveform does not reach a constant value regardless of the soil model considered. A sensible difference can be found if frequency dependent ground parameters are considered. In fact, this inclusion leads to overvoltages around the same value found in Fig. 6.



(a) soil model with constant parameters

(b) frequency dependent soil model

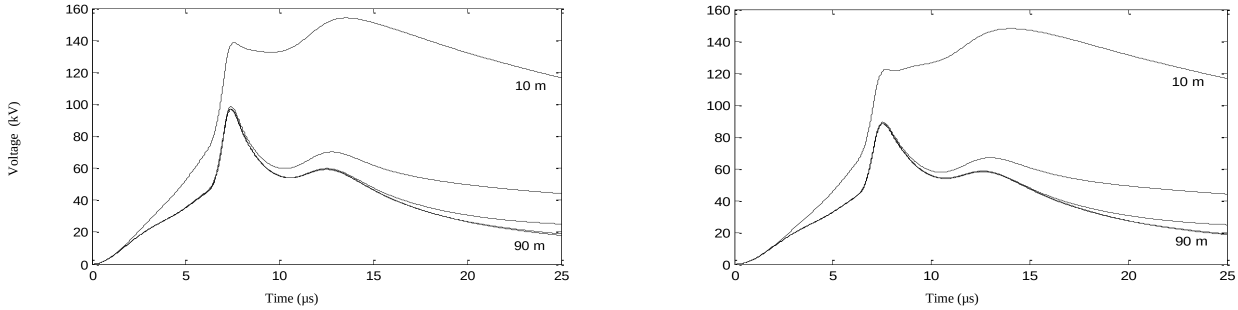
Figure 6. Overvoltage in lower string insulator for 100 Ω.m.



(a) soil model with constant parameters

(b) frequency dependent soil model

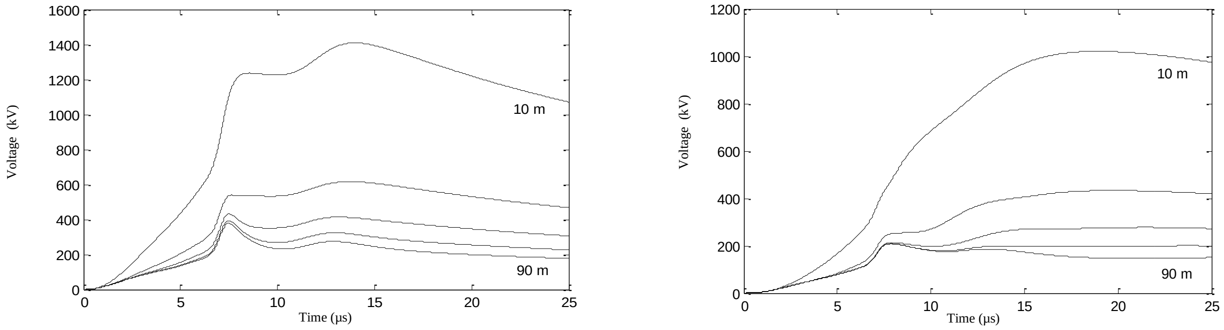
Figure 7. Overvoltage in lower string insulator for 1000 Ω.m



(b) frequency dependent soil model

(a) soil model with constant parameters

Figure 8. GPR for 100 Ω.m



(a) soil model with constant parameters

(b) frequency dependent soil model

Figure 9. GPR for 1000 Ω.m

TABLE II. EFFECT OF COUNTERPOISE LENGTH IN OVERVOLTAGE REDUCTION

COUNTERPOISE LENGTH (M)	OVERVOLTAGE REDUCTION (%)	
	ρ_0=100 Ω.M	ρ_0=1000 Ω.M
10	3	37
30	1.8	25
50	1.7	20
70	1.7	17
90	1.7	16

Table II summarizes the effect of the grounding electrode length in the overvoltage reduction considering frequency dependent soil models.

For the GPR, the results have a similar behavior, see Figs. 8 and 9. The inclusion of frequency dependent soil model is rather more pronounced if a higher value of low frequency ground conductivity is considered. For 100 Ω.m of low frequency ground resistivity and longer ground electrodes, one finds that the inclusion of frequency dependent soil model does not affect the voltage waveform. For shorter electrodes, some small differences can be found as depicted in Fig. 8 and Fig. 9. The results for the electrode length impact on GPR considering frequency dependent models is summarized in Table III.

Although not shown here, similar behavior was found considering other values for low frequency ground resistivity, i.e., the impact of the inclusion of a frequency dependent soil model is more pronounced for a higher low frequency ground resistivity. Furthermore, this inclusion has a more significant impact on the GPR than on the insulation string voltage. Thus, despite the tower grounding system has an essential role in improving the line performance, its relative importance is reduced in the presence of other elements of the transmission system, especially of the tower itself.

TABLE III. REDUCTION OF GPR MAXIMA

COUNTERPOISE LENGTH (M)	OVERVOLTAGE REDUCTION (%)	
	ρ_0=100 Ω.M	ρ_0=1000 Ω.M
10	4	28
30	10	30
50	9	36
70	9	47
90	9	45

IV. CONCLUSIONS

In this paper, a number of simulation results of the direct strike of lightning on a transmission line is presented. The simulations were performed using ATP/EMTP taking into account models consistent for the power system elements and with the inclusion of a frequency dependent tower grounding system.

The inclusion of the variation of the soil parameters in the tower grounding system implied in a reduce stress in terms of insulation strings overvoltage and also with respect to the GPR. An interesting result is that the inclusion of a frequency dependent soil model has a more significant effect for the latter, i.e., GPR.

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