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The Impact of the Frequency Dependence of Soil Electrical Parameters on Lightning Overvoltages Developed in a 138 kV Transmission Line

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Abstract: This study evaluates the overvoltages developed due to direct lightning strokes to a 138-kV transmission line tower top comparing constant and frequency-dependent soil parameters. ATP (Alternative Transients Program) was used to simulate the phenomena. The inclusion of the frequency-dependent soil parameters causes a percentage decrease of the overvoltage peaks when compared with constant soil parameters of around 15% to 33% for first strokes considering values of soil resistivity of 500 Ω.m and 2.500 Ω.m. It was also studied the counterpoise cables length reduction in order to maintain equivalent overvoltage levels to those of simulations with constant parameters. This reduction ranged from 25 to 55%, which could contribute to economic gains as well as operational efficiency in the grounding systems and transmission line construction time. Therefore, disregarding the frequency dependence of the soil parameters in simulations may lead to an overly conservative estimation of the lightning performance of the transmission line.

Keywords: ATP; ground permittivity; ground resistivity; lightning; transmission line.

1. INTRODUCTION

Lightning is a recurring cause of transmission line failures. Generally, it is responsible for more than 50% of unscheduled line outages. These failures happen when lightning strikes the line and the overvoltages developed across line-insulators exceed their lightning withstand voltage. The backflashover is widely prevalent in lines set up in zones of soils with medium and high resistivity. This event can occur when lightning strikes a tower (or the shield wires) and the voltage wave that flows to the ground finds a high tower-footing impedance. When this occurs, extremely high grounding potential rises are developed and transmitted to the tower top. High overvoltages might be experienced across the phase insulators. If such overvoltages exceed the withstand voltage, backflashover may occur (Visacro et al. 2015).

Hence, the assessment of the lightning performance of transmission lines involves the evaluation of the overvoltages developed across insulator strings, in response to lightning strikes to the line (Electrical Transmission and Distribution Reference book, 1964).

Recent papers have determined how significant is the influence of frequency dependence of soil resistivity and permittivity on the response of grounding electrodes subject to lightning currents (Visacro et al. 2011; Visacro and Alipio, 2012; Akbari et al. 2013).

This paper particularly investigates how the frequency dependence of soil parameters (resistivity ρ and permittivity ε) influences the lightning overvoltage across insulators due to direct strikes to the line leading to the occurrence of backflashovers. In this work, the associated effects with the soil ionization process are not considered due to the long counterpoise cables usually used in transmission line grounding systems, making this effect negligible without loss of consistency of the results obtained (Visacro, 2007).

2. MODELLING AND METHODOLOGY

2.1 Soil parameters frequency dependence

Although it is well known that soil resistivity and permittivity present important frequency dependence, the response of grounding electrodes is usually simulated assuming constant values for both soil parameters. In the absence of accurate equations to calculate the frequency dependence of such parameters, this influence is frequently disregarded. In a common procedure, the resistivity is presumed as the value measured at low frequency and the relative permittivity of soil is considered to vary from 4 to 81, according to the soil humidity (Visacro, 2007).

Recently, a different technique for determining the frequency variation of soil resistivity and permittivity in practical conditions was developed and experimentally validated (Visacro et al. 2011). It was methodically tested to distinct soils to determine generic equations (1) and (2) to predict these parameter behaviors in the illustrative spectrum of dominant frequencies of lightning currents (Visacro and Alipio, 2012):

$$\rho_r = \{1 + [1.2 \cdot 10^{-6} \cdot {\rho_0}^{0.73}]\} \cdot [(f - 100)^{0.65}]^{-1} \quad (1)$$

$$\varepsilon_r = 7.6 \cdot 10^3 f^{-0.4} + 1. \quad (2)$$

In these equations, suited to the 100 Hz – 4 MHz limits, ρ_r is the relative resistivity, ε_r is the relative permittivity at frequency *f* in Hz and ρ_0 is the soil resistivity at 100 Hz.

2.2 Computational Simulation

To simulate the impact of the frequency dependence of the soil parameters in the overvoltages developed in the insulator strings of a 138 kV transmission line when struck by lightning, the first step is to select the most suitable models for each element (transmission tower, transmission line, grounding system, and lightning current) considering the transient aspects intrinsic to the phenomenon. Thus, in this section, models adopted in this work for these elements will be presented.

1) Lightning Current:

The lightning current was represented using a current source according to the model proposed by Heidler et al. (1999) available in ATP and defined by:

$$i(t) = \frac{I_0}{\eta} \cdot \frac{\left(\frac{t}{\tau_1}\right)^n}{1+\left(\frac{t}{\tau_1}\right)^n} \cdot e^{\left(-\frac{t}{\tau_2}\right)}, \quad (3)$$

where

$$\eta = exp\left[-\left(\frac{\tau_1}{\tau_2}\right).\left(n.\frac{\tau_2}{\tau_1}\right)^{\frac{1}{n}}\right], \quad (4)$$

and

I_0 = Peak value of the current (kA);
τ_1 = Time constant of the current rise (μs);
τ_2 = Time constant of the current decay (μs);
η = Correction factor of the current peak;
n = Current steepness factor.

2) Transmission Tower:

The tower was modeled by lossless lines. In this model, each section of the transmission tower is represented by short lines without losses that corresponds to a cylindrical conductor with equivalent radius. The values of the surge impedance are calculated according to the dimensions and the geometric configuration of each section of the tower. The model is represented in Fig. 1 (De Vasconcellos and Moreira, 2017).

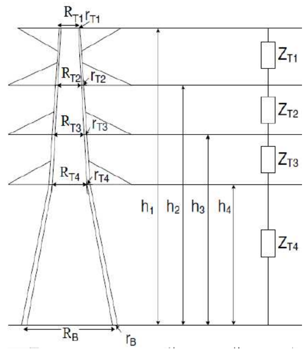

Fig. 1. Model of transmission tower by lossless lines.

3) Transmission Line:

The transmission line was modeled by the ATP Bergeron transmission line model, considering the parameters distributed and calculated for a constant typical dominant frequency, according to lightning current parameters. The line is untransposed and skin effect is taken into account. The coupling between all cables is intrinsic to the model. For the calculation of the parameters, the physical data of each of the conductors are used, such as relative physical position, diameter and ohmic resistance.

4) Grounding System:

The grounding system of the transmission towers is composed of all the metallic elements that compose the tower and that maintains contact with the ground or with the foundations, including rebar, grids, screws, etc. and any grounding devices, such as grounding rods, horizontal rings, counterpoise cables, or any combination of these that are buried in the ground. Soil resistivity is one of the main factors responsible for the performance of the grounding system of a transmission line, being influenced by the following factors: soil type, moisture content, temperature, chemical composition, retained water salt concentration, stratification and soil compaction (De Vasconcellos and Moreira, 2017).

The towers of a transmission line must be grounded in such a way to make the grounding impedance compatible with the desired performance of the line.

The electric model of the counterpoise cables is the nominal π model. The parameter values are obtained through Sunde's (Sunde, 1949) formulations:

$$R = \frac{l}{\pi . r^2} \cdot \rho_c \quad (5)$$

$$G = \frac{\pi}{\rho . l} . \left[\log\frac{2l}{\alpha} - 1\right]^{-1} \quad (6)$$

$$C = \pi . \varepsilon . l \left[\log\frac{2l}{\alpha} - 1\right]^{-1} \quad (7)$$

$$L = \frac{\mu . l}{2 . \pi}\left[\log\frac{2l}{\alpha} - 1\right] \quad (8)$$

Where,
R - Counterpoise cable resistance(Ω);
G - Counterpoise cable conductance (S);
C - Counterpoise cable capacitance(F);
L - Counterpoise cable inductance (H);

ρ_c- Counterpoise cable resistivity (Ω.m);
ρ - Soil resistivity (Ω.m);
l - Counterpoise cable length (m);
r - Counterpoise cable radius (m);
α -$\sqrt{2.r.h}$ (m);
h - Counterpoise cable bury depth (m);
μ- Soil permeability (adopted as μ_0) (H/m);
ε - Soil permittivity (F/m).

Each π circuit cell represents a standard section of the cable. The general representation of the counterpoise cable used in the simulations is modeled by j identical cells corresponding each to 1 m of the counterpoise cable, as seen in Fig. 2 (Hatziargyriou and Lorentzou, 1997).

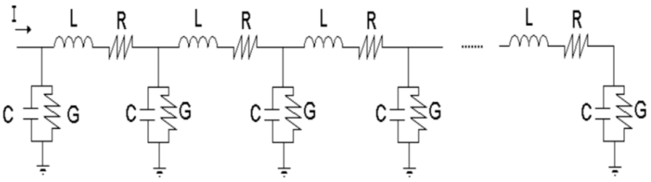

Fig. 2. Counterpoise cable general representation.

2.3 Simulated Conditons

In the simulations, the lightning strikes directly to the top of the central tower, considering two adjacent towers, according to Fig. 3 (De Vasconcellos and Moreira, 2017) and also considering first and subsequent return strokes. It is usual to consider only one adjacent span for the analysis of lightning overvoltages, as the transit time in the tower is much shorter than the transit time in the adjacent spans, so considering an adjacent span is sufficient. Typical values were obtained from measurements at the Morro do Cachimbo - MG station, in Brazil (Visacro et al. 2004), shown in Tables I, where Ip is the lightning current peak, τ1 is the front time and τ2 is the tail time. The median and critical classifications are related to the probabilistic characteristic of the measurements, in which "median" refers to measurements in which the values of the parameters associated with the lightning currents exceed in 50% those of the measured cases and "critical" to the measurements in which only 5% of the parameters exceed this set of values.

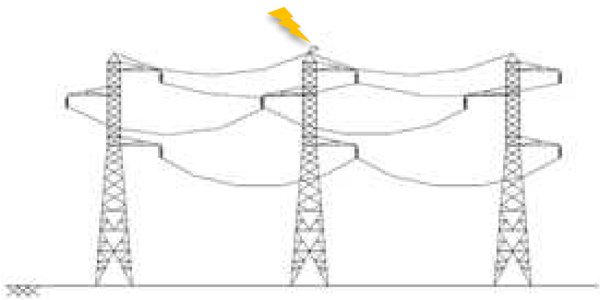

Fig. 3. Lightning strike incidence point illustration.

TABLE I. FIRST RETURN STROKE PARAMETERS

Lightning Current (type)	Ip (kA)	τ1 (μs)	τ2 (μs)
Median	45.3	5.6	53.5
Critical	85.2	9.9	145.2

Fig. 4 (Salari and Portela, 2007) shows the configuration of the simulated transmission tower, the values of the surge impedance Zt considered for each segment and the propagation speed of the surge wave, assumed to be 80% of speed of light, implemented in the simulations, respectively. In actual towers, a propagation speed lower than the speed of light is usually attributed to the effect of slants and crossarms (Chisolm, Chow and Srivastava, 1983).

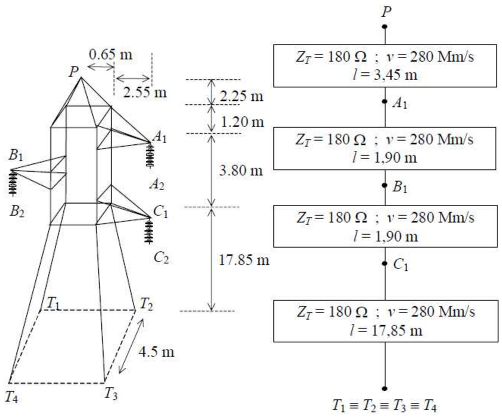

Fig. 4. 138kV transmission tower configuration and tower equivalent circuit.

The transmission line is connected to a 138 kV, 60 Hz voltage source and implemented with a 10 km length in each side of bordering towers (in this case, the reflections do not return before the end of the total study time, not affecting the results, since there is interest only in the maximum overvoltages).

The electrical and mechanical data of the cables of the transmission line are shown in Table II.

TABLE II. ELECTRICAL AND MECHANICAL DATAOF THE CABLES

Cable name	LINNET	EHS 3/8''
Type	ACSR	EHS Class A
Span length (m)	300	300
Sags (m)	7	4
Internal radius (cm)	0.2976	0
External radius (cm)	0.9155	0.476
CC Resistance (Ω/km)	0.2032	3.81

For the grounding systems, the arrangement with four 4 AWG copper-steel counterpoise cables were used, placed 60cm below the ground surface, in the longitudinal direction of the line as represented in Fig. 5 (Salari and Portela, 2007). The length of the counterpoise cables, that vary according to the soil resistivity used in the simulations are presented in the next section with each result set.

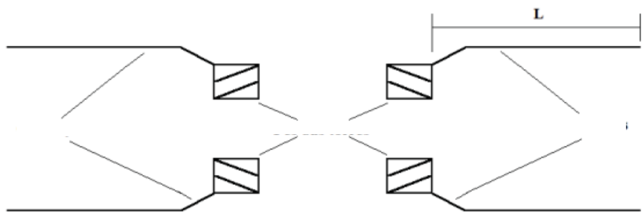

Fig. 5. Grounding arrangement representation with four counterpoise cables.

3. RESULTS

Overvoltages developed across the upper insulator string (phase with the highest peak overvoltage, in this case) of the central tower of the 138-kV line due to a direct first strike to its top (see Fig. 3 and Table I) are shown in Section 3.1, in Figs. 6, 7, 8, and 9 and in Table III. Simulations assumed the tower configuration of Fig. 5, grounding system topology of Fig. 6, and 300-m long spans. The results considering constant soil parameters in Figs. 6 to 9 and Table III were presented and discussed originally in De Vasconcellos and Moreira (2017) and are being used in this paper to compare with the results considering the inclusion of the frequency dependence of the soil parameters ρ_r and ε_r in accordance to (1) and (2). The frequency values assumed in the simulations are calculated by the inverse of the rising time of each lightning stroke current.

After finding the values of the relative resistivity and permittivity considering the calculated dominant frequency of each lightning current, they are included in all models that involve those parameters. These models are the Bergeron transmission line model and the grounding system, with the calculation of R, G, C and L of the nominal π model based on Sunde's equations with the frequency dependence of the soil parameters. Then the simulations are performed with the variation of the soil parameters as previously described.

The grounding system topologies used in De Vasconcellos and Moreira (2017) were chosen to maintain the overvoltages below the Critical Flashover Overvoltage (CFO) value, in order to reduce the probability of a backflashover occurrence and were kept the same in this work so that the results may be effectively compared.

Figures from 6 to 9 presents the overvoltage waves developed across the upper insulator string of the line under the assumption of constant and frequency-dependent soil parameters, with median and critical parameters and resistivities of 500Ωm and 2.500Ωm. Each figure has its parameters depicted on itself.

3.1 First stroke currents

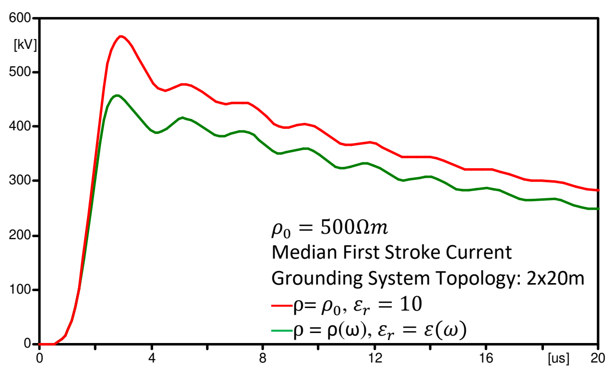

Fig. 6. Developed overvoltage waves across the upper insulator string of the line: case 1.

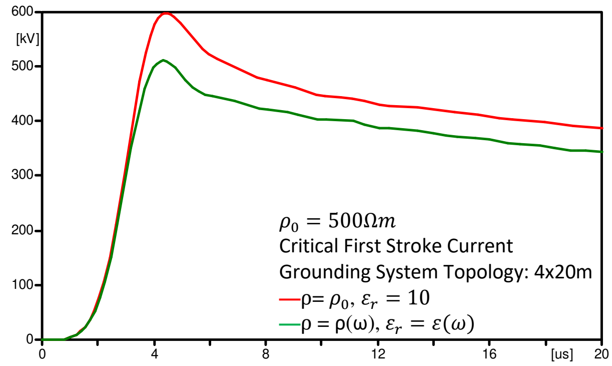

Fig. 7. Developed overvoltage waves across the upper insulator string of the line: case 2.

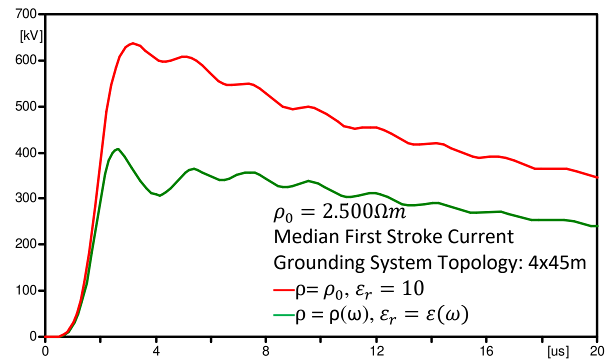

Fig. 8. Developed overvoltage waves across the upper insulator string of the line: case 3.

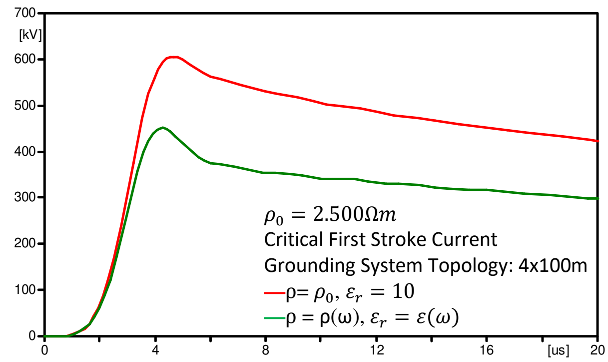

Fig. 9. Developed overvoltage waves across the upper insulator string of the line: case 4.

TABLE III. PEAK OVERVOLTAGE ACROSS THE UPPER INSULATOR STRING OF THE 138-KV LINE FOR 500 AND 2.500 Ω.M FOR MEDIAN AND CRITICAL LIGHTNING PARAMETERS.

ρ_0 (Ω.m)	**L (m)**	**Overvoltage (kV) - Upper Insulator String**		
		Ip = 45.3kA; τ1 = 5.6μs; τ2 = 53.5μs		
		$\rho = \rho_0$ $\varepsilon_r = 10$	ρ(ω) ε(ω)	Δ(%)
500	2x20m	565	458	-23%
2.500	4x45m	607	406	-33%
ρ_0 (Ω.m)	**L (m)**	**Ip = 85.2kA; τ1 = 9.9μs; τ2 = 145.2μs;**		
		$\rho = \rho_0$ $\varepsilon_r = 10$	ρ(ω) ε(ω)	Δ(%)
500	4x20m	598	510	-15%
2.500	4x100	610	451	-26%

The results presented in Table III demonstrate that, as expected, taking into account the frequency dependence of soil parameters produces a general decrease of overvoltage levels and this consequence is more significant as higher the soil resistivity is. This decrease is far more significant for overvoltages developed due to first strokes, varying from around 15% to 33% for soils with ρ_0 of 500 and 2.500 Ω.m, respectively.

The overvoltage peak values developed for first strokes indicate that considering the frequency dependence of soil resistivity and permittivity would lead to a downward trend in the number of backflashovers, since the magnitude of the overvoltages were decreased. It also contributes to keeping the peak voltages below the CFO, which is considered as 650kV for 138-kV lines, in the simulations, obtaining a more accurate and less overly conservative estimation of the lightning performance of transmission lines.

From the results previously presented, simulations were performed to study the possibility of reducing the counterpoise cable lengths, in the case of first stroke currents to make the grounding system of the line also more efficient and less conservative.

Then, in section 3.2, in Figs. 10, 11, 12, and 13, the graphs resulting from this study are presented, with the reduction of the counterpoise cables. It were reduced until the peak overvoltages reached equivalent values (values 10% above or below) to the cases shown in section A, for constant soil parameters. These figures either presents the overvoltage waves developed across the upper insulator string of the line under the assumption of constant and frequency-dependent soil parameters, with median and critical parameters and resistivities of 500Ωm and 2.500Ωm. Each figure has its parameters depicted on its legends.

The simulations result and the counterpoise cable lengths variation are summarized in Table IV.

3.2 Counterpoise cable length reduction

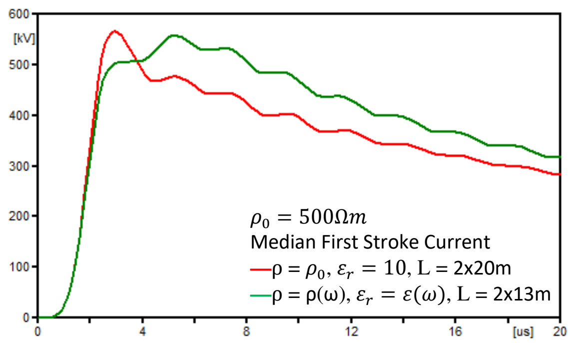

Fig. 10. Developed overvoltage waves across the upper insulator string of the line analyzing the counterpoise cable length reduction: case 1.

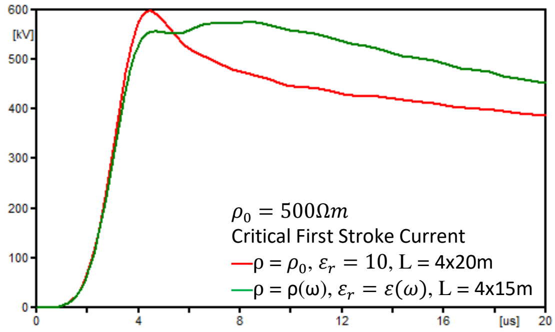

Fig. 11. Developed overvoltage waves across the upper insulator string of the line analyzing the counterpoise cable length reduction: case 2.

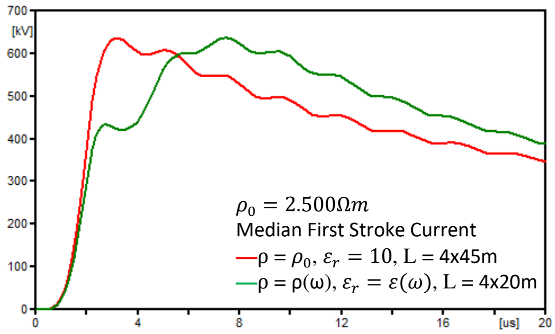

Fig. 12. Developed overvoltage waves across the upper insulator string of the line analyzing the counterpoise cable length reduction: case 3.

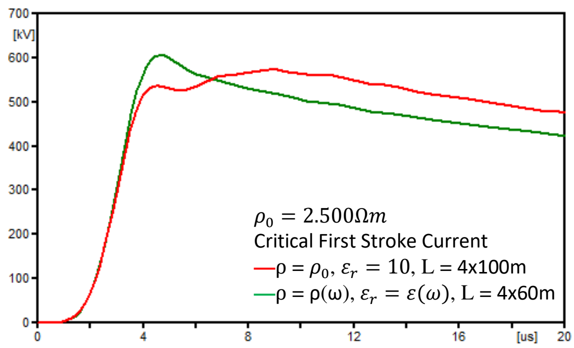

Fig. 13. Developed overvoltage waves across the upper insulator string of the line analyzing the counterpoise cable length reduction: case 4.

TABLE IV. COUNTERPOISE CABLES LENGTH REDUCTION MAINTAINING EQUIVALENT OVERVOLTAGE LEVELS ACROSS THE UPPER INSULATOR STRING OF THE 138-KV LINE FOR CONSIDERED CONDITIONS.

ρ_0 (Ω.m)	**Counterpoise Cable Length (m)**					
	Ip = 45.3kA; τ1 = 5.6µs; τ2 = 53.5µs			**Ip = 85,2kA; τ1 = 9,9µs; τ2 = 145.2µs;**		
	$\rho = \rho_0$ $\varepsilon_r = 10$	ρ(ω) ε(ω)	Δ(%)	$\rho = \rho_0$ $\varepsilon_r = 10$	ρ(ω) ε(ω)	Δ(%)
500	2x20	2x13	-35%	4x20	4x15	-25%
2.500	4x45	4x20	-55%	4x100	4x60	-40%

The graphs from section 3.2 and Table IV show that including the frequency dependence of soil parameters in the simulations could contribute to a significant decrease of counterpoise cable lengths, in order to maintain equivalent overvoltage levels compared to constant soil parameters simulations. This reduction ranged from 25 to 55%, being more prominent for higher soil resistivity values.

This percentage reduction is higher than the overvoltages reduction shown in tables III. It occurs because when the frequency dependence of the electrical soil parameters is included, the conductance of the counterpoise cables represented by the nominal π model is increased and it contributes to the reduction of resulting overvoltages from the lightning strikes. As a result, it becomes possible to moderately reduce the cables length and maintain equivalent overvoltage levels compared with the constant soil parameters simulations and below the CFO of a 138 kV transmission line.

The inclusion of the frequency dependence of the electrical soil parameters is responsible for the differences seen in the overvoltage waveforms behavior in the simulations shown in section 3. It results in a tower footing impedance with a stronger capacitive behavior than in cases when constant parameters are considered. This may be noted by the delay in the voltage wave (the peak is reached later).

4. CONCLUSIONS

The inclusion of the frequency-dependent soil parameters generates an important decrease of overvoltages for transmission lines. This decrease is relevant for first stroke currents (from about 15% to 33% for soils of 500 and 2.500 Ω.m, respectively).

As a consequence of the previous results, it was also studied the possibility of reducing the length of the counterpoise cables in order to maintain overvoltage levels equivalent to those of simulations considering constant parameters. It was shown that it would be possible to reduce the length of the transmission line counterpoise cables by 25 to 55%, which could contribute to gains of both economic and operational efficiency on the grounding systems and also on the transmission line construction time.

The simulated results suggest a relevant improvement of the lightning performance of the studied line if the simulations include the frequency dependence of the soil electrical parameters and demonstrate the generalization of the influence of this behavior on determining transmission line overvoltages.

The simulated conditions used in this work corresponds to a first investigation and other aspects will be added in the future, for example, the randomness of the parameters of the lightning current and the value of the 60 Hz phase voltages at the moment of the lightning incidence, after all, these parameters could impact the achieved results.

REFERENCES

Akbari, M; Sheshyekani, K. and Reza Alemi, M (2013). The effect of frequency dependence of soil electrical parameters on the lightning performance of grounding systems, *IEEE Trans. Electromagn. Compat*, vol. 55, no. 4, pp. 739–746.

De Vasconcellos, F. M. and Moreira, F. A (2017). Evaluation and Dimensioning of Grounding Systems for Outage Reduction due to Backflashover in Transmission Lines, in *Proc. 12th Latin-American Congresson Electricity Generation and Transmission*, pp.136.

Electrical Transmission and Distribution Reference book (1964), Central Station of Engineers of the Westinghouse Electric Corporation, East Pitsburg, Pensilvania, 4th Edition.

Hatziargyriou, N. D. and Lorentzou, M (1997). Grounding Systems Design Using EMTP, *23rdEuropean EMTP Users Group Meeting*, Barcelona.

Heidler, F; Cvetic, J. M. and Stanic, B. V (1999). Calculation of lightning current parameters, *IEEE Transactions on Power Delivery*, vol. 14, no 2, pp.399-404.

Salari, J. C. and Portela, C (2007). A methodology for electromagnetic transients calculation – an application for the calculation of lightning propagation in transmission lines, *IEEE Transactions on Power Delivery*, v. 22, n. 1, pp. 527-536.

Sunde, E.D (1949). *Earth Conduction Effects in Transmission Systems,* Dover Publ. New York.

Visacro, S; Soares Jr, A and Schroeder, M. A. O et al (2004). Statistical analysis of lightning current parameters: Measurements at Morro do Cachimbostation, *J. Geophys. Res.* (109), D01105, doi:10.1029/ 2003JD003662.

Visacro, S (2007). A comprehensive approach to the grounding response to lightning currents, *IEEE Trans. Power Del.*, vol. 22, no. 1, pp. 381–386.

Visacro, S; Alipio, R; M. Vale, M. H. and Pereira, C (2011). The response of grounding electrodes to lightning currents: The effect of frequency-dependent soil resistivity and permittivity, *IEEE Trans. Electromagn.Compat.*, vol. 53, no. 2, pp. 401–406.

Visacro, S and Alipio, R (2012). Frequency dependence of soil parameters: Experimental results, predicting formula and influence on the lightning response of grounding electrodes, *IEEE Trans. Power Del.*, vol. 27, no. 2, pp. 927–935.

Visacro, S; Silveira, F. H; M. Vale, M. H. (2015), Simplified representation of tower-footing electrodes for assessment of the lightning performance of transmission lines using EMTP-based platforms, in *International Conference on Power Systems Transients*.

W. A. Chisolm, Y. L. Chow, and K. D. Srivastava (1983), “Lightning surge response of transmission towers,” *IEEE Trans. Power App. Syst.*, vol. PAS102, no. 9, pp. 3232–3242, Sep. 1983.