Lightning Performance Analysis of Transmission Lines Using Monte Carlo Simulations

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Abstract—**The electric power transmission lines are exposed to several climatic factors, namely the incidence of atmospheric discharges that impair its operation. The performance of the transmission lines can be determined by calculating two rates: Shielding Failure Flashover Rate (SFFOR) and Back Flashover Rate (BFR). A computer program was created that allows one to simulate the behaviour of the line and the atmospheric discharges and calculate the rates using MATLAB and EMTP. The study concluded that the model that most closely approximates the actual line performance values is Eriksson's Modified Electrogeometric Model. For the practical case of Portugal it was concluded that when adding one more shield wire to the line, the rates improved considerably. For the other practical cases, reasonable values were obtained and were within the expected results.**

***Index Terms*—Monte Carlo Simulation, shielding failure, EMTP, BFR, SFFOR**

I. Introduction

One of the biggest problems affecting the normal functioning of the power transmission lines is the atmospheric discharges. To minimize the impact of line discharges and to reduce the number of interruptions, shield wires are placed, which, if they are well positioned, intercepts the atmospheric discharges, avoiding interruptions.

This dissertation aims to make an algorithm that allows to calculate performance rates of transmission lines. A routine was developed to generate these atmospheric discharges through the use of Monte Carlo simulations using MATLAB. The atmospheric discharges have a random nature and can be reproduced using a log-normal distribution. Another tool used was the EMTP (Electromagnetic Transients Program), when calculating electromagnetic transients in electric energy systems.

The efficiency of the line interception system is verified by the calculation of two rates: SFFOR and BFR. The first is the Shielding Failure Flashover Rate and represents the number of discharges, per 100km of line and per year, that are not intercepted by the shield wire, directly affecting the phase conductors and causing the flashover in the insulators. The BFR is the Back Flashover Rate and represents the number of discharges, per 100 km of line and per year, that affect the tower or shield wires, and causing the flashover in the insulators.

In order to determine if the lightning discharge reaches the phase conductor reaches on shield wire, the Electrogeometric models are used. These models are based on the concept of striking distance, which depends on the intensity of the current that characterizes the lightning discharge.

Since there are several methodologies and models for calculating the performance rates of electric power transmission lines, a study was made to perceive the differences between them and the effects on the results.

The methodology developed was applied to four different practical cases: two are from a Portuguese line, before and after its uprating, another is from an American line and the last is from a German line. This paper is divided into four main sections. Section II refers to the methodologies and models adopted, namely the lighting stroke parameters, the incidence analyses, the models for network components and the lightning performance characterization of the line. Section III presents the algorithm developed for calculating the performance of transmission lines. Finally, section IV concerns the applications of the algorithm. In this last one, the practical cases and the number of iterations are chosen and the results are presented.

II. Methodology and models

A. Keraunic activity level

In order to evaluate the performance of the lines when atmospheric discharges occur it is necessary to know the keraunic activity. After years of observation it was possible to determine the keraunic level, which is defined as the average annual number of thunderstorm days or hours for a given location, T_d. Using T_d it is possible to determine the ground flash density (GFD), Ng. This parameter is defined as the average number of strokes per unit area per unit time at a particular location and it's given by expression (1) [2]

$$N_g = 0{,}04 \times T_d^{1{,}25} \ [\text{flashes/km}^2/\ \text{year}] \qquad (1)$$

Currently there are other methods to determine ground flash density without the keraunic activity level. The atmospheric discharges are detected by electromagnetic sensors that send the data to a central analyser. Each sensor detects the electromagnetic signal and, using a GPS satellite, obtains information on location, time, intensity and polarity of the current. The European network is called the European Cooperation for Lightning Detection (EUCLID) [3].

B. Lightning stroke parameters

The parameters that characterize the atmospheric discharges have a random nature, that is, they follow probabilistic laws to characterize them and the parameters are obtained through experimental studies. The statistical variation of the lightning stroke parameters can be approximated by a log-normal distribution, with the following probability density function.

$$p(x) = \frac{1}{\sqrt{2\pi}\,\beta x}\, e^{-\left(\frac{z^2}{2}\right)} \qquad (2)$$

with

$$z = \frac{\ln\left(\frac{x}{M}\right)}{\beta} \qquad (3)$$

where M is the median parameter value and β is the logarithmic standard deviation (base e). The parameters of the current are the peak current magnitude (I), the rise time ($t_{d30/90}$) and the maximum steepness of the front (S_m). These parameters were initially indicated by Berger *et a*l. [1] and are indicated in the Table 1.

Table 1. Parameters of Log-Normal Distribution for Negative Downard Flashes for the first sroke

Parameter	M	β
$t_{d30/90}$ [μs]	3.83	0.576
S_m [kA/μs]	24.30	0.599
I [kA]	31,10	0.484

New studies on the distribution of peak current amplitudes have since been made, in which CIGRE determined that the distribution may be better approximated by two straight lines drawn through the measured data. This parameters estimated by Anderson and Eriksson are in Figure 1.

The shielding-failure domain comprises peak current of amplitudes less than 20 kA and the backflash domain comprises those currents above 20 kA.

The values of the distribution parameters are found in the expressions (4), (5) e (6).

$$I < 20\text{ kA} \begin{cases} M_I = 61\text{ kA} \\ \beta_I = 1.33\text{ kA} \end{cases}$$

$$I > 20\text{ kA} \begin{cases} M_I = 33.3\text{ kA} \\ \beta_I = 0.605\text{ kA} \end{cases} \qquad (4)$$

$$I < 20\text{ kA} \begin{cases} M_{t_{d3o}} = 1.77\, I^{0.188}\ \mu s \\ \beta_{t_{d3o}} = 0.494\ \mu s \end{cases}$$

$$I > 20\text{ kA} \begin{cases} M_{t_{d3o}} = 0.906\, I^{0.411}\ \mu s \\ \beta_{t_{d3o}} = 0.494\ \mu s \end{cases} \qquad (5)$$

$$I < 20\text{ kA} \begin{cases} M_{S_m} = 12.0\, I^{0.171}\text{ kA}/\mu s \\ \beta_{S_m} = 0.554\text{ kA}/\mu s \end{cases}$$

$$I > 20\text{ kA} \begin{cases} M_{S_m} = 6.50\, I^{0.376}\text{ kA}/\mu s \\ \beta_{S_m} = 0.554\text{ kA}/\mu s \end{cases} \qquad (6)$$

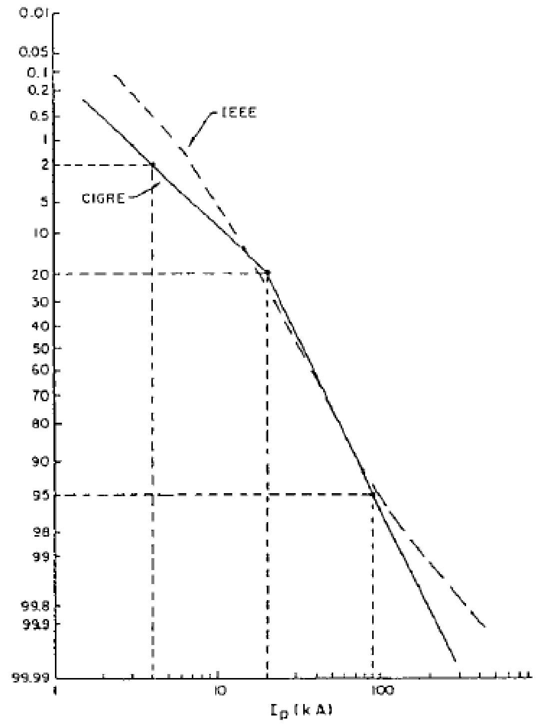

Figure 1. Distribution for negative lightning current amplitude [extracted from [1]]

Recently (2013) [4], CIGRE indicates that the parameter values estimated by Anderson and Eriksson are significantly underestimated due to the limitations of the instruments used in 1980's and the parameters proposed by Berger *et al*, which are the most reliable, should continue to be used. It is recommended that the correlations with the peak value of the current only be used for S_m and for $S_{30/90}$. In this work only the first one, given by expression (7), will be used.

$$S_m = 3.9 \times I^{0.25}\text{ kA}/\mu s \qquad (7)$$

The parameters proposed in 2013 by CIGRE [4] are shown in Table 2.

Table 2. Values for M and β proposed by CIGRE in 2013

Parameter	M	β
$t_{d30/90}$ [μs]	3.83	0.576
S_m [kA/μs]	$3.9 \times I^{0{,}25}$	0.599
I [kA]	31.1	0.484

C. <u>Incidence Analysis</u>

C.1. Striking distance

Several Electrogeometric models have been developed. All models are based on the concept of striking distance. Striking distance is the length of the last step of leader under the influence of attraction toward the point of opposite polarity to be struck. Stroke current magnitude, I, and strike distance (length of the last stepped leader) are interrelated, expression (8).

$$r = A \times I^b \qquad (8)$$

where I is the peak current of the first discharge, in kA, r is the striking distance, A and b are parameters of the model that have different values depending on the model used and on the striking distance to earth or to the conductors. A proportionality constant, k, was considered for the relationship between the striking distance to the earth and to the conductors. Parameter k varies according to the Electrogeometric Model. These parameters are in the Table 3.

Table 3. Parameters for calculating the striking distance for the different models

	Striking distance				
	Earth, r_g		Phase conductors and shield wire, r_c		
Source	**A**	**b**	**A**	**b**	**K**
1.Wagner [5]	11.25	0.49	11.25	0.49	1
2.Young. *et al.* [1]	27	0.32	*(1)	0.32	-
3.Armstrong e Whitehead [6]	6.05	0.8	6.72	0.8	0.9
4.Brown e Whitehead [7]	6.39	0.75	7.1	0.75	0.9
5.Suzuki *et al.* [8]	3.3	0.78	3.3	0.78	1
6.Love [1]	10	0.65	10	0.65	1
7.IEEE_1985 [9][10]	*(2)	0.65	8	0.65	-
8.IEEE_1985 [11]	*(3)	0.65	10	0.65	-
9.Eriksson [1]	To phase conductor: $r_{ac} = 0.67y^{0.6}I^{0.74}$				
	To shield wire: $r_{ag} = 0.67h^{0.6}I^{0.74}$				
	To earth: $r_g = 0$				

*(1) $\begin{cases} A_c = 27,\ h < 18m \\ A_c = 27 \times 444/(462 - h),\ h > 18m \end{cases}$, where h is the height of the tower

*(2) $\begin{cases} A_g = 5{,}12, V > 800kV \\ A_g = 6{,}4, 100kV < V < 800kV \\ A_g = 8, V < 100kV \end{cases}$

*(3) $\begin{cases} A_g = 5{,}5,\ y_m \geq 40m \\ A_g = (3{,}6 + 1{,}7\ln(43 - y_m)),\ y_m < 40m \end{cases}$, where y_m is the average conductor height in meters, given by the height at the tower minus two-thirds of the midspan sag.

C.2. Electrogeometric Model

- Classic Electrogeometric Model

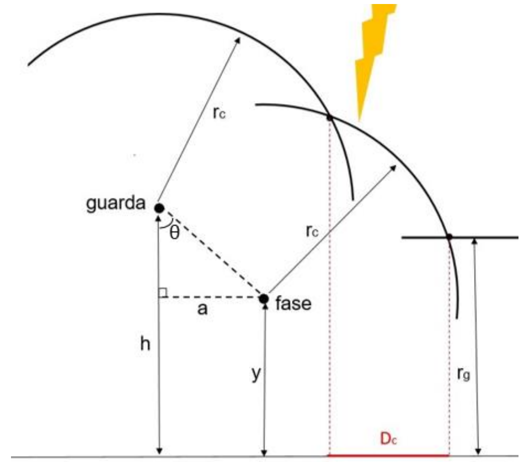

Figure 2. Application of the Electrogeometric Model with a partial phase conductor protection

Figure 2 represents the Electrogeometric Model with an inefficient line protection. Assuming that all leaders are vertical, the exposure distance for a shielding failure is D_c [1], that is, there is the possibility of the atmospheric discharge being able to reach the phase conductor. The exposure distance, Dc, decreases when the intensity of the discharge increases. Therefore, it is possible to design the location of the shield wires that provide a perfect shield, as shown in Figure 3

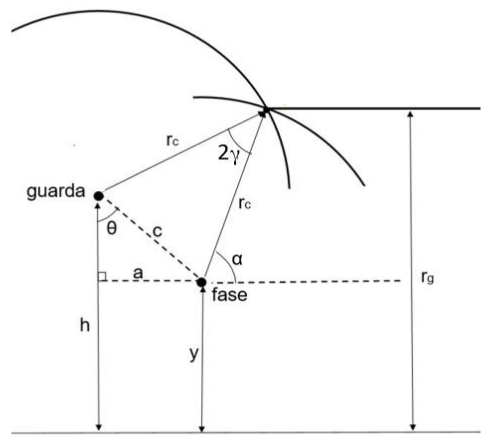

Figure 3. Electrogeometric Model with a perfect shielding

The current for which the exposure distance is zero is the minimum current from which it is guaranteed that any atmospheric discharge will not reach the phase conductor, ie perfect shielding occurs. To define the exposure distance, it is necessary to take into account the striking distance and the position of the phase conductor and the shield wires. These two positions form in the space an angle, the protection angle θ. From Figure 3 it is possible to determine the equations (9), (10), (11) and (12):

$$c = \sqrt{(h - y)^2 + a^2} \tag{9}$$

$$\theta = \tan^{-1}\left(\frac{a}{h - y}\right) \tag{10}$$

$$\gamma = \sin^{-1}\left(\frac{c}{2 \times r_c}\right) \quad (11)$$

$$\alpha = \sin^{-1}\left(\frac{r_t - y}{r_c}\right) \quad (12)$$

where h is the height of the shield wire next to the tower, in meters, y is the height of the phase conductor next to the tower, in meters, rc is the striking distance to the conductor, in meters, rg is the striking distance to the earth, in meters, θ is the protection angle, in degrees, a is the horizontal distance between the conductor phase and the shield wire, in meters, α and γ are auxiliary angles, in degrees and c is an auxiliary variable, in meters. Equation (13) determines the exposure distance, D_C.

$$D_c = r_c \times [\cos\theta - \cos(\alpha + \gamma)] \quad (13)$$

- Modified Electrogeometric Model

In 1987, Eriksson presented a new model called Modified Electrogeometric Model. The main difference between this model and the classic one is that in this model the striking distance to the earth is not considered and the height of the tower is considered. As in the classic Electrogeometric Model the line can be completely protected (perfect shielding) or only partially protected. In Figure 4 we can see the Modified Electrogeometric Model with partial protection, where r_{ac} is used for the attractive radius to the phase conductor and r_{ag} for the attractive radius to the shield wire. According to [11] it is possible to deduce the formula for the calculation of the penetration arc, A, in red in Figure 4.

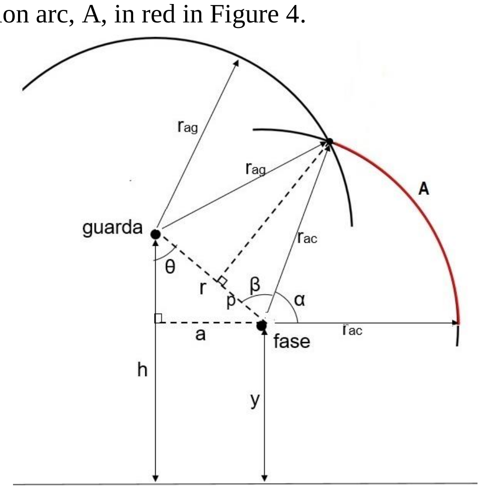

Figure 4. Modified Electrogeometric Model with partial protection

Using trigonometry methods we get expressions (14), (15), (16) and (17).

$$\alpha = \theta + 90° - \beta \quad (14)$$

$$\beta = \cos^{-1}\left(\frac{p}{r_{ac}}\right) \quad (15)$$

$$p = \frac{{r_{ac}}^2 - {r_{ag}}^2 + r^2}{2 \times r} \quad (16)$$

$$r = \frac{h - y}{\cos\theta} \quad (17)$$

where h is the height of the shield wires, in meters, y is the height of the phase conductor, in meters, β is an auxiliary angle in the calculations, in degrees, and p and r are auxiliary variables of the calculations, in meters. It is therefore possible to obtain an expression for the penetration arc, A, expression (18).

$$A = \frac{r_{ac}}{57{,}3}\left[\theta + 90° - \cos^{-1}\left(\frac{{r_{ac}}^2 - {r_{ag}}^2 + r^2}{2 \times r \times r_{ac}}\right)\right] \quad (18)$$

where r_{ac} is the attractive radius of the conductor, in meters, r_{ag} is the attractive radius to the shield wires, in meters, θ is the protection angle of the line, in degrees and r is an auxiliary variable to the calculation, in meters.

As in the classical Electrogeometric Model, the penetration arc also varies with the intensity of the atmospheric discharge current. For currents higher than the maximum shielding failure current, the discharges never reach the phase. In this way, it is possible to determine if a line with a certain geometry is protected.

C.*3 Maximum shielding failure current*

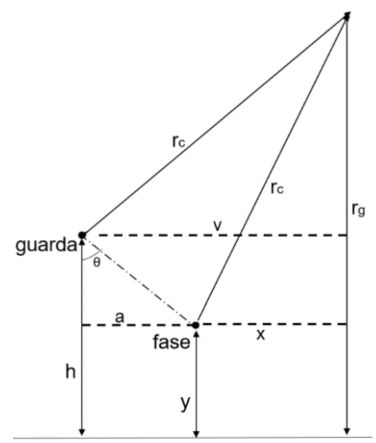

Figure 5. Perfect shielding for the Classical Electrogeometric Model

When the lightning current increases, the exposure distance, D_c, decreases and the limit current of shielding failure will be the one that makes the exposure distance equal to zero. Using trigonometric expressions that are taken from the Figure 5 it is possible to obtain an expression for the striking distance, expression (19).

$$ {r_c}^2 = (k\,r_c - h)^2 + \left(\sqrt{{r_c}^2 - (k\,r_c - y)^2} + a\right)^2 \quad (19)$$

where r_c is the striking distance to the phase conductors and shield wires, r_g is the striking distance to the earth and x and v are auxiliary variables to the calculations. The variable k, which is the relationship between the striking distance to the earth and the striking distance to the phase, varies according to the Electrogeometric Model and is shown in Table 3.

Using expression (8) to find the striking distance to the phase conductors it is possible to determine the limit current of shielding failure, in expression (20).

$$I = (\frac{r_c}{A_c})^{\frac{1}{b_c}} \quad (20)$$

Where r_c is the striking distance to the phase conductors, obtained by expression (19).

In the case of the Modified Electrogeometric Model, the method is similar to the Classic Model. Figure 8 shows the perfect shielding for the Modified Electrogeometric Model.

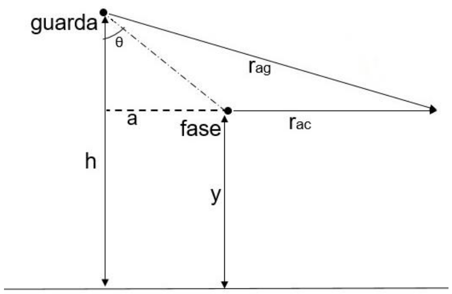

Figure 6. Perfect shielding for the Modified Electrogeometric Model

Applying the Pythagoras's Theorem to Figure 8 and using the expressions for the attractive radius to the phase conductors and for the attractive radius to the shield wires it is possible to obtain the system of equations (21).

$$\begin{cases} r_{ac} = \sqrt{{r_{ag}}^2 - (h-y)^2} - a \\ r_{ag} = 0{,}67h^{0{,}6}{I_{max}}^{0{,}74} \\ r_{ac} = 0{,}67y^{0{,}6}{I_{max}}^{0{,}74} \end{cases} \quad (21)$$

Having solved the system of equations (21) it is possible to obtain the value of I_{max}, in kA, which corresponds to the maximum current that can penetrate the phase. This value is calculated from the attractive radius to the shield wires and to the phase conductor, and depends on the geometry of the tower. For currents above the limit current of shielding failure, the line is protected (perfect shielding), whilst atmospheric discharge currents below the value of the limit current will reach the phase conductor.

C.4 Attraction width

The attraction width, W, is different for each Electrogeometric Model. Figure 7 shows attraction width in the case of the Classic Electrogeometric Model (a) and in the case of the Modified Electrogeometric Model (b).

For the Classic Electrogeometric Model it is necessary to calculate the intersection point of striking distance, r_c, with the height, r_g, to determine W. In case of the Modified Electrogeometric Model it is possible to determine the value of W by the expression (22)

$$W = 2 \times r_{ag} + s \quad (22)$$

where s is the horizontal distance between the two shield wires and r_{ag} is the attractive radius to the shied wires.

If we know the ground flash density (N_g) and W, it is possible to obtain the annual number of lightning flashes to the line per 100 km, N_L, by expression (23)

$$N_L = \frac{N_g}{10} \times W \text{ [descargas/100km/ ano]} \quad (23)$$

where N_g is the ground flash density and W is attraction width.

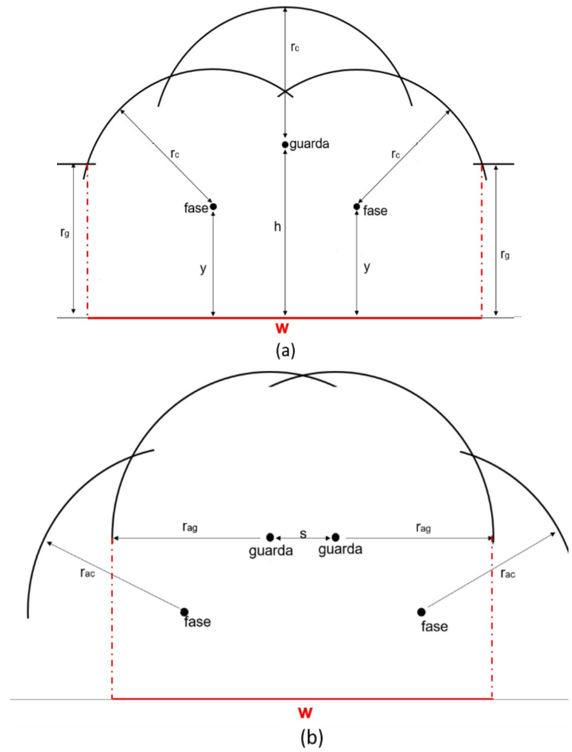

Figure 7. Attraction width, W, in the Classical Electrogeometric Model (a) and in the Modified Electrogeometric Model (b) (adapted from [12])

D. Models for network components

Electromagnetic Transients Program (EMTP) was used to calculate the electromagnetic transients in electrical energy systems. The following paragraphs summarize the models for network components used in this work:

- The line is modelled by an internal model of the EMTP program. An FD line (frequency dependent parameter) shall be used based on the characteristic impedance and propagation function, calculated from the line parameters in the phase domain, using a constant and a real transformation matrix. The transformation matrices are complex and frequency dependent and the EMTP only uses the real part of the matrices since the complex part has a much lower value [13]. Note that it is considered that the line is always uniform.
- The model used to represent the tower was the Multi-Story Transmission Tower. The representation of each of the sections varies according to the size of the section. Sections with a length of less than 9 meters are represented by an equivalent inductance of 1μH per unit length of the transmission line (1μH/m), depending on their dimensions. Sections with a length greater than 9 meters are represented by a constant parameter line (CP), i.e. independent of frequency [14][15].
- The earthing electrode will be represented by a resistance, R_t. Knowing the value of the grounding resistance along all towers of the line it is possible to characterize statistically the ranges values of Rt in each line.

- The insulators are represented with an internal EMTP model. This model is based in leader progression model (LPM), expression (24).

$$\frac{dl}{dt} = k \cdot u(t) \left[\frac{u(t)}{d_G - l(t)} - E_0\right] \tag{24}$$

where l(t) is the leader length, in meters, d_G is the gap length, in meters, u(t) is the voltage across the gap, in kV, k is an empirical constant that depends of the configuration of the gap and E_0 is the critical leader inception gradient in kV / m. The leader propagation stops if the gradient in the unbridged part of the gap falls below E_0. According to this model, the flashover mechanism consists of three steps: corona inception, streamer propagation and leader propagation. A flashover occurs when the leader crosses the gap between the arcing horns. Therefore, the total time (T_t) to flashover can be expressed as follows:

$$T_t = t_c + t_s + t_l \tag{25}$$

where t_c is the corona inception time, t_s is the streamer propagation time and t_l is the leader propagation time.

- The line is modeled by 5 towers, with two spans at each side of the point of impact (tower 3), as can be seen in Figure 8. At the beginning of the line, a voltage source will be used to simulate the network equivalent. The representation of a line termination is needed at each side of the line to avoid reflections that could affect the simulated overvoltages around the point of impact. This can be achieved by adding a long enough section of line, in this case 50 km, at each side [14].

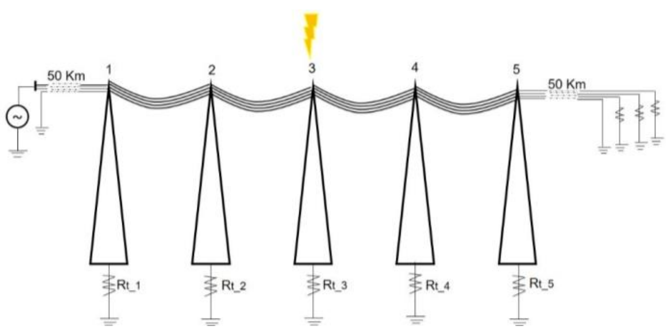

Figure 8. Schematic line used in EMTP

E. Lightning Performance Characterization of the Line

The number of strokes which terminates on the phase conductors and result in flashover is the Shielding Failure Flashover Rate (SFFOR). According to CIGRE [1] and IEEE [11], SFFOR is calculated by expression (26)

$$\mathrm{SFFOR} = 2 \times \frac{N_g}{10} \times \int_{I_{limite}}^{I_{max}} D_c(I) \times f(I)\, dI \tag{26}$$

where N_g is the ground flash density, per year and per km^2, I_{limite} is the limit current of shielding failure, I_{max} is the maximum current caused by atmospheric discharges and f (I) is the probability density function. Equation (26) is valid when the lines are symmetrical and have the same exposure distance (D_c), which is why the integral is multiplied by 2.

The Back Flashover Rate (BFR) is the number of lightning strikes that terminate on the tower or in the shield wires and result in insulator flashover. The BFOR (referred to 100 km of line-year) is then calculated as

$$\mathrm{BFR} = 0{,}6\, N_L \int_{I_{limite}}^{I_{max}} f(I)\, dI = 0{,}6\, N_L \times P_{BFR}(I) \tag{27}$$

where N_L is the annual number of lightning flashes to the line per 100 km (expression (23)) and $P_{BFR}(I)$ is the quotient between the discharges that cause backflash and all discharges occurred. BFR is based only on strokes to the tower so the BFR will be significantly greater than if strokes terminating within span are considered. Since it is necessary to do some adjustment, the 0.6 is a multiplicative coefficient that accounts for strokes terminating within the span.

III. Algorithm for Calculating the Performance of Transmission Lines

Due to the random nature of lightning, an accurate evaluation of the lightning performance must be based on a statistical approach. A Monte Carlo simulation is the most usual method for this purpose.

The EMTP (Electromagnetic Transients Program) was used to determine if a flashover occurred when there is an atmospheric discharge with certain characteristics. EMTP is a specialized software for the simulation of electromagnetic, electromechanical and control systems in power systems. With MATLAB and using the Monte Carlo simulations it is possible to simulate the atmospheric discharges.

The computational program that was developed allows the user to choose if he wants to use the values of M and β proposed by CIGRE in 1991, which are presented in expressions (4), (5) and (6), or the values suggested more recently by CIGRE in 2013, which are presented in Table 2. The program also allows the user to select the Electrogeometric Model that he wants to use.

Comparing the limit current of Shielding Failure with the current value of the atmospheric discharge, I, allows the program to decide if the discharge will affect the phase conductor or the shield wire. When the randomly generated peak current value is greater than the limit current, the atmospheric discharge will reach the shield wire and the phase will be protected. On the other hand, when the peak current value is less than the limit current value, the atmospheric discharge reaches the phase. In EMTP, the only difference between the atmospheric discharge reaching the phase conductor or the tower is the node to which the lightning strokes (the current source) must be connected. In each simulation, the algorithm sends the current parameters to the corresponding EMTP program file, depending on whether the discharge reaches the shield wire or phase.

The expression (26) used to calculate the SFFOR will be given by the expression (28)

$$\mathrm{SFFOR} = N_L \times P_{SFFOR}(I) \tag{28}$$

where N_L is the annual number of lightning flashes to the line per 100 km and P_{SFFOR} (I) is the quotient between the discharges that cause flashover and all discharges occurred.

There are several ways of determining the grounding resistance. In this program the user can choose if the value for the resistance of tower 3 will be constant for all simulations or if the resistance value will be variable in each simulation, using a probabilistic distribution obtained from real values of the line.

In this dissertation four different practical cases will be studied. The first case will be a line in Portugal (Case 1A - base case), the second case will be the same line but after an uprating (case 1B), the third case will be a line in the United States of America (Case 2) and finally, Case 3 will be a German line. In the computer program that was developed the user will also be able to choose which practical case he wants.

IV. Applications

A. Practical cases

- Case 1- Portugal

Figure 9 shows the distribution of values of the grounding resistance in the line. This distribution is the same in cases before and after uprating (case 1A and case 1B). The average resistance value is 16.16 Ω and will be the value of the grounding resistances to the towers 1, 2, 4 and 5 in the EMTP program. In this case T_d=10 days/year was used.
The characteristics of the phase conductors and shield wires used in the line are shown in Table 4 and in Table 5, respectively. The Figure 11 shows the line tower geometry to the line before uprating (a)) and in the line after uprating (b)).

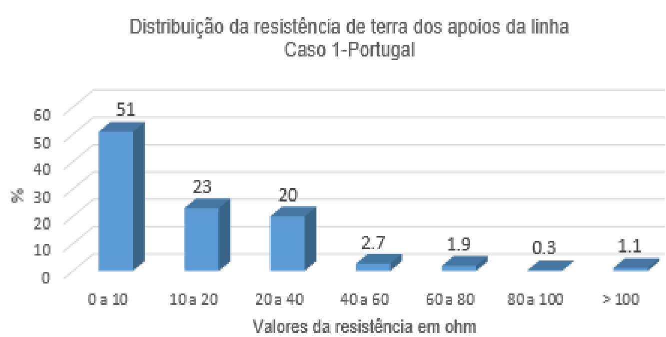

Figure 9. Grounding resistance distribution, in Portugal

Table 4. Phase conductors and shield wires characteristics, case A1

Portugal Before uprating	Cable	Diameter (cm)	R_{cc} (ohm/km)	Skin Effect	Span (Km)
Wire	SWG 19/13	1,170	1,82	0,20	0,30
Phase conductor	Bear	2,345	0,11	0,29	

Table 5. Phase conductors and shield wires characteristics, case A2

Portugal After uprating	Cable	Diameter (cm)	R_{cc} (ohm/km)	Skin Effect	Span (Km)
Shield Wire	Guinea	1,46	0,359	0,20	0,30
	OPGW	1,63	0,288		
Phase conductor	Bear	2,35	0,112	0,29	

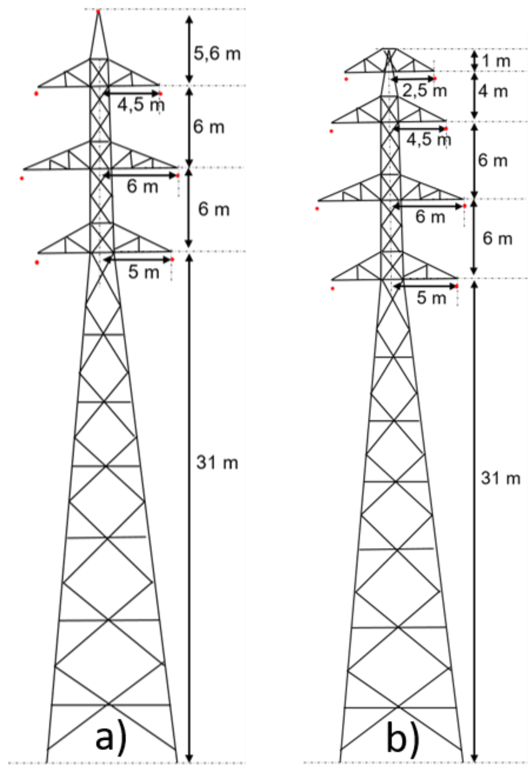

Figure 10. Tower geometry of the line, before (a)) and after (b)) uprating

- Case 2 – United States of America

Figure 10 shows the distribution of values of the grounding resistance in the line, in case 2. The average resistance value is 17,75 Ω and will be the value of the grounding resistances to the towers 1, 2, 4 and 5 in the EMTP program. In this case N_g=1,05 flashes/km^2/year was used.
The characteristics of the phase conductors and shield wires used in the line are shown in Table 6. Figure 12a) shows the line support geometry to the line, to case 2.

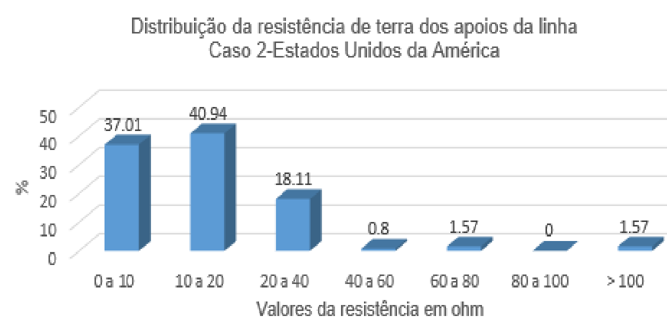

Figure 11. Grounding resistance distribution, in USA

Table 6. Phase conductors and shield wires characteristics, case B

United States of America	Cable	Diameter (cm)	R_{cc} (ohm/km)	Skin Effect	Span (Km)
Shield Wire	Hawk	2,18	0,39	0,2	0,27
Phase conductor	Hawk	1,40	0,11	0,32	

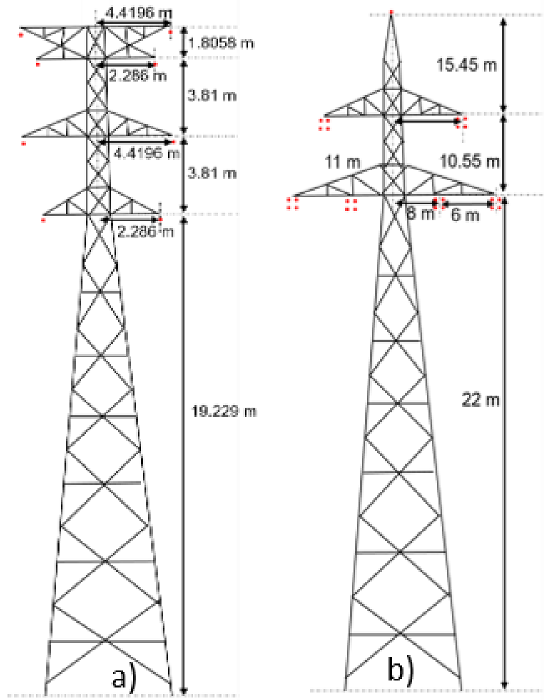

Figure 12. Tower geometry of the line, case 2 (a)) and case 3 (b))

- Case 3 – Germany

Figure 13 shows the distribution of values of the grounding resistance in the line, in case 3. The average resistance value is 4,66 Ω and will be the value of the grounding resistances to the towers 1, 2, 4 and 5 in the EMTP program. In this case N_g=2,36 flashes/km^2/year was used.

The characteristics of the phase conductors and shield wires used in the line are shown in Table 7. Figure 12b) shows the line support geometry to the line, to case 3.

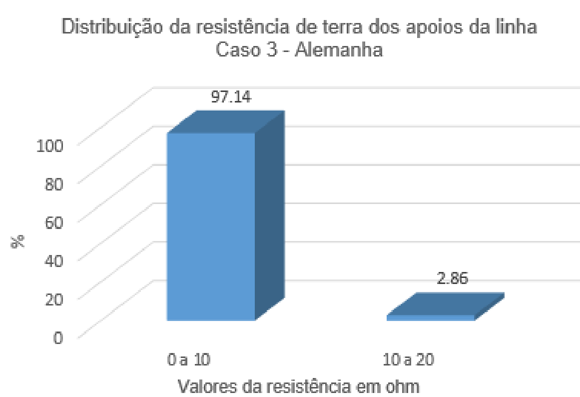

Figure 13. Grounding resistance distribution in the line, case 3

Table 7. Phase conductors and shield wires characteristics, case B

Germany	Diameter (cm)	R_{cc} (ohm/km)	Skin Effect	Span (Km)
Shield Wire	2,18	0,12	0,316	0,34
Phase conductor	2,18	0,12		

B. *Choose the number of iterations*

It was important to decide how many simulations were necessary to run in order to obtain reliable results. The base case will be used for this purpose. Two tests were done: one using 5000 simulations and one using 1000 simulations. The histograms of the current distribution with for both test are shown in Figure 14 and Figure 15, respectively. After having verified that the results obtained for 1000 and for 5000 simulations are similar and go according to the distribution initially imposed on the algorithm, a log-normal distribution, the number of simulations used in this work will be 1000.

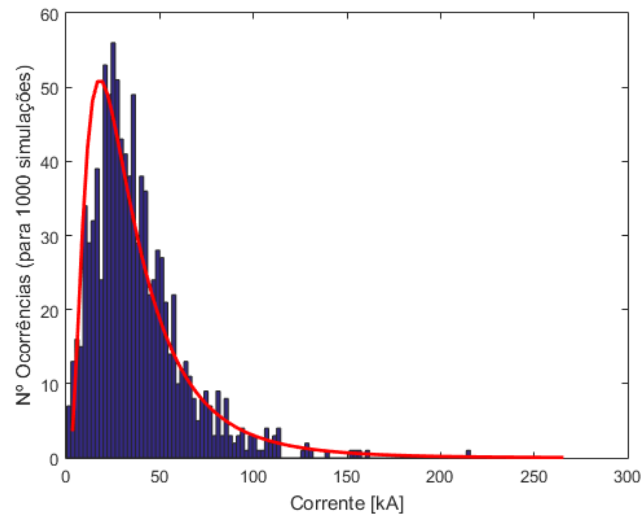

Figure 14. Histogram to 1000 simulations

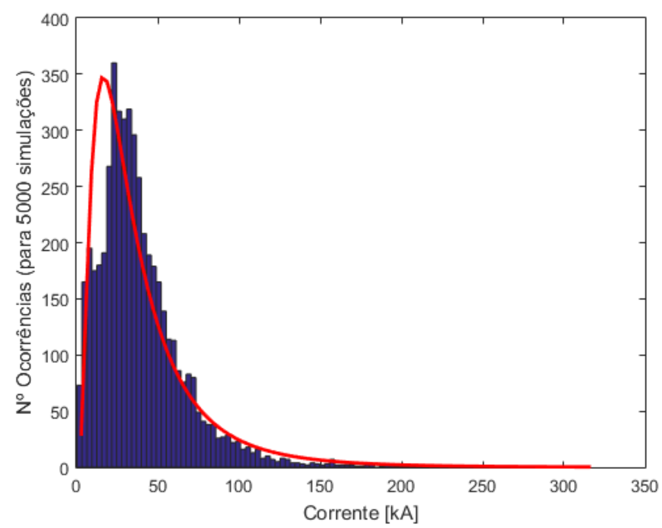

Figure 15. Histogram to 5000 simulations

C. *Methodology and models*

For the choice of methodologies and models the base case (case 1A) was used. The atmospheric discharges generally have negative polarity. Thus, the atmospheric discharge will be represented by a current source with negative polarity.

Influence of the incidence model: Table 8 shows the results obtained for the performance rates corresponding to the various Electrogeometric models, using the mean current value for the calculation of the attraction width, using the recommendation by CIGRE Working Group 2013 for the current curve and using the probabilistic method to determining the grounding resistance. Analysing Table 8, verifies that the incidence model used has a great influence on the results obtained. According to the results relating to the real performance of the line, the total should be around 5.18. It is verified that the model closest to this value is the Modified Electrogeometric Model, model 9. This was the model that was chosen to obtain results in this work.

Table 8. Performance rates to the various Electrogeometric Models

	I_{limite}	SFFOR	BFR	Total
1	130.70	9.21	0.01	9.22
2	170.78	10.13	0.00	10.13
3	55.61	13.08	0.81	13.89
4	67.56	12.71	0.35	13.06
5	102.88	7.91	0.04	7.95
6	47.21	9.93	1.07	11.00
7	216.51	11.60	0.00	11.60
8	126.5	14.99	0.01	15.00
9	21.57	3.12	2.84	5.96

<u>Influence of the attraction width</u>: The option for the current curve by CIGRE 2013 and the grounding resistance calculated by the probabilistic method were again considered. Eriksson's Electrogeometric Model (model 9) was used. To calculate the pickup width a value for the current is necessary. The different currents used are the maximum current (which corresponds to the maximum W), the mean current (which corresponds to the mean W) and the shielding fault limit current (which corresponds to W Ilimite). The results are shown in Table 9. Based on the Electrogeometric Model, when we increase the value of the current, the value of the attraction width also increases, which is in line with the results obtained. As the value of the attraction width, h increases, the value of the rates also increases, which is also in line with the results. A mean current value will be used because it is the closest to the real value.

Table 9. Performance rates to different attraction widths

	W ($I_{médio}$) = 189,20 m $I_{médio}$ = 34,50 kA	W ($I_{máximo}$) = 565,40 m $I_{máximo}$ = 151,40 kA	W (I_{limite}) = 133,70 m I_{limite} = 21,60 kA
SFFOR	3.12	9.33	2.21
BFR	2.84	8.47	2.00
Total	5,96	17.80	4,21

- <u>Influence of grounding resistance:</u> There are two ways to determine ground resistance of the tower: using the probabilistic method based on real values or a user-determined value. For this work, the chosen value was the average value of the grounding resistance which is 16.16 Ω. In Table 10 it is possible to see the results obtained for each incidence model and for each mode of generating the ground resistance. The 2013 option for the current curve was once again used and the attraction width was calculated with average current value. The differences observed in SFFOR and BFR are small and are due to variations of the current, since vectors with random current values have been generated for each case. For the presentation of results of this work, the probabilistic mode based on real values to generate the grounding resistance will be used since it is the closest to reality.

Table 10. Performance rates for the two ways to determine ground resistance

Model	I_{limite} [kA]		SFFOR	BFR	Total
1	130.7	Rt prob.	9.21	0.01	9.22
		Rt médio	9.23	0.01	9.24
2	170.80	Rt prob.	12.13	0.00	12.13
		Rt médio	12.06	0.00	12.06
3	55.60	Rt prob.	13.08	0.81	13.89
		Rt médio	12.83	1.26	14.09
4	67.60	Rt prob.	12.71	0.35	12.81
		Rt médio	12.74	0.45	13.19
5	102.9	Rt prob.	7.91	0.04	7.95
		Rt médio	7.86	0.02	7.88
6	47.2	Rt prob.	9.93	1.07	11.00
		Rt médio	10.03	1.37	11.40
7	216.5	Rt prob.	11.60	0.00	11.60
		Rt médio	11.61	0.00	11.61
8	126.5	Rt prob.	14.99	0.01	15.00
		Rt médio	14.87	0.03	14.90
9	21.6	Rt prob.	3.12	2.84	5.96
		Rt médio	3.28	3.31	6.59

D. *<u>Results</u>*

The influence of each model and methodology on the result obtained was considered. The models and methodologies used are:

- Eriksson Modified Electrogeometric Model (model 9);
- Resistance calculated using probabilistic mode (real values);
- Pickup width calculated using the average current value;
- CIGRE 2013 current curve;
  - Case A1 (base case)

Table 11. Performance rates to case A1

I_{limite} [kA]	21.57
SFFOR	3.12
BFR	2.84
Total	5.96

  - Case A2

Table 12. Performance rates to case A2

I_{limite} [kA]	11.88
SFFOR	0.36
BFR	2.58
Total	2.94

Comparing the practical case 1A and the case 1B (Table 11 and Table 12) it is verified that after the uprating the SFFOR rate decreased, which would be expected. As for the BFR the result has also improved.

- Case 2

Table 13. Performance rates to case 2

I_{limite} [kA]	3.14
SFFOR	0.00
BFR	10.09
Total	10.09

In this case it is verified that the shield fault limit current has a very low value which means that the current value of the atmospheric discharge is never less than the value I_{limite} and therefore no atmospheric discharge reaches the phase. For this reason the SFFOR rate is zero. On the other hand, all the atmospheric discharges that reached the shield wire led to the flashover of the insulators, which causes the BFR rate to be high. The results are in Table 13.

- Case 3

Table 14. Performance rates to case 3

I_{limite} [kA]	16.72
SFFOR	4.72
BFR	0.16
Total	4.88

The results obtained in the practical case 3 (Table 14) are within what was expected.

V. Conclusion

Since there are several methodologies and models for calculating the performance rates of electric power transmission lines, a study of the various authors and the various methods that exist was made, in order to perceive the differences between them and what effects these differences cause in the results.

To accomplish the objectives, a computer program was developed using MATLAB and EMTP where the user can select which model and which methodology he wants to use. After the study of the influence of each model and methodology, the model that presents values closer to the real ones was chosen to obtain these results.

It became apparent that the Electrogeometric Model has a great influence on the performance of the lines. The model that came closest to the real result was Eriksson's Electrogeometric Model and was consequently used in the presented results. Another factor that influences the line performance value is the current value that is used to calculate the line pickup width. The value used was the average current value since it has a value closer to the actual value and is recommended by the IEEE [13]. It should be noted that the option used for the CIGRE lightning current curve does not have much influence on the result of the rates, but it should be noted that for the most recent option (2013) the values obtained for the current, and consequently the value of the rates are slightly lower. Regarding the value for grounding resistance, the use of the mean or probabilistic value based on actual values has no influence on the final result. In spite of this, the value obtained in a probabilistic way was used based on real values since it is closer to real values.

For the practical cases studied in this dissertation was used the Eriksson Modified Electrogeometric Model, the probabilistic method based on real values to generate the ground resistances of the towers, the average value of the lightning current for the calculation of the capture width and the CIGRE 2013 current curve.

In the case of Portugal (case 1A and case 1B), performance rates fell when a shield wire was added to the line: SFFOR before uprating was 3.12 and lowered to 0.36 after uprating. The BFR had the value of 2.84 and dropped to 2.58 after the uprating of the line. For practical case 2 (USA) the SFFOR has a value of 0 and the BFR has a value of 10.09. Finally, the practical case 3 (Germany) has a SFFOR value of 4.72 and BFR of 0.16. In other words, we obtained reasonable values for all the practical cases that were studied.

References

[1] CIGRE WG01 SC33, «Guide to procedures for estimating the lightning performance of transmission lines», *CIGRE Rep. 63*, vol. 1, n. October, p. 64, 1991.

[2] IEEE Std 998-1996, *Guide for Direct Lightning Stroke Shielding of Substations*. 1996.

[3] T. Correia, «Análise de padrões temporais e espaciais de descargas eléctricas atmosféricas em portugal continental», Instituto de Geografia e Ordenamento do Território, 2012.

[4] CIGRE WGC4.407, «Lightning Parameters for Engineering Applications Working Group c4.407 CIGRE», *CIGRE Rep. 549*, n. August, 2013.

[5] C. F. Wagner, «The Relation Between Stroke Current and the Velocity or the Return Stroke», *IEEE Trans. Power Appar. Syst.*, vol. 82, n. 68, pp. 609–617, 1963.

[6] H. R. Armstrong e E. R. Whitehead, «Field and Analytical Studies of Transmission Line Shielding», *IEEE Trans. Power Appar. Syst.*, vol. PAS-87, n. 1, pp. 270–281, 1968.

[7] G. W. Brown e E. R. Whitehead, «Field and Analytical Studies of Transmission Line Shielding: Part II», *IEEE Trans. Power Appar. Syst.*, vol. 88, n. 5, pp. 617–626, 1969.

[8] T. Suzuki, K. Miyake, e T. Shindo, «Discharge path model in model test of lightning strokes to tall mast», *IEEE Trans. Power Appar. Syst.*, vol. PAS-100, n. 7, pp. 3553–3562, 1981.

[9] J. G. Anderson, a R. Hileman, e W. Chisholm, «A Simplified Method for Estimating Lightning Performance of Transmission Lines», *IEEE Trans. Power Appar. Syst.*, vol. PAS-104, n. 4, pp. 918–932, 1985.

[10] A. M. P. Jorge, «Avaliação da eficácia de sistemas de intercepção de descargas atmosféricas em linhas de transmissão de energia eléctrica», IST, 2011.

[11] IEEE Std 1243-1997, «IEEE guide for Improving the lightning performance of Transmission Lines», 1997.

[12] M. T. Barros, «“Apontamentos da Cadeira de Alta Tensão”». 2016.

[13] A. F. Imece *et al.*, «Modeling guidelines for fast front transients», *IEEE Trans. Power Deliv.*, vol. 11, n. 1, pp. 493–501, 1996.

[14] R. Atte, R. Atte, R. Atee, e O. No, «Technical Report IEC Tr 60071-4 Insulation Co-ordination», vol. 2004, n. 6, 2004.

[15] C. Yao *et al.*, «Multistory Transmission Tower Model for Lightning Surge Analysis», *IEEE Trans. Power Deliv.*, vol. 6, n. 3, pp. 1327–1335, 1991.