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A methodology for estimating transmission lines lightning performance using a statistical approach

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***Abstract*— This paper describes the application of a Monte Carlo statistical method to evaluate the lightning performance of transmission lines. Monte Carlo routines were developed in Matlab software, to conduct calculation of transients in EMTP-RV-RV, using custom Electro-Geometric Model and acceleration algorithms. The main goal of this paper is to increase the accuracy of flashover rates calculation through the accurate modelling of network components, simulation of non-vertical strokes and lightning current calculation from the LLS data for the region where the line passes. The methodology was validated with Portuguese typical transmission line configurations, by comparing simulated and actual performance indexes. The use of the EGM model with non-vertical strokes and LLS data was also validated.**

Keywords: Lightning performance, transmission lines, Monte Carlo method, guidelines, procedures for estimating lightning performance, LLS, SFFOR, BFOR, statistical approach.

I. INTRODUCTION

Estimating lightning performance of transmission lines may have different approaches, depending on the requirements. Therefore, many authors suggest specific procedures for each group of methodologies: (1) experimental, (2) deterministic, (3) analytical and (4) statistical studies. It is up to transmission line's designers to define the best methodology that suits their electrical system.

Experimental approaches are usually considered when a specific transmission line segment, or one or more towers, present a poor lightning performance and the cause is evident. In this case, applying corrective measures will only prove its success in the years to come. On the other hand, those measures can be insufficient for a considerable performance improvement or not be technically/economically viable.

Deterministic methodologies are based on the definition of a threshold current that guarantees a certain level of transmission line's protection. The main advantages relate to the ease of transmission line's planning and reliability adjustment (i.e. using conservative values may produce considerable improvements). However, this approach does not account for all the variables at stake, may also be technically/economically not viable and needs time to prove its effectiveness and efficiency.

Analytical calculation methodologies are based on the transmission line's lightning performance improvement guides by IEEE or CIGRE. The main advantages derive from the proven analytical models, with many years of usage, and fast results. Nevertheless, theoretically excessive models are often impractical, being currently surpassed by statistical ones.

Statistical methods are becoming popular, mainly due to their ease of usage and having the possibility to consider all the desired variables, producing interesting results. There are two different approaches for this type of methodology – dedicated software, for example TFlash, and Monte Carlo based methods, and both may be burdensome to parameterize based on the level of detail required. Not only TFlash simulation models may be insufficient to correctly characterize the line's performance but also, due to its limited outputs, it doesn't allow custom result analysis. On the other hand, using custom Monte Carlo based methodologies take the advantage of using proven models and variable freedom to produce thorough studies.

For this study, a Monte Carlo methodology was developed in Matlab software using EMTP-RV environment and a modified Electro-Geometric Model (EGM) to determine specific transmission lines outage rate. Despite the struggle of specifying every parameter, the level of detail obtained with custom line and equipment (insulator strings, surge arresters, etc.) models proved returning realistic results. On the other side, it is possible to provide acceleration algorithms for faster results without compromising the representativeness of the results. Lastly, having independent routines, one for Monte Carlo procedure and the other for the transient's calculation on EMTP-RV, is useful when applying this methodology to different transmission lines configurations.

II. Monte Carlo Procedure

A. Developed Routine

Due to the random nature of lightning activity, the performance calculations of an HV overhead transmission line should be based on a statistical approach. So, for that purpose, a methodology based on a Monte Carlo simulation was developed. The procedure is based on the following steps:

- Generation of random numbers to obtain the random nature parameters of the lightning stroke, the overhead line and grid conditions;
- Incidence model application to deduce the point of impact of every lightning stroke – it will be used a modified Electro-geometric model, considering non-vertical strokes;
- Calculation of the overvoltage generated by each stroke, depending on the point of impact – using the EMTP-RV software;
- Calculation of the flashover rate, usually expressed as the number of flashovers per 100 km and year.

The developed methodology is based on the interaction of two softwares: MATLAB and EMTP-RV (*ElectroMagnetic Transients Program)*. The Monte Carlo routine is programmed on MATLAB language and controls all the steps sequence, starting with the random data generation, followed by the iteration control and the flashover rate calculation. The interactions between the different routines and tasks are shown in Figure 1.

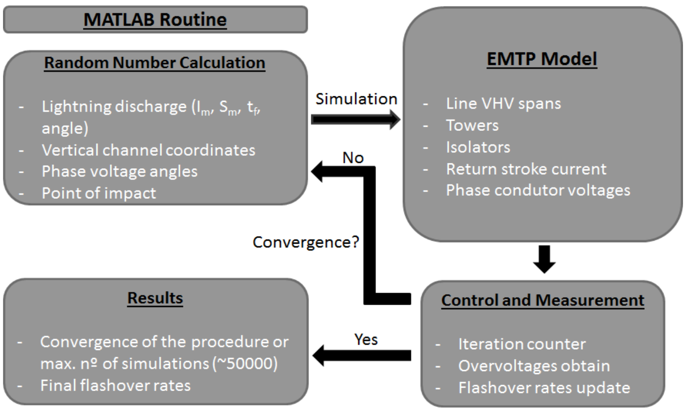


Figure 1. Interactions between tasks implemented for lightning flashover rate calculation

The MATLAB routine contains all the Monte Carlo steps information and its sequence. As it is possible to see in Figure 1. , the first step consists on random data generation for the lightning stroke parameters, characteristics and location, and for grid conditions. With that data, the point of impact is calculated using the modified Electro-geometric model. In the next step, the MATLAB routine loads the EMTP-RV line model with the information generated, and runs the simulation, which produces, as an output, the overvoltage values for the generated lightning stroke. The MATLAB routine updates the flashover rates with the simulation results. At the same time, all the process control is performed and convergence is checked. The process will continue if the convergence is not obtained nor the maximum iteration number achieved. At the end of the Monte Carlo simulation the final flashover rates are presented.

For each HV transmission line, the simulation model is built on EMTP-RV software, which is followed by its ".netlist" file generation that contains all the model information. This is the file that is used and modified by the MATLAB routine during the simulations. More than one EMTP-RV model can be used at the same time, to simulate different configurations within the same line, with specified ratios.

Figure 3. shows the procedure flowchart implemented in EMTP-RV when the lightning performance of the test line is analyzed, by assuming that only single-polarity single-strokes are produced. The flowchart is explained in detail next.

1. A maximum number of runs is established, being, for most of the cases, a number between 30000 and 50000 simulation runs, to achieve an error margin of 5 % [3];
2. The vertical channel coordinates are generated along the line span corridor (d), being used a uniform distribution, Figure 2. In this work, only two incidence points at the tower are considered, the shield wires or phase conductors;
3. The random parameters of the lightning stroke are generated. This data will include the front time, the maximum steepness, the peak current value (obtained from the LLS data for the region where the line is installed) and the angle of the lightning stroke (Gaussian distribution), since it considers non-vertical strokes;

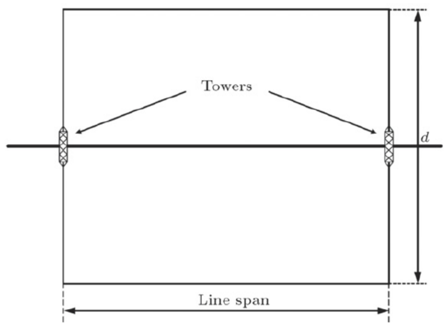


Figure 2. Area of impacts around the line span

4. The modified Electro-geometric model is applied to the randomly generated data, and the point of impact is obtained;
5. The random voltage grid angle is obtained subsequently (uniform distribution);
6. On the next step, the MATLAB routine updates the ".netlist" file that contains the EMTP-RV model of the HV transmission line, with all the lightning stroke data and the point of impact location;
7. With the simulation results, the flashover rates are updated (shielding failure flashover rate – SFFOR and

back flashover rate – BFOR). The Monte Carlo procedure is stopped when the maximum number of runs, specified by the user, is reached or when the convergence is obtained (error margin of less than 5 %), otherwise, the process continues. At the end, the final flashover rates for the line are calculated and printed.

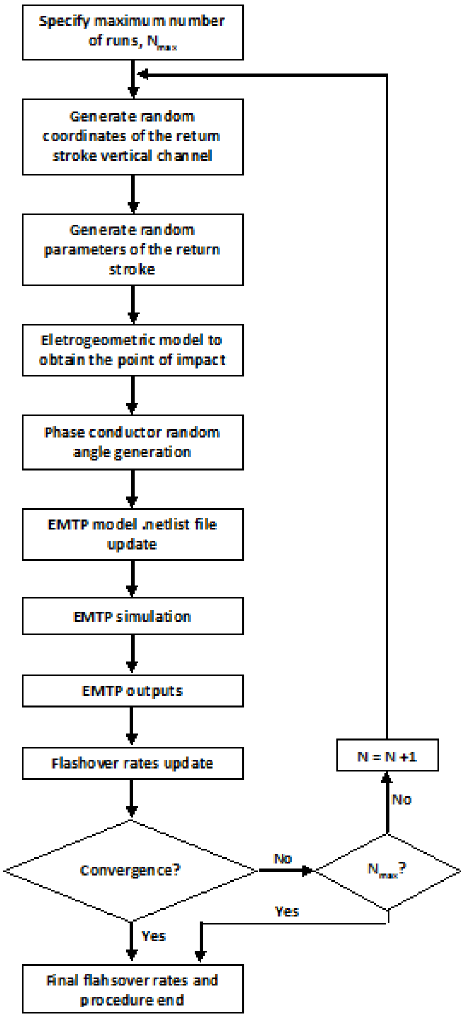


Figure 3. Flowchart of the Monte Carlo Method

The flashover rates are calculated in each iteration through Eq. (1):

$$n_F = N_g * 100 * d * \frac{F}{N} \qquad (1)$$

In which:

- n_F flashover rate, due to SFFOR or BFOR;
- N_g local flash density for 100 km^2, per year;
- d corridor width;
- F number of runs where the flashover occurred;
- N total number of runs.

Some acceleration algorithms are also employed to save simulation time. These are based on the definition of thresholds for stroke peak current magnitudes and rise times, for which a flashover occurs or does not occur for sure, without having to run EMTP-RV [6].

The modified Electro-geometric model, considering non-vertical strokes, will be explained in the following point.

B. Modified Electro-geometric Model [2]

In most studies, lightning strokes are considered vertical, while they can also impact non-vertically. Correspondingly, the stroke angles show a random behavior that can be displayed with a probability density function by Eq. (2) [2].

$$p(\psi) = \begin{cases} 0 & \psi < -\frac{\pi}{2} \\ k*\cos^m\psi & -\frac{\pi}{2} < \psi < \frac{\pi}{2} \\ 0 & \psi < -\frac{\pi}{2} \end{cases} \qquad (2)$$

Where ψ is the angle of the stroke, and m is an exponent constant.

Distribution curves for the stroke angle are shown in Figure 4. The type of distribution function, proportional to m values, will be determined. For example, for m = 0, the distribution function is uniform, while for values of m > 2, they tend to be a Gaussian curve. In this work it will be considered m = 2 and k = $2/\pi$, for a Gaussian distribution curve.

Even though transmission lines are built with shield wires, it is not possible to guarantee the total protection of the line against shielding failures, and insulation failure may happen with both lightning strokes directly hitting the phase conductors and shield wires. The last step of a return stroke is determined by means of the Electro-geometric model. The striking distances to the phases, the shielding wires and to the ground are considered equal and provided by Eq. (3).

$$r = 8 * I^{0,65} \qquad (3)$$

To determine the impact probability of non-vertical lightning strokes, each of the angles $\psi 1$ to $\psi 4$ must be obtained for each lightning current (Figure 5.).

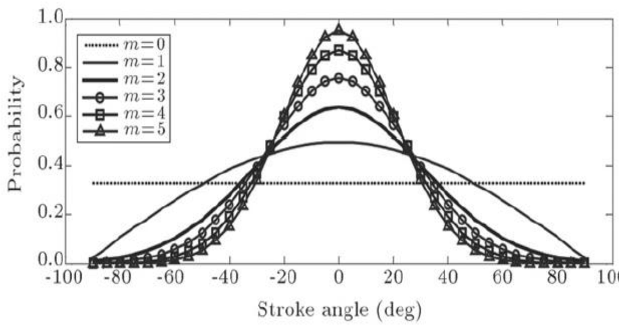


Figure 4. Probability density function of stroke angle

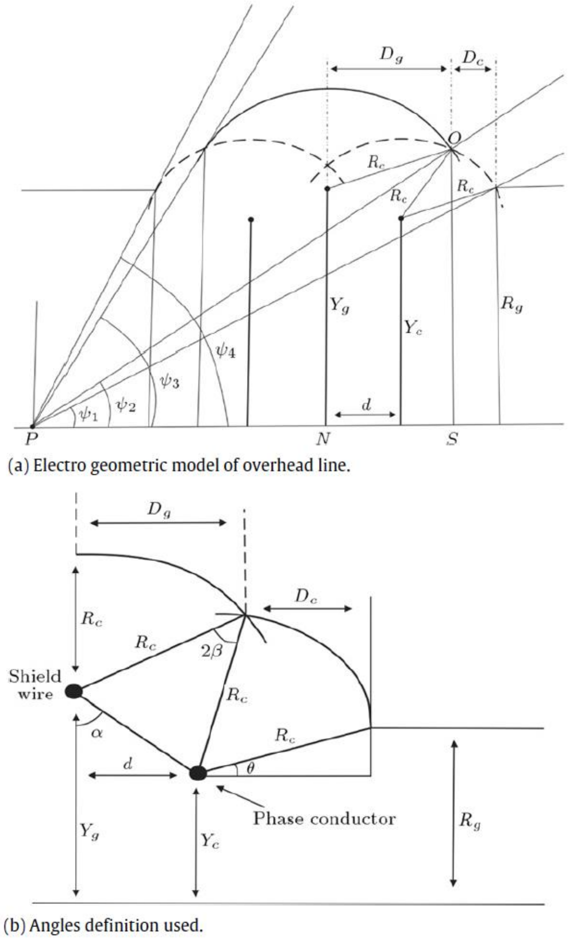


Figure 5. Modified Electro-geometric model, for point of impact determination

With regard to Figure 5. , Eqs. (4) – (7) are obtained:

$$\alpha = \tan^{-1}\frac{d}{Y_g - Y_c} \qquad \theta = \sin^{-1}\frac{R_g - Y_c}{R_c} \tag{4}$$

$$\beta = \sin^{-1}\frac{(Yg\text{-}Yc)\sqrt{1+(\tan(\alpha))^2}}{2*Rc} \tag{5}$$

$$D_c = R_c*[\cos(\theta) - \cos(\alpha+\beta)]$$

$$D_g = R_c*\cos(\alpha+\beta) \tag{6}$$

$$SO = Y_c + R_c*\sin(\alpha+\beta) \tag{7}$$

If R_g is less than or equal to Y_c, set $\boldsymbol{\theta} = 0$ in Eq. (6).

Consequently, angles ψ_1 to $\psi 4$ can be calculated as Eqs. (9a) – (8d):

$$\psi_1 = \tan^{-1}\left(\frac{R_g}{PN + D_c + D_g}\right) \tag{9a}$$

$$\psi_2 = \tan^{-1}\left(\frac{SO}{PN + D_g}\right) \tag{9b}$$

$$\psi_3 = \tan^{-1}\left(\frac{SO}{PN - D_g}\right) \tag{9c}$$

$$\psi_4 = \tan^{-1}\left(\frac{R_g}{PN - (D_c + D_g)}\right) \tag{9d}$$

Thus, regarding Figure 5. (a), the lightning stroke will hit the phase conductor or the shield wire, respectively, if random angle, ψ, in Eq. (2), is between (ψ_1, ψ_2) or (ψ_3, ψ_4) and between (ψ_2, ψ_3).

The lightning peak current estimation, which is crucially important to the point of impact determination, is calculated with the data provided by the Portuguese lightning location systems for the region where the line is installed. Therefore, and observing Figure 6. , for each line is drawn a rectangle that includes the line and for that region the parameters of a distribution curve are obtained. As the peak current distribution curve assumes the form shown on Figure 7. , it is well represented by the curve defined on Eq. (10).

$$P_I = \frac{1}{1 + \left(\frac{I}{a}\right)^b} \tag{10}$$

In Eq. (10), **a** is the peak current median value for the strokes detected and **b** is a constant exponent. Those parameters are obtained for every region where the line is installed and represent the data adaptation to Eq. (10) curve. With the median value for each line, a biased curve from the original is obtained. The original cumulative probability distribution curve for the first negative strokes is shown on Figure 7. , containing the data for Portugal continental territory between 2003 and 2014 [4]. The parameter **a** is set at 18 kA and **b** at 2.5.

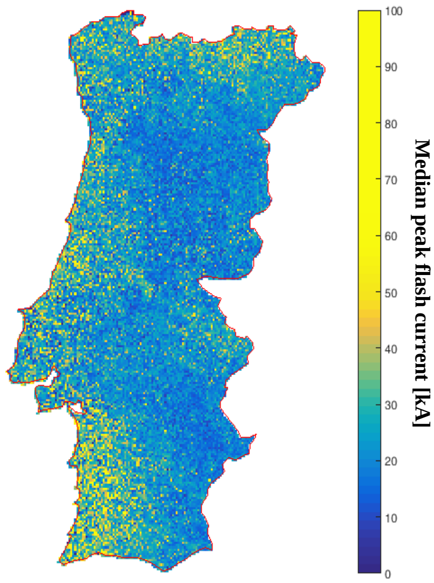


Figure 6. Overall median peak flash current map between 2003-2014

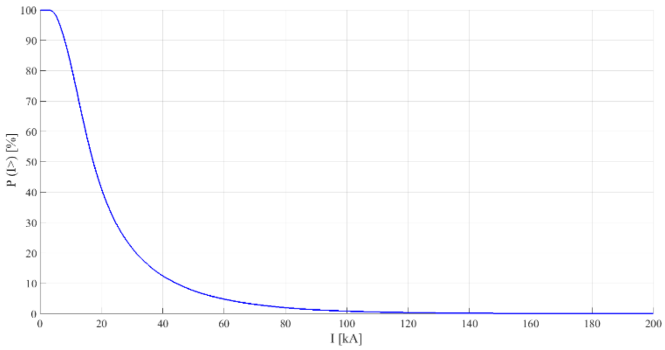


Figure 7. Cumulative probability distribution of lightning for negative first strokes between 2003-2014, continental territory of Portugal

C. *Modelling Guidelines*

The models used to represent different parts of the network in simulations are detailed below.

(1) Transmission lines are modeled by 4 spans on each side, followed by long line terminations to avoid reflections. Each span is represented by a multi-phase, untransposed, frequency-dependent and distributed parameter line section;

(2) The transmission towers were represented by a multistory model, in accordance with IEC 60071-4:2004;

(3) The representation of insulator strings relies on application of the leader progression model;

(4) The lightning stroke is represented by the CIGRE concave shape source;

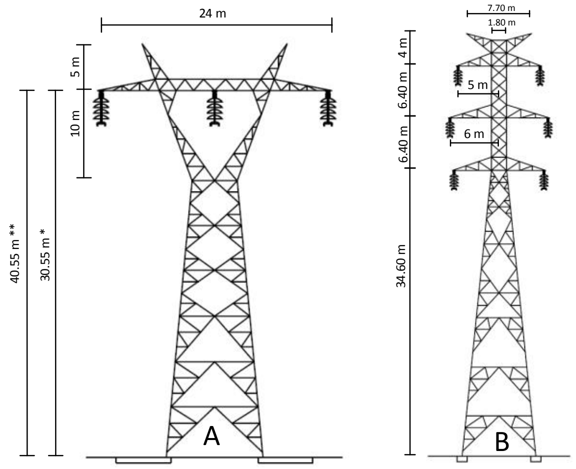
(5) The phase conductor reference angle is distributed uniformly between 0º and 360º.

III. CASE STUDY

The methodology described in II was validated by simulating a 400 kV (line A) and a 150 kV (line B) typical Portuguese transmission line configurations, comparing actual measurements with simulation results.

Line A, Figure 8. , presents a horizontal, single circuit configuration with two different segments. The main differences for Segment 1 relate to lower average tower height, and frequent back flashover outages due to high tower footing impedances, when compared to Segment 2. On the other hand, Segment 2 crosses sloped terrains and valleys, and present significantly higher average tower height, as well as lower tower footing impedances, resulting in a significantly higher shielding failure flashover rate and a lower back flashover rate.

Line B, Figure 8. , presents a vertical double circuit configuration, leading to a higher average tower height, and consequently, increasing the lateral exposure of the line to lightning strikes. Moreover, having the same soil conditions as Segment 1 of Line A implies, also, high tower footing impedances. The LLS distribution curve for the region where the lines are installed is biased from the one presented in Figure 7. , with parameters set to: a = 20; b = 2.9.



* Segment 1 of Line A
** Segment 2 of Line A

Figure 8. Transmission lines case study: A – 400 kV single circuit tower; B – 150 kV double circuit tower

Besides the similar conditions of both lines, flashovers distribution and types, along the line, is very different between Line A and Line B. Line B registered lightning strikes flashovers evenly distributed along the entire line length, but Line A registered concentrated lightning activity in some segments. For this reason, it is important to simulate Line A with both segments independent. Applying the methodology described in II, the actual and simulated data of the transmission lines described above, is shown in TABLE I.

TABLE I. PORTUGUESE TRANSMISSION LINES CASE STUDY

	Transmission Line		
Characteristics	***A – Segment 1***	***A – Segment 2***	***B***
Voltage Level [kV]	400	400	150
Line Length [km]	43	17	55
Corridor Window [m]	400	400	400
Average Span Length [m]	400	400	400
Average Tower Footing Impedance [Ω]	80	155	110
Actual global SFFOR [inc./100km.year]	0.98 – 2.10		1.07 – 1.34
Actual global BFOR [inc./100km.year]	0.28 – 1.40		5.34 – 5.61
Simulated SFFOR [inc./100km.year]	0.35	3.8	1.6
Simulated BFOR [inc./100km.year]	0.85	0.2	5.1
Global Simulated SFFOR [inc./100km.year]	1.3		1.6
Global Simulated BFOR [inc./100km.year]	0.7		5.1

The uncertainty in the presented values of the actual performance indexes derives from the uncertainty of classifying each registered lightning event into a shielding failure or back flashover outage. Nevertheless, the simulation results validate the methodology, showing a realistic approach to each line configuration, being the small deviations related to the difficulty in representing the entire transmission lines' conditions in the models, especially slopes and vegetation profiles that have a strong influence in shielding failure rates, and also insulator pollution and moisture contents. Still, splitting Line A into two segments and calculating the overall performance index proved to return accurate results.

Finally, the results from the table validate the relationship between high tower footing impedances and high BFOR, as well as the relationship between higher average tower heights and shielding angles, and a higher SFFOR. They also validate the data gathered from the Portuguese LLS.

The possibility of checking the effect of considering a modified Electro-geometric model, with non-vertical strokes, was also raised. As such, the same lines were simulated with a simple EGM model with only vertical strokes. The results are presented in TABLE II.

TABLE II. DIFFERENCE BETWEEN RESULTS OF MONTE CARLO METHOD WTH EGM MODELS CONSIDERING NON-VERTICAL (NV) AND ONLY VERTICAL (V) STROKES

Flashover rate	**Transmission Line Case Study**					
	Line A-1		***Line A-2***		***Line B***	
	NV	***V***	***NV***	***V***	***NV***	***V***
BFOR [inc./100km.year]	0.85	0.7 (-18%)	0.2	0.15 (-25%)	5.1	3.3 (-35%)
SFFOR [inc./100km.year]	0.35	0.2 (-43%)	3.8	2.1 (-45%)	1.6	0.3 (-81%)
TFOR [inc./100km.year]	1.2	0.9 (-25%)	4	2.3 (-43%)	6.7	3.6 (-46%)

The effect of considering also non-vertical strokes in the EGM model is evident from the results, not only for the SFFOR, but also for the BFOR, in a smaller scale. The most significant effect is in the vertical double-circuit line SFFOR, due to the large phase conductor lateral exposed areas. These differences also contribute to the validation of the Monte Carlo methodology developed in this work, as the actual measured performance indexes are much closer to the simulated ones, considering non-vertical strokes.

Having these models validated by actual flashover data, enables the possibility of using them as a base to test performance improvement practices, if needed. The use of MATLAB and EMTP-RV opens the opportunity of testing complex improvement measures.

IV. CONCLUSIONS

There are various types of methodologies for estimating lightning performance of transmission lines: experimental, deterministic, analytical and statistical.

Due to the random nature of lightning activity, the performance calculations of an HV overhead transmission line should be based on a statistical approach. Thus, a statistical Monte Carlo methodology was developed for lightning performance analysis of Portuguese transmission lines. The developed methodology is based on the interaction of two software applications: MATLAB and EMTP-RV. The Monte Carlo routine is programmed on MATLAB language and controls all the steps sequence. For each HV transmission line, the simulation model is built on EMTP-RV software. In this work, a modified Electro-geometrical model, considering a Gaussian distribution of stroke impact angles, was used. The random generation of stroke peak currents was based in data gathered with the Portuguese LLS. The EMTP-RV models were built having in account IEEE and CIGRE recommendations.

The developed routine enables that more than one EMTP-RV model can be used at the same time, to simulate different configurations within the same line, with specified ratios. Some acceleration algorithms are also employed to save simulation time. With the simulation results, the flashover rates are determined (shielding failure flashover rate – SFFOR and back flashover rate – BFOR).

The methodology was validated with two Portuguese typical transmission line configurations for 400 kV (single-circuit, horizontally arranged phase conductors) and 150 kV (double-circuit vertically arranged), showing a realistic approach to each line configuration, being the small deviations related to the difficulty in representing the entire transmission lines' conditions in the models, especially slopes and vegetation profiles that have a strong influence in shielding failure rates, and also insulator pollution and moisture contents. The results also validate the relationship between high tower footing impedances and high BFOR, as well as the relationship between higher average tower heights and shielding angles, and a higher SFFOR. They also validate the data gathered from the Portuguese LLS.

Modeling lightning strokes also influences the performance indexes, being too optimistic if only vertical strokes are considered. Therefore, the data obtained with non-vertical stroke modeling suggests the importance of including this consideration in EGM application of Monte Carlo Method.

ACKNOWLEDGMENT

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