ENGENHARIA ELÉTRICA:

COMUNICAÇÃO INTEGRADA NO UNIVERSO DA ENERGIA

João Dallamuta
Henrique Ajuz Holzmann
(Organizadores)

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APRESENTAÇÃO

A engenharia elétrica tornou-se uma profissão há cerca de 130 anos, com o início da distribuição de eletricidade em caráter comercial e com a difusão acelerada do telégrafo em escala global no final do século XIX.

Na primeira metade do século XX a difusão da telefonia e da radiodifusão além do crescimento vigoroso dos sistemas elétricos de produção, transmissão e distribuição de eletricidade, deu os contornos definitivos para a carreira de engenheiro eletricista que na segunda metade do século, com a difusão dos semicondutores e da computação gerou variações de ênfase de formação como engenheiros eletrônicos, de telecomunicações, de controle e automação ou de computação.

Não há padrões de desempenho em engenharia elétrica e da computação que sejam duradouros. Desde que Gordon E. Moore fez a sua clássica profecia tecnológica, em meados dos anos 60, a qual o número de transistores em um chip dobraria a cada 18 meses - padrão este válido até hoje – muita coisa mudou. Permanece porem a certeza de que não há tecnologia na neste campo do conhecimento que não possa ser substituída a qualquer momento por uma nova, oriunda de pesquisa científica nesta área.

Produzir conhecimento em engenharia elétrica é, portanto, atuar em fronteiras de padrões e técnicas de engenharia. Também se trata de uma área de conhecimento com uma grande amplitude de subáreas e especializações, algo desafiador para pesquisadores e engenheiros.

Neste livro temos uma diversidade de temas nas áreas níveis de profundidade e abordagens de pesquisa, envolvendo aspectos técnicos e científicos. Aos autores e editores, agradecemos pela confiança e espírito de parceria.

Boa leitura

João Dallamuta
Henrique Ajuz Holzmann

SUMÁRIO

SUMÁRIO

CAPÍTULO 6

THE INFLUENCE OF THE FREQUENCY-DEPENDENT BEHAVIOR OF GROUND ELECTRICAL PARAMETERS ON THE LIGHTNING PERFORMANCE OF TRANSMISSION LINES

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ABSTRACT: This study evaluates the lightning performance of a 138 kV transmission line under the premises of constant and frequency-dependent soil electrical parameters. A wideband model was used to include the frequency-dependent impedance behavior of the tower grounding system. The overvoltages across the insulator strings were simulated using ATP and considering representative first stroke current waveforms. Backflashover outage rates were determined using the Disruptive Effect (DE) method. It was found that the decrease of soil resistivity and relative permittivity resulting from the frequency dependence effect is responsible for the significant decrease of the expected outage rates of the tested line, in a range of 29-55% for realistic distributions of soil resistivity along the line and a consequent relevant improvement of the lightning performance of the line.

KEYWORDS: Transmission lines; grounding systems, frequency-dependent soil electrical parameters, lightning performance, backflashover**.**

A INFLUÊNCIA DO COMPORTAMENTO DEPENDENTE DA FREQUÊNCIA DOS PARÂMETROS ELÉTRICOS DO SOLO NO DESEMPENHO DAS LINHAS DE TRANSMISSÃO FRENTE A DESCARGAS ATMOSFÉRICAS

RESUMO: Este estudo avalia o desempenho de uma linha de transmissão de 138 kV frente a descargas atmosféricas sob as premissas de parâmetros elétricos constantes e dependentes da frequência do solo. Um modelo de banda larga foi usado para incluir o comportamento de impedância dependente de frequência do sistema de aterramento da torre. As sobretensões através das cadeias de isolador foram simuladas usando o ATP e considerando as formas de onda representativas de onda de primeira corrente de retorno. As taxas de desligamento por Backflashover foram determinadas usando o método do Efeito de Disruptivo (DE). Verificou-se que a diminuição da resistividade do solo e da permissividade relativa resultante do efeito de dependência de frequência é responsável pela diminuição significativa das taxas de desligamento esperadas da linha testada, em uma faixa de 29-55% para distribuições realísticas de resistividade do solo ao longo da linha e uma consequente melhoria relevante do desempenho da linha em termos de relâmpagos.

PALAVRAS-CHAVE: Linhas de transmissão, Sistemas de aterramento, parâmetros elétricos do solo dependents da frequência, performance frente a descargas atmosféricas, backflashover.

1 I INTRODUCTION

The incidence of lightning strikes is a frequent cause of transmission line outages. Direct discharges to the line develop overvoltages through the insulation chain that can result in insulation rupture, leading to faults [1,2]. The backflashover prevails as the main mechanism responsible for the lightning outages of lines below 500 kV installed in regions with unfavorable soil resistivity [1]. The tower-footing grounding impedance has a great influence on the amplitude of lightning overvoltages [2,3], and this is the reason for the quite usual practice of reducing this impedance to improve the lightning performance of the lines [1,2].

Several studies demonstrate how significant the influence of frequency dependence on soil resistivity and permittivity is on the lightning response of grounding electrodes [4-8]. In this scenario, it is interesting to evaluate the corresponding impact on the lightning performance of transmission lines, in terms of variation in the backflashover outage rate, and this is what this work aims to investigate.

Similar investigations can be found in other papers [9,10]. However, the application of the HEM (Hybrid Electro Magnetic Model) model to simulate the entire transmission system results in a great computational effort. Thus, this work has the goal of presenting a computationally efficient solution that allows the interface of wideband modeling of grounding systems with the Alternative Transients Program – ATP [11], n order to accurately assess the influence and impact of the frequency-dependent behavior of ground electrical parameters on the backflashover rate of transmission lines.

This paper is organized as follows: in section 2 the methodology and modeling used are briefly described, in section 3 the numerical results are presented and analyzed, and in section 4 the conclusions are exposed.

2 I METHODOLOGY AND MODELS

The simulation of the lightning overvoltages and the corresponding study of the transmission line lightning performance were carried out considering the incidence of the representative first return strikes, measured in an instrumented tower in Morro do Cachimbo - MG [12]. This study considered only the incidence of first return strikes as a function of the lower relevance of subsequent discharges in the occurrence of backflashover in lines from 138 kV onwards [13].

The Disruptive Effect (DE) method was applied to the overvoltages resulting from each simulated condition in order to calculate the value of the critical current of the first strikes capable of inducing backflashover outages [14,15]. The probability of occurrence of each critical current was calculated using cumulative peak current probability distributions. Finally, derived from the calculated probabilities and considering a wide range of soil resistivities at low frequency (values from 300 to 10,000 Ω□m), which are necessary to make a sensitivity analysis of the impact of the frequency dependence effect, the performance of the 138-kV line was determined considering constant and frequency-dependent soil electrical parameters.

For this purpose, three towers with two 400 m spans of a 138-kV line were considered, with the lightning striking the top of the central tower. To avoid voltage wave reflections, the ends of the lines are perfectly matched in the whole frequency range using infinitely long lines. The silhouette of the tower and the line cable heights (in meters) are illustrated in Fig. 1 (half span values are shown in brackets). The transmission line has one ACSR conductor per phase, LINNET code, and a 3/8'' EHS shield wire. A pair of adjacent towers (identical to Fig. 1) is included in the simulations to consider the propagation effects of overvoltage waves on the line conductors as well as reflections occurring in the adjacent spans.

Fig. 2 shows the typical grounding arrangement of the studied transmission towers. It consists of 4 counterpoise cables, buried at 0.5 m depth, with a 7 mm radius, and each one starting from a tower “foot”. The length L of the counterweight cables is selected according to the soil resistivity value, considering common practices of Brazilian energy concessionaires, as shown in Table I [16].

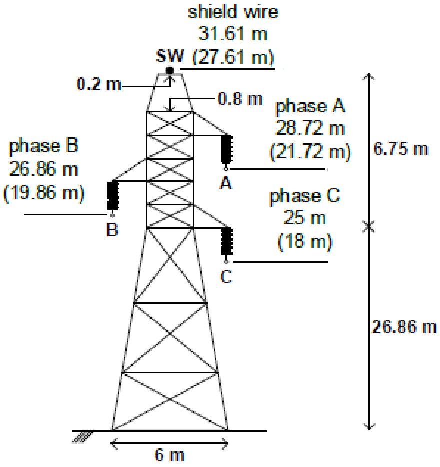


Fig. 1. Typical tower silhouette.

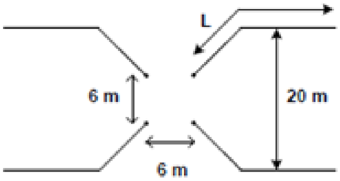


Fig. 2. Typical arrangement of tower-footing grounding electrodes.

ρ (Ω.m)	1,000	3,000	5,000	10,000
L (m)	40	60	80	130

TABLE I - Counterpoise cable length according to soil resistivity

The simulations presented in this work were developed in ATP. The advantage of using this type of tool is in its low computational effort when compared to tools that use electromagnetic fields approach, and still maintain adequate precision, especially when dealing with engineering applications [17].

In this work, the effects associated with the soil ionization process were neglected, as this effect is significant only when large values of lightning currents are applied on short electrodes, different from the frequency dependence effect, which is independent of the amplitude of the current and the length of the electrodes. According to the usual protection practices in transmission lines, long electrodes are used to achieve low values of ground resistance of tower “foot” resulting in a low linear density of dispersed current along with these [18].

The modeling guidelines of the simulated power system is then briefly described.

A. Lightning Current Waveform

A proper evaluation of lightning effects on power systems relies upon, among other factors, on an appropriate representation of the lightning current waveform since the quality of the simulation results depends on the representativity of the assumed lightning current waves.

According to [19], the first stroke currents are characterized by a pronounced concavity at the front and by the occurrence of multiple peaks, being the second peak usually the highest one, and the maximum steepness occurring near the first peak according to measurements of instrumented towers, such as those presented in [12,20].

Considering the previous aspects, the simulations were performed considering some Brazilian conditions, as the current waveform depicted in Fig. 3, that approximately reproduces the main median parameters of first strokes measured at Morro do Cachimbo Station. As detailed in [21], the waveform of Fig. 3 is obtained by a sum of Heidler functions.

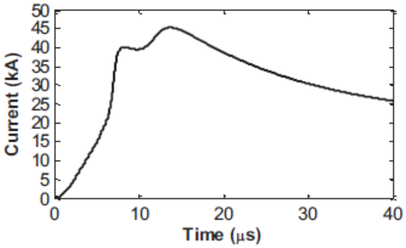


Fig. 3. Representative lightning current waveform of first strokes measured at Morro do Cachimbo Station.

B. Phase Cables and Shield Wire

For modeling the transmission line conductors, the model developed by J. Marti [22], which is implemented in the ATP, was used. In this platform, the JMarti model of the line is implemented via routine Line and Cable Constants (LCC) whose data input corresponds, essentially, to the geometric positions of the line conductors and the electromagnetic characteristics of the conductors involved (air and ground).

This model was adopted in the simulations because it considers the variation of the longitudinal parameters of the line with the frequency. In the simulations, the adjustment of these longitudinal parameters was considered for the frequency range between 1 Hz and 10 MHz, covering all the frequency content of the incident discharges. The modal transformation matrix was calculated in the frequencies of 200 kHz and 1.2 MHz for first and subsequent strikes, respectively (due to their front times).

C. Transmission Line Tower

The transmission tower is modeled as a lossless single-phase transmission line, and its surge impedance is calculated using the revised Jordan's formula, that was extended in [23] to consider vertical multiconductor systems. Assuming that the tower can be represented by n vertical conductors that are connected at the same current injection point, it is possible to model the whole multiconductor system as a single transmission line with equivalent surge impedance given by [23]

$$Z_{eq} = \frac{V}{I} = \frac{Z + Z_{12} + \,.\,.\,. + Z_{1n}}{n} \qquad (1)$$

where

$$Z = 60\left[ln\frac{4h}{r} - 1\right] \qquad (2)$$

$$Z_{ij} = 60ln\frac{2h + \sqrt{4h^2 + {d_{ij}}^2}}{d_{ij}} + 30\frac{d}{h} - 60\sqrt{\frac{1 + {d_{ij}}^2}{4h^2}} \qquad (3)$$

In (2) and (3), *h* is the height of the conductor, *r* is the conductor radius, and d_{ij}

corresponds to the distance between the center of the conductors *i* and *j*. Particularly, the tower of Fig. 1 was sectioned in four segments, each one represented by four vertical conductors. The lower part of the tower was represented as a cascade of three transmission lines (two of 9 m and one of 8.86 m), while its upper part was represented as a single 6.75-m long transmission line. This was made to consider the variation of the cross section of the tower with position, which changes the mutual surge impedance as a function of height. The equivalent impedance of each tower section was computed using (1), (2) and (3), considering the average distances between tower conductors and assuming r = 6.5 cm. The propagation speed of the surge wave was assumed to be 80% of speed of light, as in [23]. The final tower model is illustrated in Fig. 4.

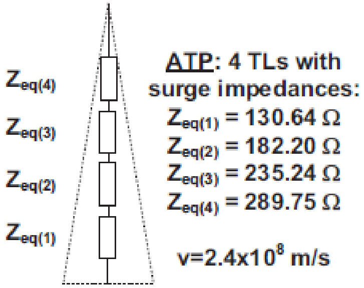


Fig. 4. Transmission tower model.

D. Tower-footing Grounding

The rigorous modeling of the tower-footing grounding system has an essential function in the physical consistency of the impulsive behavior of this system and the determination of the overvoltages developed through the insulator chains of the transmission lines by the incidence of lightning strikes in the shielding cable or directly at the top of the tower [18]. These strikes have associated currents that are often defined by a frequency content from zero to Mega-hertz, in which the tower-footing grounding system reveals a different behavior in different frequency ranges [24].

Therefore, the adequate evaluation of the lightning overvoltages and consequently the performance of a transmission line is not possible unless the wideband frequency behavior of the grounding system impedance is adequately taken into account [25]. However, this is not a simple task, considering that the procedure for including the wideband model of the grounding systems in the determination of the impulse response is not well established in numerical simulators of electromagnetic transients, such as ATP.

In this work, the ground conductors were represented using a transmission line model composed of an L inductance in series, and a G conductance and a C capacitance in parallel. They can be modeled as ‘pi-equivalent’ circuits connected in series with distributed

R-L-C elements, where each ‘pi-equivalent’ circuit corresponds to a small segment of the ground conductor [26], as illustrated in Fig. 5.

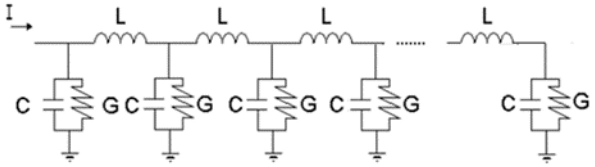


Fig. 5: Representation of the ground conductor. Adapted from [26].

An adaptation of the original model was made, in which the internal resistance of the cable was neglected, as it was included as a direct current resistance in the ‘pi’ cell serial branch, which is not physically consistent at high frequencies. It is worth mentioning that even the internal resistance in alternating current, considering the skin effect, is insignificant concerning to the grounding impedance. This can be concluded, since the transversal resistance of the soil is infinitely greater than the internal resistance of the cable, after all the resistivity of the soil is always extremely greater than that of the grounding electrode, assuming that it is manufactured using conductive material.

The R-L-C parameters of ‘pi-equivalent’ circuits are calculated using (4), (5) and (6), based on the well-known Sunde [27] expressions:

$$R = G^{-1} = \frac{\rho}{\pi} . \left[log \frac{2l}{\sqrt{2da}} - 1 \right], (l \gg a, d \ll l) \quad (4)$$

$$C = \frac{\rho \epsilon}{R} \quad (5)$$

$$L = \frac{\mu}{2\pi} . \left[log \frac{2l}{\sqrt{2da}} - 1 \right] \quad (6)$$

where ρ (Ω·*m*) is the soil resistivity, *l* (*m*) is the length of the electrode, *a* (*m*) is the radius of the electrode, *d* (em *m*) is the depth at which the counterpoise cable is buried, *ε* is the soil permittivity (*F/m*) and *μ* (*H/m*) is the soil permeability.

To include the frequency-dependent behavior of the grounding system impedance, the harmonic impedance Z(jω) of the arrangement shown in Fig. 2 was calculated in a frequency range of 1 Hz to 10 MHz. This parameter is useful to evaluate the performance of a grounding system independently of the characteristics of the injected lightning strike current and is defined as:

$$Z(j\omega) = \frac{V(j\omega)}{I(j\omega)} \quad (7)$$

Where *V* (*jω*) and *I* (*jω*) are the potential at the injection point and the injected current, respectively.

The impedance of the tower grounding system is calculated using two different approaches, both using the wideband model, one with constant electrical parameters in the ground and the other considering its frequency dependence, using (8) and (9), based on a large number of field measurements, Kramers-Kronig's causal relationships and Maxwell's equations [28]:

$$\sigma = \sigma_0 + \sigma_0 \cdot h(\sigma_0)\left(\frac{f}{1MHz}\right)^{\gamma} \tag{8}$$

$$\varepsilon_r = \varepsilon_{r\infty} + \frac{tan\left(\frac{\pi\zeta}{2}\right)\cdot 10^{-3}}{2\pi\varepsilon_0(1MHz)^{\gamma}}\sigma_0 \cdot h(\sigma_0) \cdot f^{\gamma-1} \tag{9}$$

In (8) and (9), σ is the soil conductivity (*mS/m*), σ_0 is the low frequency (100 Hz) conductivity (*mS/m*), $\mathcal{E}_r$ is the relative permittivity, $\mathcal{E}_{r\infty}$ is the relative permittivity at higher frequencies, $\mathcal{E}_0$ is the vacuum permittivity ($\mathcal{E}_0 \cong 8.854 \cdot 10^{-12}$ *F/m*) and f is the frequency in Hz. The parameters , $\mathcal{E}_{r\infty} = 12$, $y = 0.54$ and $h(\sigma_0)$ in (10), are recommended to obtain average results for the frequency dependence of the soil parameters [28]:

$$h(\sigma_0) = 1.26 \times \sigma_0{}^{0.73} \tag{10}$$

It is worth mentioning that the physical consistency of these expressions to determine the frequency dependence of soil parameters was provided by experimental results [5,28].

The rational model that approximates the frequency response to Z(jω) harmonic impedance is obtained using the Vector Fitting technique proposed by Gustavsen & Semlyen [29]. The vector fitting algorithm implemented in MATLAB® is public domain and available online [30]. This routine was used to adjust the grounding admittance in the frequency range between 1 Hz and 10 MHz in all cases of this work. From the rational model, an equivalent circuit is synthesized using the routine netgen.m developed by Gustavsen [30], and this circuit is exported in a text file that can be easily inserted into the ATP.

E. Insulation Breakdown

The disruptive effect method (DE method) is applied to determine whether or not the line insulation breakdown. The DE method concept is based on the idea of the existence of a critical disruptive effect DE_C for each isolator configuration. Each non-standard voltage surge has an associated disruptive effect (DE). If this DE value exceeds the critical value, a disruptive discharge occurs, which causes the insulation to break [15]. The disruptive effect associated with a voltage waveform is determined by:

$$DE = \int_{t_0}^{t} [e(t) - V_0]^k \, dt \tag{11}$$

where *e*(*t*) corresponds to the voltage waveform applied over the insulator chain, V_0 refers to the voltage threshold from which it has begun the process of rupture in the insulator, t_0 is the instantaneous value of *e(t)* exceeds V_0, *k* is a no-dimensional factor, and DE is the variable called "disruptive effect". For a typical 138 kV line, DE method constants can be obtained according to Hileman [15]: $DE_c = 1.1506(CFO)^k$; k = 1.36; $V_0 = 0.77\text{CFO} = 500.5$ kV.

3 I RESULTS AND DISCUSSIONS

A. Transmission Line Overvoltages

The simulations were performed considering the incidence of the current in Fig. 3, the tower configuration in Fig. 1 and the grounding system arrangement in Fig. 2, and spans of 400 m in length as described in Section II.

The overvoltages developed through the upper insulator chain (phase A) of the 138 kV line due to the incidence of a lightning strike at the top of the tower are shown in Fig. 5. It was decided to present only the graphs and values corresponding to phase A because it was the phase that presented the highest overvoltage values in all the cases studied, thus being the most relevant for the protection design, besides providing a less polluted graphical representation.

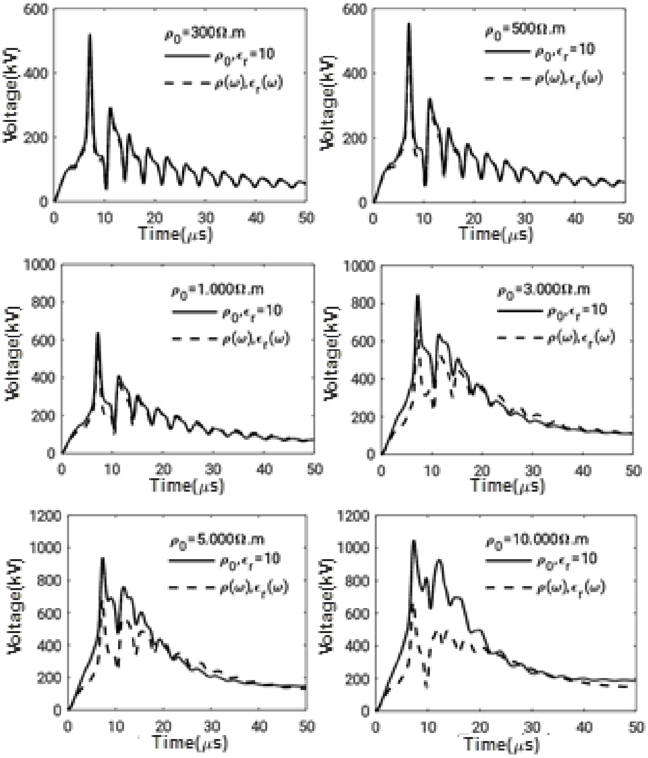


Fig. 5 Simulated overvoltages considering constant and frequency-dependent soil parameters.

The results show that the frequency dependence of soil parameters does not significantly affect the peak of overvoltages for soils of resistivity up to 500 Ω·m, but becomes important from this value. This is consistent with the results obtained in other studies, which even use diverse modeling [4,10].

Table II clearly shows the impact of the frequency dependence effect of the soil electrical parameters on the peak overvoltage waves of Fig. 5. It can be observed that the reduction of the overvoltage peak (Δ) is significant, being approximately 11% to 34% for ρ_0 ranging from 1,000 to 10,000 Ω·m.

Insulator Chain A Overvoltages (kV)				
ρ_0 (Ω·m)	L (m)	$\rho=\rho_0$, $\varepsilon_r = 10$	$\rho=\rho(\omega)$, $\varepsilon(\omega)$	Δ(%)
300	20	522	501	-4.0%
500	30	556	522	-6.1%
1,000	40	641	572	-10.8%
3,000	60	846	660	-22.0%
5,000	80	942	682	-27.6%
10,000	130	1050	693	-34.0%

TABLE II - Peak values of simulated overvoltages considering constant and frequency dependent electrical soil parameters.

B. Critical Currents

For a given set of line conditions and defined current waveform, it is possible to easily identify the critical peak current that leads to the insulator chain breakdown. With the current waveform maintained, it is sufficient to increase its value until the peak current corresponding to the overvoltage amplitude required to reach the breaking condition is found. Fig. 6 illustrates the procedure for determining the critical peak current of a representative first-return strikes.

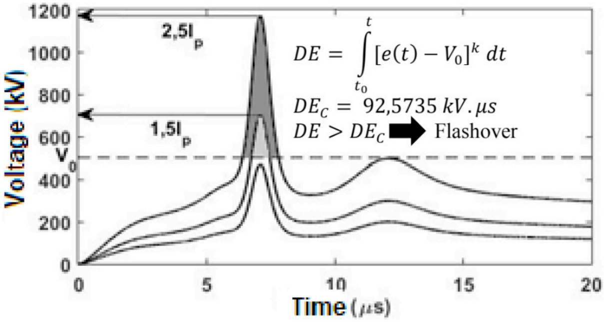
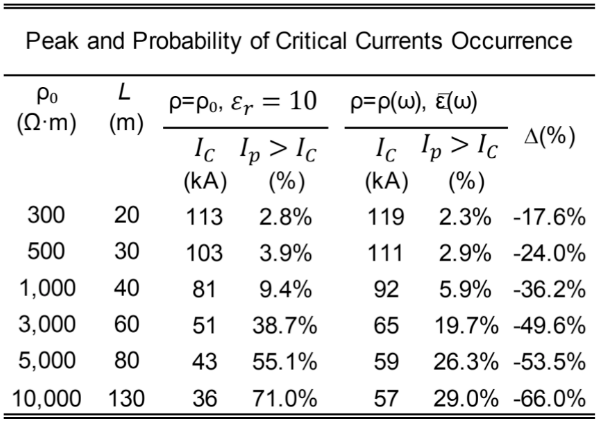


Fig. 6. Application of the DE method to evaluate the backflashover condition.

It can be seen in Fig. 5 that for soil resistivity values above 1000 Ω·m, the frequency dependence effect decreases not only the peak voltage but also the instantaneous voltage values over an interval after the peak and until the two curves stabilize. This may be relevant for reducing the value resulting from integration when using the DE method to evaluate the backflashover condition.

To quantify this effect, the DE method was applied to the overvoltage curves obtained through each soil resistivity condition to determine the peak value of the critical current I_c, under the assumption of constant and frequency-dependent soil parameters. The I_c corresponds to a threshold, i.e. currents above it lead the line insulators to breakdown.

The calculated values of I_c are shown in Table III, together with the percentage of peak currents that exceed the critical value ($I_p > I_c$), determined from the cumulative probability distribution of peak currents for first return discharges measured at the Morro do Cachimbo - MG station [12], which is approximately $P_I = 1/[1+(I/45{,}3)^{3{,}9}]$. When considering the effect of frequency dependence of soil parameters, the critical currents I_c are increased in all cases, and this increase becomes more significant with higher values of soil resistivity. Thus, the percentage of peak currents higher than I_c (events that lead the line to insulation breakdown) is decreased, as indicated by Δ. The impact of the effect is significant even in soils of low resistivity, starting from approximately 18% for soils of 300 Ω-m and reaching 66% for soils of 10,000 Ω-m.



Peak and Probability of Critical Currents Occurrence						
ρ_0 ($\Omega\cdot$m)	L (m)	$\rho=\rho_0$, $\varepsilon_r = 10$		$\rho=\rho(\omega)$, $\bar{\varepsilon}(\omega)$		Δ(%)
		I_C (kA)	$I_p > I_C$ (%)	I_C (kA)	$I_p > I_C$ (%)	
300	20	113	2.8%	119	2.3%	-17.6%
500	30	103	3.9%	111	2.9%	-24.0%
1,000	40	81	9.4%	92	5.9%	-36.2%
3,000	60	51	38.7%	65	19.7%	-49.6%
5,000	80	43	55.1%	59	26.3%	-53.5%
10,000	130	36	71.0%	57	29.0%	-66.0%

TABLE III - Critical Current Peaks and Occurrence Probabilities calculated considering constant and frequency dependent ground electrical parameters.

C. Backflashover Outage Rate

The evaluation of the impact of the frequency dependence of soil parameters on the rate of backflashover transmission line disconnection was developed following a procedure similar to that indicated by Anderson [31]. The proposed methodology requires certain preliminary definitions/information to be applied, such as the density of atmospheric discharges (N_g) along the line to be studied, the geometry of its towers and a set of soil resistivity values to be analyzed, covering a distribution of values found along with the soil resistivity of the regions that the line is installed.

N_g=10 was used because it is an average value found in the state of Minas Gerais, where the Morro do Cachimbo station is also located. Besides this, another important parameter is the number of discharges that strikes a transmission line per 100 km per year (), which is defined by the following expression [32]:

$$N_S = N_g \times \left(\frac{28h^{0,6}+b}{10}\right) \quad (12)$$

where h (m) is the tower height and b (m) is the distance between the shield wire of the towers. The division by “10” occurs to convert units, because N_g is measured in strikes/km²/year and h and b in meters.

When calculating the backflashover rate, only lightning strikes that directly affect the tower are considered. In an empirical way, it is assumed that 60 % of the discharges that reach a transmission line affect directly the towers [33,34]. Thus, the number of lightning strikes that hit the tower of a line (N_T) is given by (13):

$$N_T = 0{,}6 \times (N_s) \quad (13)$$

where (N_S) is the number of lightning strikes hitting a transmission line per 100 km per year.

Finally, the backflashover rate (N_{BF}) can be calculated. In (14) is defined the calculation N_{BF} (number of backflashover outages per 100 km of line per year), represented below:

$$N_{BF} = \frac{N_T}{100} \times P[I \geq I_c] \qquad (14)$$

where $P\,[I \geq I_C\,]$ is the probability that a lightning strike current is greater than the minimum lightning current enough to lead the transmission line outage. The division by “100” into (14) is to transform the value of the probabilities ($P\,[I \geq I_C\,]$) from percentage to p.u.

Based on the critical current probabilities in Table 4, the expected backflashover rates have been calculated under the assumption of constant and frequency-dependent ground parameters.

The analysis considers nine different soil resistivity distributions along the line: six uniform distributions (ρ_0 from 300 to 10,000 Ω·m) and three non-uniform distributions, these represent different soil conditions along the line, thus being more realistic. Of these three, one predicts only soils of low to moderate resistivity (not including samples above 1,000 Ω·m), another predicts soils of moderate resistivity (samples of all resistivity values included, most often soils with resistivity of 500 and 1,000 Ω·m), and the latter predicts soils of high to extremely high resistivity (no samples below 3,000 Ω·m).

Considering the uniform distributions, the results of Table 4 show that frequency dependence causes a strong decrease in backflashover rates in all cases, from 20% to approximately 60%.

The estimated rates (per 100 km per year) under the hypothesis of constant soil parameters vary from 1 to 26, which demonstrates the sharp growth as the soil resistivity is increased.

This reduction is also significant for non-uniform distributions. Considering the shutdown rates of 2.1; 7.6 and 19.5 (for soil resistivity conditions from low to moderate, and high to extremely high) are reduced by 28.6%, 50%, and 54.4%, respectively, due to the frequency dependence effect.

Table IV summarizes the results reported above and indicates the reduction in expected shutdown rates (Δ).

Hypothesis of ρ_0 along the transmission line (%)						N_{BF} (outages/100 km/year)		
300 (Ω·m)	500 (Ω·m)	1,000 (Ω·m)	3,000 (Ω·m)	5,000 (Ω·m)	10,000 (Ω·m)	$\rho=\rho_0$, $\varepsilon_r = 10$	$\rho=\rho(\omega)$, $\varepsilon(\omega)$	Δ(%)
100%	0%	0%	0%	0%	0%	1	0,8	-20,0%
0%	100%	0%	0%	0%	0%	1,4	1,1	-21,4%
0%	0%	100%	0%	0%	0%	3,4	2,2	-35,3%
0%	0%	0%	100%	0%	0%	14,1	7,2	-48,9%
0%	0%	0%	0%	100%	0%	20,2	9,6	-52,5%
0%	0%	0%	0%	0%	100%	26	10,6	-59,2%
30%	30%	40%	0%	0%	0%	2,1	1,5	-28,6%
10%	30%	30%	10%	10%	10%	7,6	3,8	-50,0%
0%	0%	0%	40%	30%	30%	19,5	8,9	-54,4%

TABLE IV - Estimated backflashover rates considering constant and frequency-dependent soil electrical parameters and various soil resistivity distributions along the line.

From the results presented, it is clear that including the dependence on the frequency of the soil parameters can strongly affect the outage rates of the transmission lines, causing a significant improvement in their lightning performance in all the cases studied.

4 I CONCLUSIONS

The influence of the frequency-dependent effect of resistivity and soil permittivity on the lightning performance of transmission lines was evaluated and discussed. The results presented imply a significant reduction of the overvoltages of atmospheric origin of the tested line due to the dependence on the frequency of the soil electrical parameters.

The dependence on the frequency of soil parameters causes a relevant reduction in the overvoltages associated with the first-return strikes to lines installed in soils above 500 Ω·m. This results in a significant increase in the peak values of critical currents, leading to a consequent reduction in the probability of backflashover outages.

It was found that the frequency dependence or soil parameters affects very significantly backflashover rate of the studied line for the whole range of resistivities of the studied soil. As the resistivity is increased, the impact becomes more pronounced. Considering the non-uniform, and more realistic, soil distributions indicated in Table 4, reductions in expected shutdown rates of about 28% to 54.4% were found.

The results presented demonstrate a significant improvement in the performance of the line tested against atmospheric discharges due to the dependence on the frequency of the soil electrical parameters, and attribute a certain generality to the impact of this effect on transmission lines.

From these conclusions, it is clear the importance of including the frequency-dependent effect of soil resistivity and permissiveness in the performance assessments against atmospheric discharges of transmission lines that cross regions with soil resistivity above 500 Ω·m.

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