Modeling of Overhead Transmission Lines for Lightning Studies

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***Abstract*—The aim of this paper is to analyze the influence of the models proposed for representing overhead transmission lines in lightning calculations. A full model of a transmission line for lightning overvoltage calculations can be split into several parts: wires (shield wires and phase conductors), towers, footing impedances and insulators. An additional component, the arrester, should be added if the study is aimed at selecting the arrester ratings needed to achieve a given performance of the line. This paper presents a sensitivity study whose main goal is to determine the effect that the model and the parameters selected for representing the main parts of a transmission line can have on the flashover rate.**

***Index Terms*—Transmission Lines, Lightning Overvoltages, Insulation Coordination, Modeling, Simulation.**

I. Introduction

A procedure aimed at obtaining the lightning performance of an overhead line can consist on the following steps [1]: Generation of random numbers to obtain those parameters of the lightning stroke and the overhead line of random nature; application of an incidence model to deduce the point of impact of the return stroke; calculation of the overvoltage generated by each stroke, depending on the point of impact; calculation of the flashover rate. The procedure must be performed with limitations and uncertainties, e.g. the knowledge of the lightning parameters is usually incomplete. These limitations can be partially overcome by performing a parametric study that could detect those parameters for which an accurate knowledge is required. The aim of this paper is to analyze the limitations related to the representation of an overhead transmission line in lightning calculations.

The paper presents the application of the ATP to a sensitivity study whose main goal is to determine the effect that the model and the parameters selected for representing the main parts of a transmission line can have on the flashover rate. The models whose effect is analyzed are those used to represent the tower, the footing impedance and the insulator strings.

The document has been organized as follows. Section II presents an introduction to modeling guidelines. The procedure developed to obtain the flashover rate of a transmission line is summarized in Section III. The configuration of the test line is presented in Section IV, while Section V includes a detailed analysis of this line.

II. Summary of Modeling Guidelines

Modeling guidelines for lightning transient calculations have been presented elsewhere [2], [3]. They are discussed in the subsequent paragraphs, although a more detailed description is given for those parts analyzed in this paper.

- The transmission line has to be represented by means of several multi-phase untransposed distributed-parameter line spans at both sides of the point of impact. This representation can be made by using either a frequency-dependent or a constant parameter model.
- A line termination is needed at each side of the above model to prevent reflections that could affect the simulated overvoltages. This can be achieved by adding a long enough line section at each side.
- Phase voltages at the instant at which the lightning stroke impacts the line are deduced by randomly determining the phase voltage reference angle.
- Tower models have been developed using a theoretical approach [4] - [10] or a experimental work [11]. They can be classified into the three groups detailed below.
  a) Single vertical lossless line models: The tower is represented by means of a simple geometric form [4], [5], [6]. The model recommended by CIGRE [12] was based on that presented in [7], while that implemented in the Flash program is a modified version of the same model [13].
  b) Multiconductor vertical line models: Each segment of the tower between cross-arms is represented as a multiconductor vertical line, which is reduced to a single conductor. The tower model is then a single-phase line whose section increases from top to ground, as shown in Fig. 1 [8] - [10]. The model shown in Fig. 2 was presented in [9] and includes the effect of bracings (represented as lossless lines in parallel to the main legs) and cross-arms (represented as lossless line branched at junction points).
  c) Multistory model: It is composed of four sections that represent the tower sections between cross-arms. Each section consists of a lossless line in series with a parallel R-L circuit, included for attenuation of the traveling waves, see Fig. 3. Although the parameters of this model were initially deduced from experimental results [11], their values, and the model itself, have been revised in recent years [14]. The approach was originally developed for

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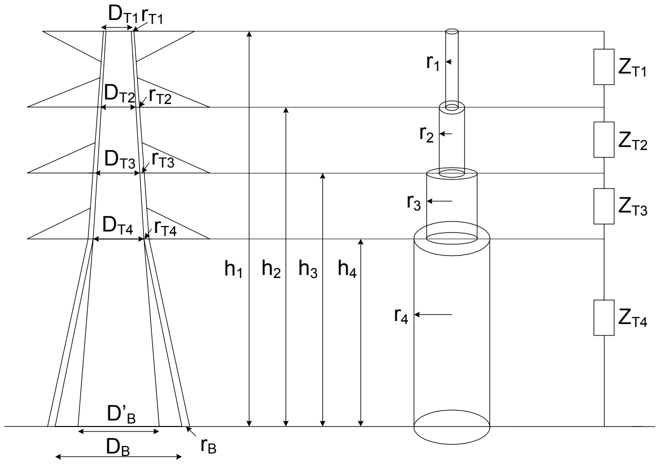


Fig. 1. Multiconductor vertical line model.

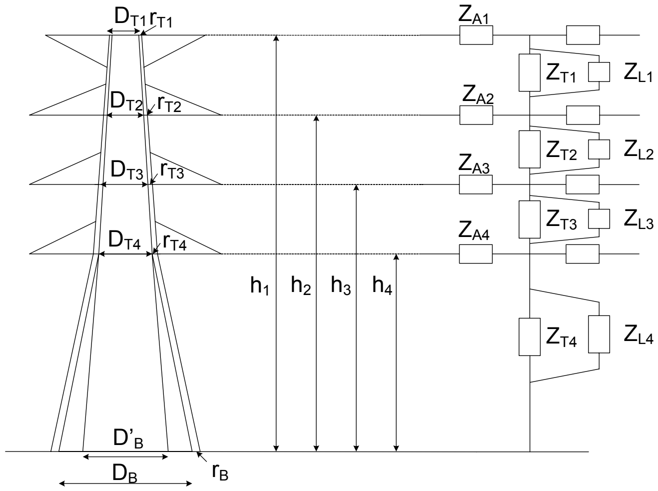


Fig. 2. Multiconductor vertical line model, including bracings and cross-arms.

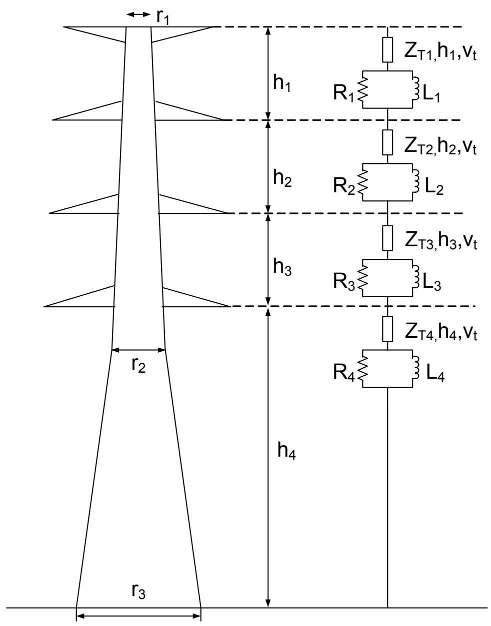


Fig. 3. Multistory model.

representing towers of UHV transmission lines. A study presented in [15] concluded that it is not adequate for representing towers of lower voltage transmission lines: the model for shorter towers can be less complex, i.e. four loss-less lines with a smaller surge impedance would suffice. In any case, the propagation velocity is that of the light.

- An accurate model of the grounding impedance has to account for a decrease of the resistance value as the discharge current value increases [16] – [19]. It is accepted that the resistance value is greater for small lightning currents, and its variation with respect the low current and low frequency values is only significant for large soil resistivities. When the soil ionization effect is incorporated, the grounding impedance model can be approximated by a nonlinear resistance given by [2], [20]

$$R = \frac{R_0}{\sqrt{1 + I/I_g}} \qquad (1)$$

being R_0 the grounding 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 calculated as follows

$$I_g = \frac{E_0 \rho}{2\pi R_0^2} \qquad (2)$$

where ρ is the soil resistivity (ohm-m) and E_0 the soil ionization gradient (about 400 kV/m) [17].

The frequency-dependent behavior can be represented by adding new parameters into the model. Fig. 4 shows two models presented in [21] and [22], respectively. The resistive parameters are related by the following relationships

$$R_c = \alpha \cdot R_0 \qquad (3)$$

$$R_n = \frac{R_0 - R_c}{\sqrt{I/I_g}} \qquad (4)$$

R_0 is the low current, low frequency value of the whole grounding impedance, as in the above model; R_c is a constant parameter, while R_n is a nonlinear resistance whose value depends on the current through this branch and varies according to expression (4), see [22].

The factor α is used to determine the percentage of the resistance that is not affected by the discharge current.

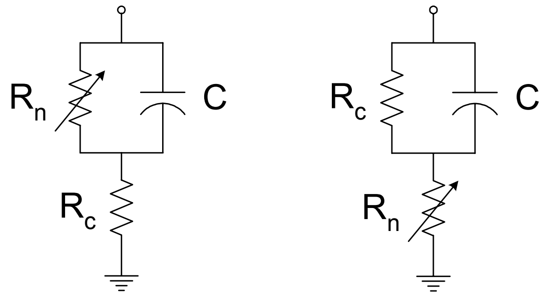
- The insulator string model can be based on the leader progression model [12] or on a simple voltage-dependent flashover switch with a random behavior.

Using the first approach, streamers propagate along the insulator string when the applied voltage exceeds the corona inception voltage; if the voltage remains high enough, these streamers will become a leader channel. A flashover occurs when the leader crosses the gap between the cross-arm and the conductor.

The total time to flashover can be expressed as follows

$$t_t = t_c + t_s + t_l \qquad (5)$$

where t_c is the corona inception time, t_s is the streamer propagation time and t_l is the leader propagation time. Usually t_c is neglected, while t_s is calculated as follows



a) Model C1 b) Model C2

Fig. 4. Grounding impedance models.

$$t_s = \frac{E_{50}}{1.25E - 0.95E_{50}} \tag{6}$$

where E_{50} is the average gradient at the critical flashover voltage and E is the maximum gradient in the gap before breakdown. The leader propagation time, t_l, can be obtainned from the following equation

$$\frac{dl}{dt} = k_l v(t)\left[\frac{v(t)}{g-l} - E_{l0}\right] \tag{7}$$

where $v(t)$ is the voltage across the gap, g is the gap length, l is the leader length, E_{l0} is the critical leader inception gradient, and k_l is a leader coefficient. The leader propagation stops if the gradient in the unbridged part of the gap falls below E_{l0}.

- The lightning stroke is represented as a current source. Fig. 5 shows the concave waveform chosen in this work, it is the so-called Heidler model.

  If lightning stroke parameters are assumed independently distributed, their statistical behavior can be approximated by a log-normal distribution, with the following probability density function [23]

$$p(x) = \frac{1}{\sqrt{2\pi}x\sigma_{\ln x}} \exp\left[-0.5\left(\frac{\ln x - \ln x_m}{\sigma_{\ln x}}\right)^2\right] \tag{8}$$

where σ_{lnx} is the standard deviation of lnx, and x_m is the median value of x.

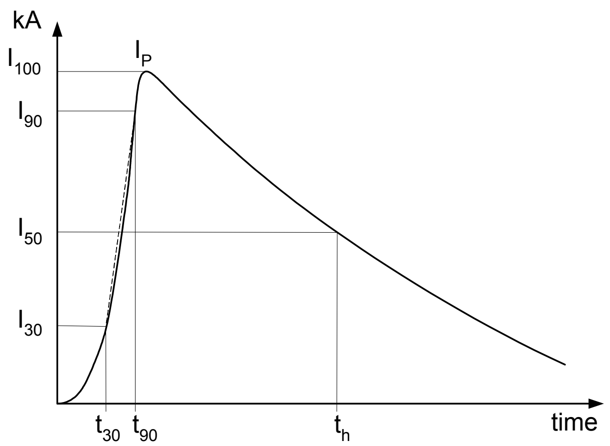


Fig. 5. Concave waveform (I_{100} = peak current magnitude, t_f (= *1.67* $(t_{90} - t_{30})$)= rise time, t_h = tail time)

III. Monte Carlo Procedure

The following paragraphs detail the most important aspects of the procedure developed for this work [1].

a) The calculation of random values includes the parameters of the lightning stroke, phase conductor voltages, the footing resistance and the insulator strength.
b) The point of impact is determined by means of the electrogeometric model, as suggested in IEEE Std. 1243 [23].
c) Overvoltage calculations are performed once the point of impact has been determined. Overvoltages caused by nearby strokes to ground are not simulated, since their effect can be neglected for transmission insulation levels.
d) If a flashover occurs in an insulator string, the counter is increased and the flashover rate updated.
e) The convergence of the Monte Carlo method is checked by comparing the probability density function of all random variables to their theoretical functions; the procedure is stopped when they match within the specified error.

IV. Test Line

Fig. 6 shows the tower design for the line tested in this paper. It is a 400 kV line, with two conductors per phase and two shield wires.

TABLE I
CHARACTERISTICS OF WIRES AND CONDUCTORS

	Type	Diameter (cm)	Resistance (Ω/km)
Phase conductors	CURLEW	3.163	0.05501
Shield wires	94S	1.260	0.642

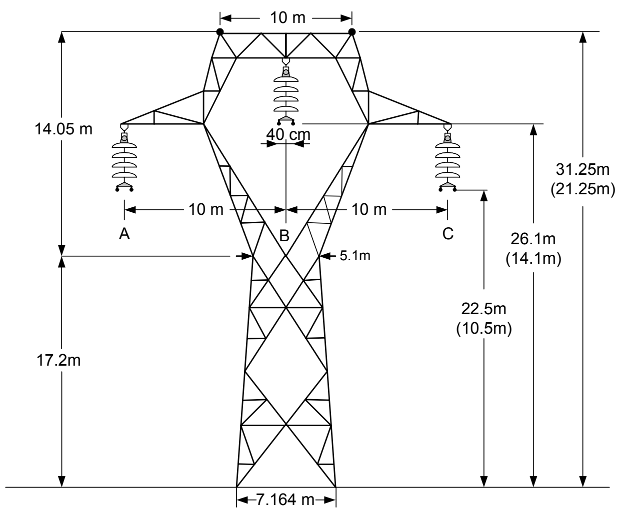


Fig. 6. 400 kV line configuration
(Values within parenthesis are midspan heights).

V. Simulation Results

A. Transmission Line and Lightning Parameters

A model of the test line was created using ATP capabilities and following the guidelines summarized in Section II. The common values to all studies were those detailed below.

- The lines were represented by means of eight 400-m spans plus a 30-km section as line termination at each side of the point of impact. The parameters were calculated at 500 kHz.
- Only negative polarity and single stroke flashes were considered.
- The phase conductor reference angle had a uniform distribution between 0 and 360 degrees.
- The stroke location, before the application of the electro-geometric model, was generated by assuming a vertical path and a uniform ground distribution of the leader.

No flashovers other than those across insulator strings, e.g. flashovers between conductors, have been considered.

B. Sensitivity Studies

The sensitivity studies are aimed at analyzing respectively the effect that the representation of the grounding impedance, the insulator strings and the tower can have on the flashover rate.

1) The first study presents the flashover rates derived from the two different approaches mentioned above for representing insulator strings. The calculations were performed by assuming
   - a normal distribution for the footing resistance, being the mean value of the resistance at low current and low frequency 50 Ω and the standard deviation 5 Ω. The soil resistivity was 500 ohm-m;
   - a lossless line model for representing towers; the surge impedance value was calculated according to the modified version of the "waist" model [7], [13], being the estimated value of the surge impedance 100.4 Ω.

   The median value of the return stroke tail time was 77.5 μs, while the values of the standard deviation for each parameter of the return stroke waveshape, see Fig. 5, were as follows [23]: peak current magnitude (I_{100}), 0.740 kA; rise time (t_f), 0.494 μs; tail time (t_h), 0.577 μs.

   The characteristics of the insulator string models were those detailed below:

   a. A controlled-switch whose strength was calculated according to the expression proposed by IEC 60071-2 for negative polarity strokes and lines located at sea level [24]

   $$CFO^{-} = 700 \cdot d_s \qquad (9)$$

   being d_s the striking distance of the insulator string (3.212 m in this work).

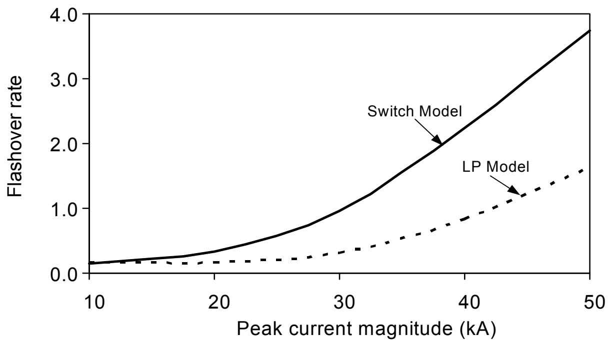
   From the geometry of the insulator strings, a Weibull distribution with CFO^{-}=2248 kV and σ/CFO=5% was used in calculations.

   b. The parameters used in the equations of the leader progression model were k_l = 1.3E-6 m^2/(V^{2}s) and E_{l0} = 570 (kV/m). The value of the average gradient at the critical flashover voltage, E_{50}, was assumed to be the same that E_{l0}. A Weibull distribution was also assumed for parameter E_{l0}. The mean values are those mentioned above, while the standard deviation was 5%.

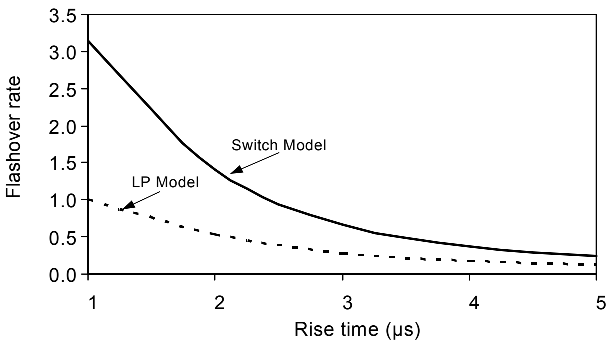
   Fig. 7 shows the flashover rate, calculated with the two insulator string models, as a function of the median values of both the peak current magnitude and the rise time of the return stroke current. The conclusions from these results are very obvious: the trend is the same with both models but the differences between the flashover rates obtained with both approaches can be important and they increase with the peak current magnitude and decrease with the rise time. However, different values of parameters to be specified in each model from those used in this paper have been also proposed, see for instance [25] and [26].

2) The second study is aimed at analyzing the influence that the different parameters of the grounding models can have on the flashover rate. The calculations were performed by using
   - the same approach applied in the previous study for representing towers
   - the leader progression model for representing insulator strings, with the same parameters and the same statistical behavior that were considered in the previous study
   - the concave waveform depicted in Fig. 5 for representing the return stroke current, being the median values of the main parameters I_{100} = 34 kA, t_f = 2 μs, t_h = 77.5 μs.

   Plots of Fig. 8 show the flashover rate for different combinations of the grounding impedance parameters. The main conclusions can be summarized as follows:
   - the soil resistivity influence decreases for high capacitance values; this is specially evident with model C1

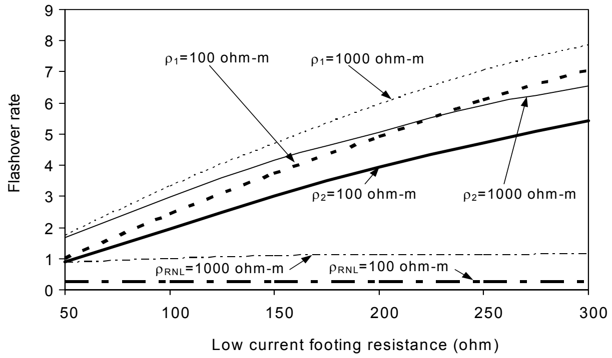


a) Flashover rate vs. peak current magnitude (t_f = 2 μs, t_h = 77.5 μs)

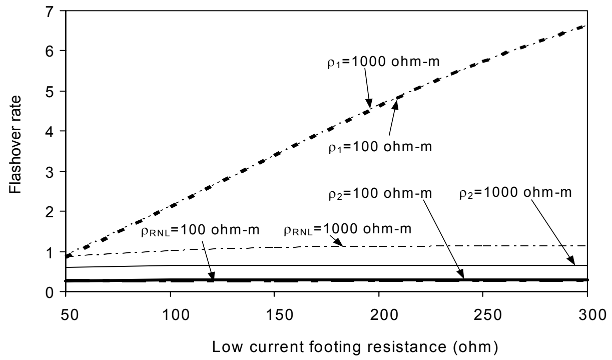


b) Flashover rate vs. rise time (I_{100} = 34 kA, t_h = 77.5 μs)

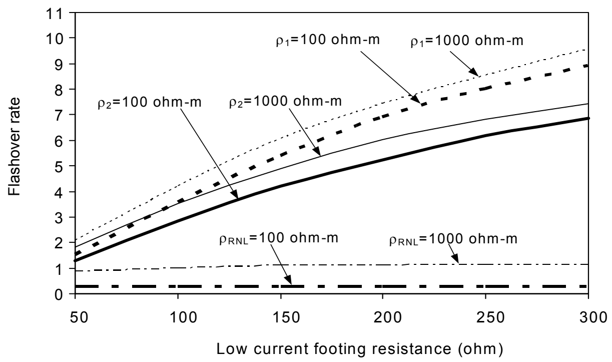
Fig. 7. Influence of the insulator string model - (R_0 = 50 Ω, ρ = 500 Ω.m, N_g = 1 fl/km^2).



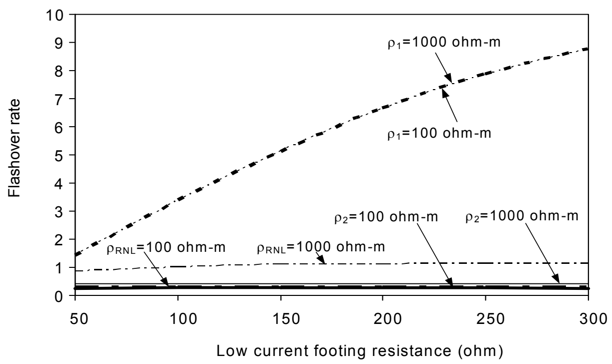
a) $\alpha = 0.4$, $C = 0.01$ µF



b) $\alpha = 0.4$, $C = 0.5$ µF



c) $\alpha = 0.6$, $C = 0.01$ µF

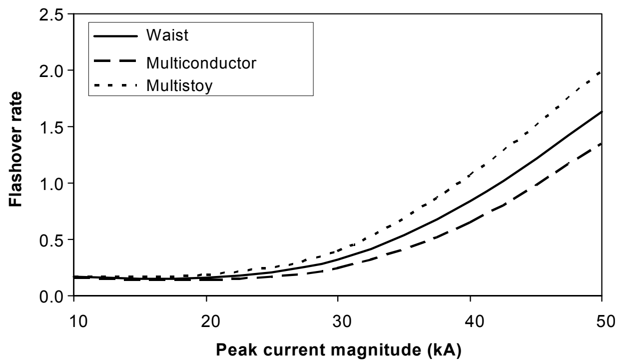


d) $\alpha = 0.6$, $C = 0.5$ µF

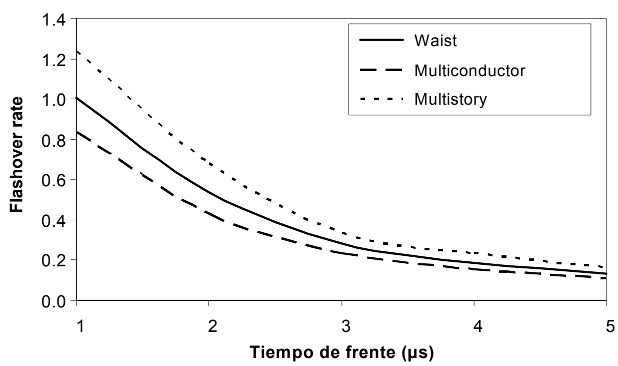
Fig 8. Effect of the low current, low frequency resistance and soil resistivity (I_{100} = 34 kA, t_f = 2 µs, t_h = 77.5 µs, N_g = 1 fl/km^2) ρ_1≡ Model C1, ρ_2≡ Model C2, ρ_{RNL}≡ Nonlinear resistance.

- the flashover rate increases as factor α increases, but the effect of this factor is not very pronounced
- the influence of R_0 is very important with model C1, but the flashover rate is less sensitive with respect to this value if model C2 is used, which is very evident when the capacitance value is high
- the flashover rate is not very sensitive with respect to R_0 if the non-linear resistive model is used, but the rate increases with the soil resistivity.

3) The last study is aimed at deducing the flashover rate that could be derived with some tower models by varying the median values of the peak current magnitude and the rise time of the return stroke current. In all cases the median value of tail time was 77.5 µs. The models and parameters used for representing grounding resistances and insulator strings were those used in the first study.
Fig. 9 shows the flashover rates that were derived with some tower models. The trend of the flashover rate is the same with all of them: it increases with the peak current magnitude, and decreases as the median value of the rise time increases.
The highest and the lowest rates are derived from the multistory and the multiconductor models, respectively. Only when the median values of the peak current magnitude and the rise time are below 20 kA and above 4 µs, respectively, the differences between rates obtained with different models are not very significant.



a) Flashover rate vs. peak current magnitude (t_f = 2 µs, t_h = 77.5 µs)



b) Flashover rate vs. rise time (I_{100} = 34 kA, t_h = 77.5 µs)

Fig. 9. Sensitivity analysis (N_g = 1 fl/km^2)

VI. Conclusions

This paper has presented the main results of some sensitivity studies whose goals were to analyze the influence of the models used for representation of some parts of a transmission line (the insulator strings, the grounding impedance and the tower) on the lightning flashover rate. The main conclusions are summarized below.

- The differences between the flashover rates calculated with the two insulator models were significant. However, both models show the same trend in all sensitivity studies. The leader progression model is more accurate and has been validated in some studies [27], but it is a simplification of the model presented in [26], and parameters different to those used in this work have been proposed [12].
- The flashover rates derived from some grounding models were also very different. The two capacitive models analyzed in this work are very sensitive to some of the parameters used to describe them, namely factor α and the capacitance. In addition, when using the same parameters for both capacitive models, the flashover rate is always higher with model C1. A careful selection of the grounding model is required and an accurate determination parameters is advisable.
- The tower representation can also have a significant influence on the flashover rate. Some care is advisable when selecting the model and calculating its parameters; these aspects are less critical when tower structures are about or less than 30 meters.

VII. Acknowledgement

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IX. Biographies

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