Parametric Analysis of the Lightning Performance of Overhead Transmission Lines Using an Electromagnetic Transients Program

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***Abstract* – This paper presents the application of the ATP package to the study of the lightning performance of transmission lines using a statistical approach. The study is based on the use of the electrogeometric model and the application of the Monte Carlo method. Parametric studies have also been performed to determine the sensitivity of the flashover rate with respect some parameters of the transmission line and the return stroke.**

Keywords –Lightning Overvoltages, Modeling, ATP, Statistical Analysis, Sensitivity Analysis, Monte Carlo Method.

I. INTRODUCTION

A voltage The prediction of the overvoltages that can be produced in power systems is fundamental for the selection of the dielectric strength of power equipment. Insulation design of power equipment is based on the frequency of occurrence of a specific event, the overvoltage probability distribution corresponding to this event, and the failure probability of the insulation. The lightning performance of an overhead line can be measured by the flashover rate, usually expressed as the number of flashovers by 100 km and year. 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. This type of analysis is usually carried out using a digital computer, being the EMTP and like the most popular tools [1].

The general procedure to deduce the lightning performance of a transmission line consists of the following steps

- generation of random numbers to obtain those parameters of the lightning stroke and the overhead line of random nature
- application of a model to deduce the point of impact of every lightning stroke
- calculation of the overvoltage generated by each stroke, depending on the point of impact
- calculation of the flashover rate.

Each of these steps can be critical since the knowledge of the lightning parameters is usually incomplete; the model generally applied to determine the point of impact, the electrogeometric model, is very simple; the representation of overhead lines is not always accurate enough, as some component models are too simple and no accurate information is usually available, for instance to represent tower footing impedances; and the postprocessing of the lightning overvoltages must be carefully done, since only a "phase peak" approach can be accurate enough. All these limitations can be partially overcome by performing parametric studies that could detect those critical methods and parameters for which an accurate information is required.

This paper presents a sensitivity analysis of the lightning performance of transmission lines using the ATP. This tool is a well known member of the EMTP family, so its main solution methods are those common to all EMTP-like tools. The type of applications that can be presently covered by the ATP can be grouped as follows [2]

- *Time-domain simulations*: They are generally used for simulation of transients, such as switching or lightning overvoltages. However, they can also be used for analyzing harmonic distortion.
- *Frequency-domain simulations*: They are useful to obtain the steady state of linear systems and to analyze problems related to harmonics propagation. ATP capabilities can be used to obtain driving point impedances versus frequency, detect resonance conditions, design filter banks or analyze harmonic propagation.
- *Sensitivity studies*: They are usually performed to evaluate the variation of some variables caused by changes of some parameters. When one or more parameters cannot be accurately specified, a parametric study will determine the range of values for which a parameter is of concern.
- *Statistical studies*: Power system overvoltages are characterized by parameters that can be statistically described. Statistical switching is a built-in capability of most transients programs. Several ATP capabilities can be now combined to perform all types of Monte Carlo simulations, not covered by statistical switches.

The paper includes an introduction to the causes of lightning overvoltages in transmission lines, a discussion on modeling guidelines for representing power equipment in lightning overvoltage calculations, and a detailed analysis of a test case. The study case covers both deterministic and statistical calculations, as well as parametric calculations, aimed at determining the sensitivity of lightning overvoltages with respect some line and stroke parameters.

II. LIGHTNING OVERVOLTAGES IN TRANSMISSION LINES

Since transmission lines are usually shielded by one or several wires, lightning overvoltages can be caused by strokes to either a shield wire or a phase conductor. The first type of stroke can produce a flashover if the backflash overvoltage exceeds the insulator strength. Overvoltages caused by a shielding failure, that is, by a stroke to a phase conductor, are more dangerous, but their frequency is usually very low due to the shielding provided by sky wires.

Fig. 1 illustrates the backflash phenomena; the stroke current reaching the shield wire at a tower will divide between each section of the wire and the tower. Stroke currents along the shield wire induce coupled voltages and currents on the phase conductors.

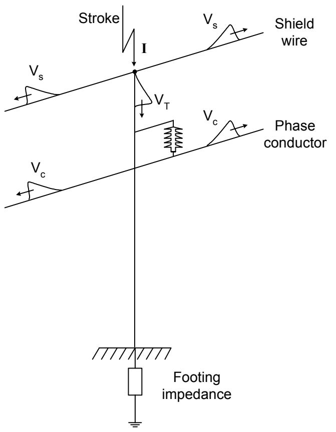


Fig. 1. Lightning stroke to a transmission line.

Due to the random nature of lightning flashes, the analysis of the lightning performance of transmission lines must be based on a statistical approach. The goal is to determine the failure rate per km and year. Based on the above statements, the Flashover Rate of a transmission line can be divided into the Backflashover Rate (BFOR) and the Shielding Failure Flashover Rate (SFFOR). To obtain these two quantities it is required a model to discriminate between strokes to shield wires from those to phase conductors and those to ground and a tool to calculate lightning overvoltages originated by strokes to any type of conductor.

III. Modeling For Lightning Overvoltage Calculation

Several documents have been published during the last years to provide modeling guidelines of power components in lightning overvoltage simulations [3], [4], [5]. The following paragraphs summarize the modeling guidelines used in this work.

- The line is modeled by two or three spans at each side of the point of impact. Each span is represented by a multi-phase untransposed distributed parameter line section. This representation can be made by using either a frequency-dependent or a constant parameter model. If the second option is chosen, then it is recommended to calculate parameters at a frequency of 400/500 kHz.
- The representation of a line termination is needed at each side of the above model to avoid that reflections could affect the simulated overvoltages around the point of impact. This can be achieved by adding a long enough section, e.g. 3 km, at each side or by inserting a resistance matrix at each termination whose values equal the line surge impedances.
- Towers will be represented as a single conductor distributed parameter line terminated at their footing impedances. Given the height of the test line towers, this is an acceptable representation. Tower surge impedance values range from 100 to 300 ohms [5]. As for the footing impedance, a frequency-dependent representation is the most accurate representation. However, since it is difficult to obtain such a model, a nonlinear resistance is usually chosen.
- Phase voltages at the instant of the lightning stroke must be included. For a deterministic calculation, worst case conditions should be determined and used. For statistical calculations, phase voltage magnitudes are deduced by randomly determining the phase voltage reference angle and considering a uniform distribution between 0º and 360º.
- The lightning stroke is represented as a current source whose polarity can be positive or negative. The parameters of the stroke, as well as its polarity, can be randomly determined according to the distribution density functions recommended in the literature [6], [7].
- Insulators are represented as voltage-dependent flashover switches. Every time a flashover is produced, a counter is increased and the flashover rate is updated. Parallel capacitors between conductors and the tower can be added.

IV. The Test Line

Fig. 2 shows the 400 kV tower design for the line tested in this paper.

	Type	Diameter (cm)	Resistance (Ω/km)
Phase conductors	CURLEW	3.162	0.06604
Shield wires	7N8	0.978	1.901

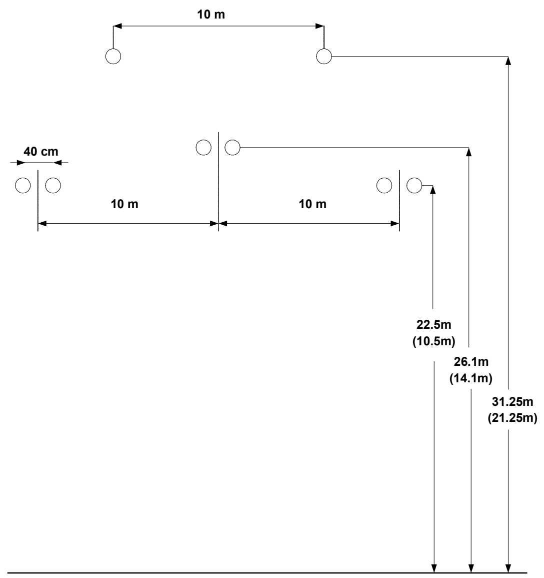


Fig. 2. 400 kV line configuration
(Values between parenthesis are midspan heights).

V. LIGHTNING STROKE PARAMETERS

Standards recommend a double-exponential waveshape to represent lightning return stroke currents. Presently, it is assumed that a concave waveform of the first stroke is a better representation since it does not shows a discontinuity at t=0. Several expressions have been proposed for such a waveform, being the so-called Heidler model one of the most widely used. It is given by [8]

$$i(t) = \frac{I_p}{\eta} \frac{k^n}{1+k^n} e^{-t/\tau_2} \qquad (1)$$

being I_p the peak current, η a correction factor of the peak current, n the current steepness factor, $k = t/\tau_1$, τ_1, τ_2 time constants determining current rise and decay-time, respectively.

Fig. 3 depicts the waveform of a concave return stroke. Main parameters used to define this waveform in the present work are the peak current magnitude, I_{100}, the rise time, t_f (= $1.67\ (t_{90} - t_{30})$), and the tail time, t_h, that is, time interval between the start of the wave and the 50% of peak current on tail. The main difficulty to synthesize a concave waveform is the determination of the parameters to be specified in (1) from those of the return stroke (I_{100}, t_f, t_h). Fig. 4 shows the effect of factor n. Although the three waveforms have the same rise and tail times, the time intervals between the start of the wave and the crest are different.

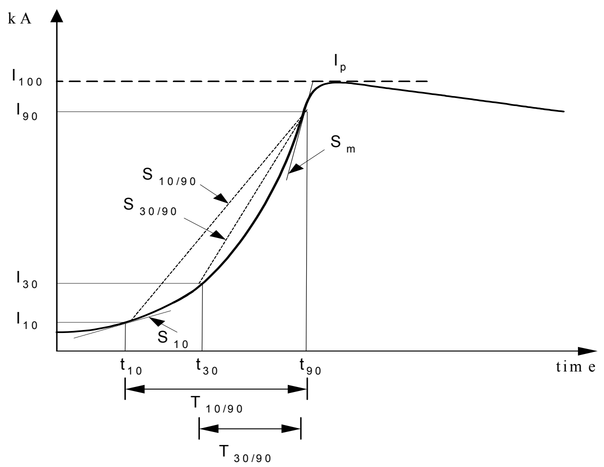


Fig. 3. Parameters of a return stroke – Concave waveform.

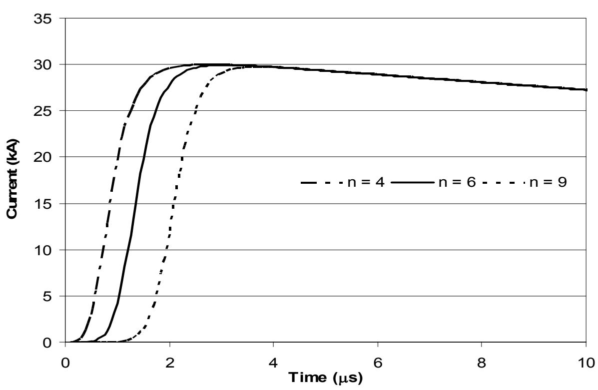


Fig. 4. Heidler model. Effect of factor n (t_f = 1.2 µs, t_h = 50 µs).

VI. FOOTING IMPEDANCE

The footing impedances of line towers have a significant effect on the peak overvoltages caused by strokes to shield wires. An accurate representation of this impedance is not easy as its behavior is nonlinear and frequency-dependent. In this work it is represented as a nonlinear resistance R_T given by [5], [9]

$$R_T = \frac{R_o}{\sqrt{1 + I/I_g}} \qquad (2)$$

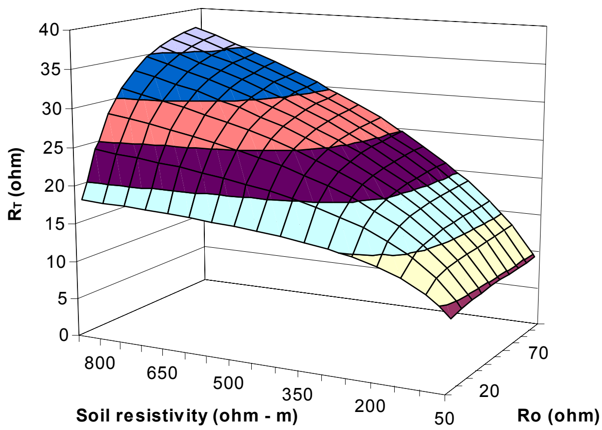
being R_o the footing resistance at low current and low frequency, I_g the limiting current to initiate sufficient soil ionization, I the stroke current through the resistance.

The limiting current is given by

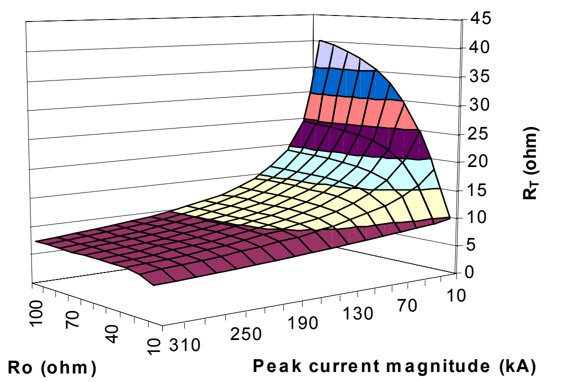
$$I_g = \frac{E_o \rho}{2\pi R_o^2} \qquad (3)$$

where ρ is the soil resistivity (ohm-m) and E_0 the soil ionization gradient (about 300/400 kV/m).

Fig. 5 shows the variation of R_T as a function of I, R_o and ρ. It is evident from these plots the nonlinear behavior of the footing resistance and its strong dependency with respect to the soil resistivity and the lightning current. From these plots one can conclude that the resistance value is greater for small lightning currents, and its variation with respect Ro is only significant for large soil resistivity values.



a) Current through resistance = 34 kA



b) Soil resistivity ρ = 300 ohm-m

Fig. 5. Variation of the footing resistance.

VII. Deterministic Calculation of Lightning Overvoltages

A model of the test line was created according to the guidelines summarized above. The studies presented below have been split into two groups, the goal is to simulate backflash and shielding failure overvoltages, and determine the influence that some parameters have on the peak voltages.

A. Backflash Overvoltages

A backflash overvoltage can be originated by a stroke to a shield wire. The most frequent situation is a stroke to a tower. Fig. 6 depicts the waveform of the voltage originated across insulator terminals, being the peak current 1 kA and the rise time 1 μs. This simulation was made by assuming that the footing resistance was constant. As explained above this is not the actual case; however, the study will be useful to evaluate the influence that the actual value of the footing resistance can have on the overvoltages caused by strokes to shield wires.

The relationship between the peak voltage and the stroke peak current in such a situation is linear; however, this relationship is more complex with respect to the rise time and the footing resistance. Fig. 7a shows the relationship with respect these two parameters. One can easily deduce that both of them have a strong influence: the greater the constant resistance value and the shorter the rise time, the higher the backflash overvoltages.

All previous simulations were performed without considering initial conditions in the overhead line. These conditions do actually exist and balanced phase voltages can be assumed. Fig. 7b shows the variation of the peak voltages across insulators as a function of the stroke peak current and the voltage angle.

One can observe that for a given peak current magnitude, the overvoltages do change with the voltage angle, but this variation is rather small compared to the effect of the peak current magnitude.

B. Shielding Failure Overvoltages

Overvoltages originated by strokes to phase conductors will be much higher than those originated by strokes to shield wires. Fig. 8 depicts the overvoltages originated by a stroke to the outer phase, being the main parameters of the line and the stroke the same that above. The phase *a* angle was 150 degrees. One can easily separate the effect of the operating voltage from that of the lightning stroke current. The later is adding more than 150 kV, which is about five times that originated by a stroke to the tower, see Fig. 6.

A parametric study was made to deduce the influence of the stroke peak current and the voltage angle. Fig. 9 shows the results obtained by considering the worst case from each simulation. Although the plot is depicting very high voltages, it is worth noting that shield wires will prevent strokes with a peak current higher than 30 kA from reaching phase conductors, as it will be shown in the subsequent section.

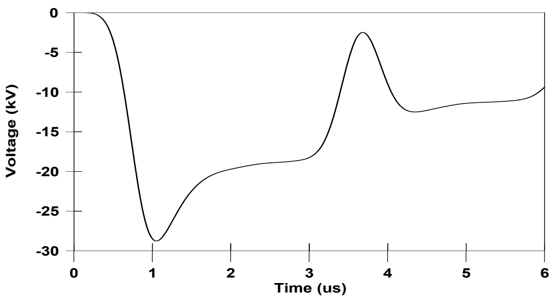
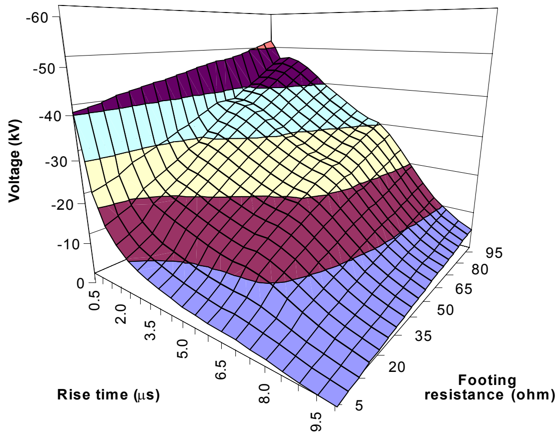
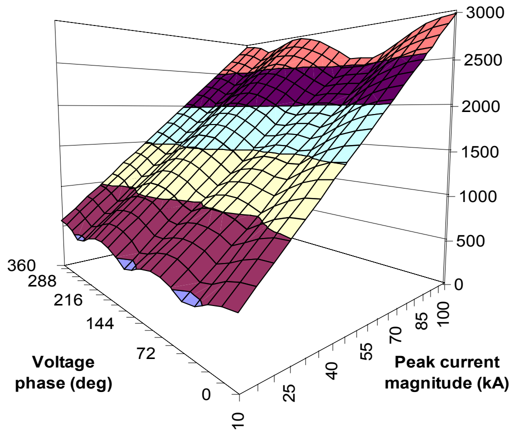


Fig. 6. Backflash insulator stress – Outer phase (I_{max} = 1 kA, t_f = 1 μs, R_{tower} = 20 Ω)



a) As a function of the footing resistance and rise time (I_{max} = 1kA)



b) As a function of the voltage phase and peak current magnitude (t_f = 1μs, R_{tower} = 20 Ω)

Fig. 7. Backflashover insulator stress

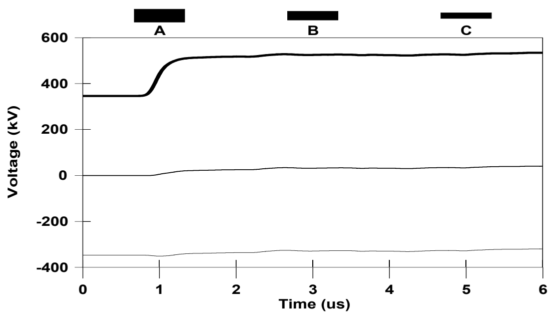


Fig. 8. Shielding failure insulator stress (1 kA, t_{max} = 1 μs). Phase voltages are included in the simulation.

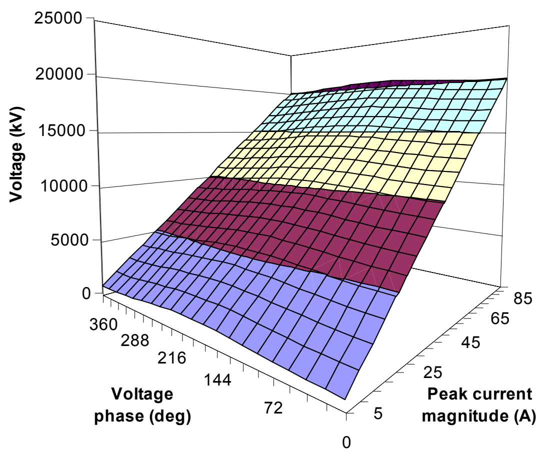


Fig. 9. Shielding failure. Insulator stress as a function of the peak current and the voltage angle (t_f = 1 μs).

VIII. STATISTICAL CALCULATION OF LIGHTNING OVERVOLTAGES

A. General Procedure

Some aspects of the statistical procedure used in this work, see Section 1, for the analysis of the lightning performance of a transmission line are discussed below

a) The calculation of random values must include the parameters of the lightning stroke (peak current, rise time, tail time, and location of the vertical channel), the phase conductor voltages, the footing resistance and the insulator strength.
b) The determination of the point of impact requires of a method for discriminating strokes to line conductors from those to ground. As for strokes to the line, it is important to distinguish those to shield wires from those to phase conductors. This step will be based on the application of the electrogeometric model [6], [10].
c) The overvoltage calculations can be performed once the point of impact of the randomly-generated stroke has been determined. Actually, the only difference between backflash and shielding failure simulations is the node to which the current source that represents the stroke must be connected. It is assumed that overvoltages caused by nearby strokes to ground can be neglected.
d) The overvoltages calculated at every run are compared to the insulator strength; if the peak voltage at one insulator exceeds this random value, the counter is increased and the flashover rate updated. The advantage of this option is that the flashover rate is fully determined without requiring any additional tool.

B. The Monte Carlo Method

ATP capabilities were used to develop a procedure based on the principles above presented

- a multiple-run option is used to perform all the runs required by the Monte Carlo method
- the values of the random parameters are generated at every run according to the probability distribution function assumed for each one
- phase-to-ground voltages across insulators are continuously monitored; when the voltage stress in a single phase exceeds the strength, the flashover counter is increased
- the simulation is stopped when the convergence of the Monte Carlo method is achieved or the maximum number of iterations is reached.

The convergence can be checked by comparing the probability density function of one or several variables to their theoretical functions; the procedure is stopped when they match within the maximum error.

The following probability distributions have been assumed for each random value

- lightning peak current magnitude: log-normal, I_m = 34 kA, σ = 0.74 kA
- rise time: log-normal, t_m = 2 μs, σ = 0.4943 μs
- phase voltage reference angle: uniform, between 0 and 360 degrees
- insulator flashover : normal/Weibull.
- footing resistance : normal, with a mean value for R_o of 50 Ω, being the standard deviation σ = 5 Ω.

All lightning parameters were independently distributed, that is the coefficient of correlation of the joint probability was ρ_c = 0. See [11] for a detailed description of the probability density functions of lightning stroke parameters

The insulator strength was calculated according to the method proposed by IEC 60071-2 [9], and taking into account insulator dimensions and distances between the conductors and the tower.

As for the footing resistance, it was represented by the model analyzed in Section 6. The value indicated above is the footing resistance at low current and low frequency.

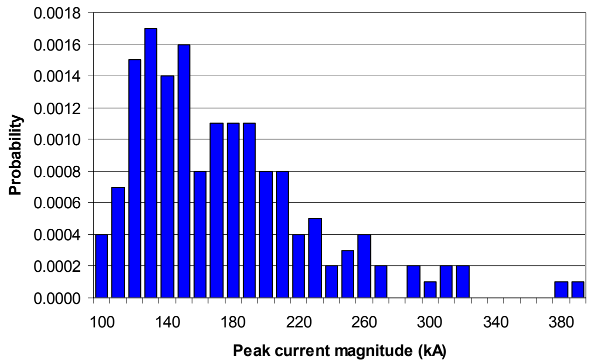
Fig. 10 and 11 show some of the results derived from the initial study. By comparing the two distributions of Fig. 10, one can see there is a range of values for every type of failure and a range of peak current magnitudes that cause no failure. As for the rise time, it is obvious that the probability of a failure with stroke rise times above 5 μs is negligible.

C. Sensitivity Studies

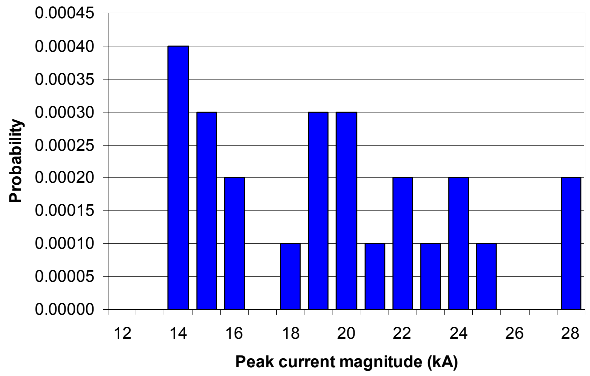
As shown in the previous section, parametric calculations can be very useful to analyze the influence of some line and stroke parameters, and to determine what range of values can be of concern. Sensitivity studies based on the Monte Carlo method described above were performed to analyze the influence that the mean values of the peak current magnitude and the rise time of the return stroke have on the flashover rate.

Fig. 12a and 12b shows the number of flashovers per 100 km and year as a function of these two parameters. The values indicated in both figures are the median values of the probability density functions. As expected from the results presented in Section 7, the rate increases with the peak current magnitude and decreases with the rise time.

These values were deduced by assuming the following footing resistance parameters: R_o = 50 Ω, ρ = 500 Ω.m.



a) Strokes to shield wires



b) Strokes to phase conductors

Fig. 10. Distribution of stroke currents that cause flashover.

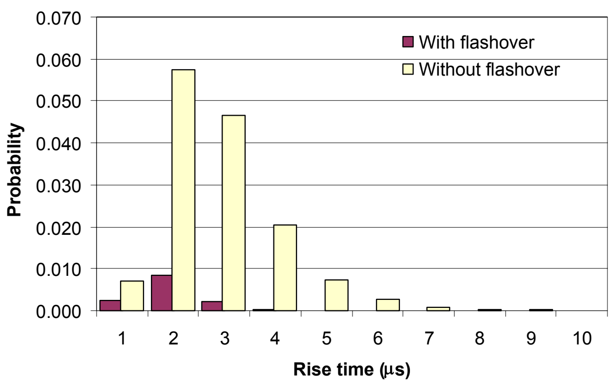


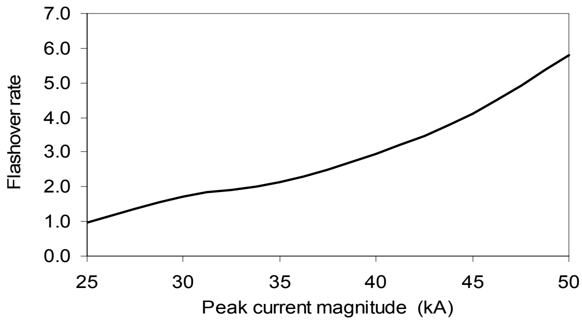
Fig. 11. Lightning stroke rise time distribution.

IX. Conclusions

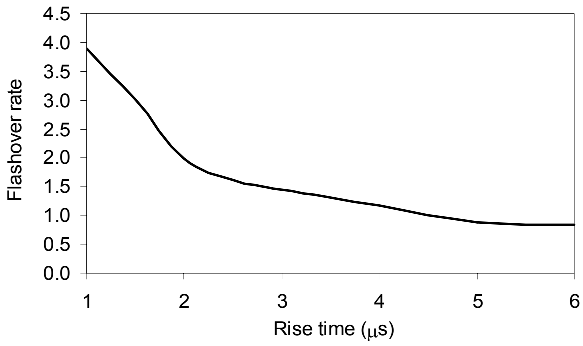
The ATP has been applied to the calculation of the lightning flashover rate of transmission lines. The main goal was to analyze the influence that some parameters can have on the flashover rate of a transmission line. The possibility of performing parametric calculations is a very important aspect.

Sensitivity studies can be used to evaluate the influence of every parameter involved in the lightning performance and decide with which accuracy some parameters should be specified.

Future work should consider a more accurate representation of the footing impedances, the incorporation of the corona effect and the calculation of induced voltages by any stroke to the line.



a) Flashover rate vs. peak current magnitude (median value)
(Median value of rise time = 2 μs)



b) Flashover rate vs. lightning stroke rise time (median value)
(Median value of peak current magnitude = 34 kA)

Fig. 12. Parametric study (N_g = 1fl/km^2).

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