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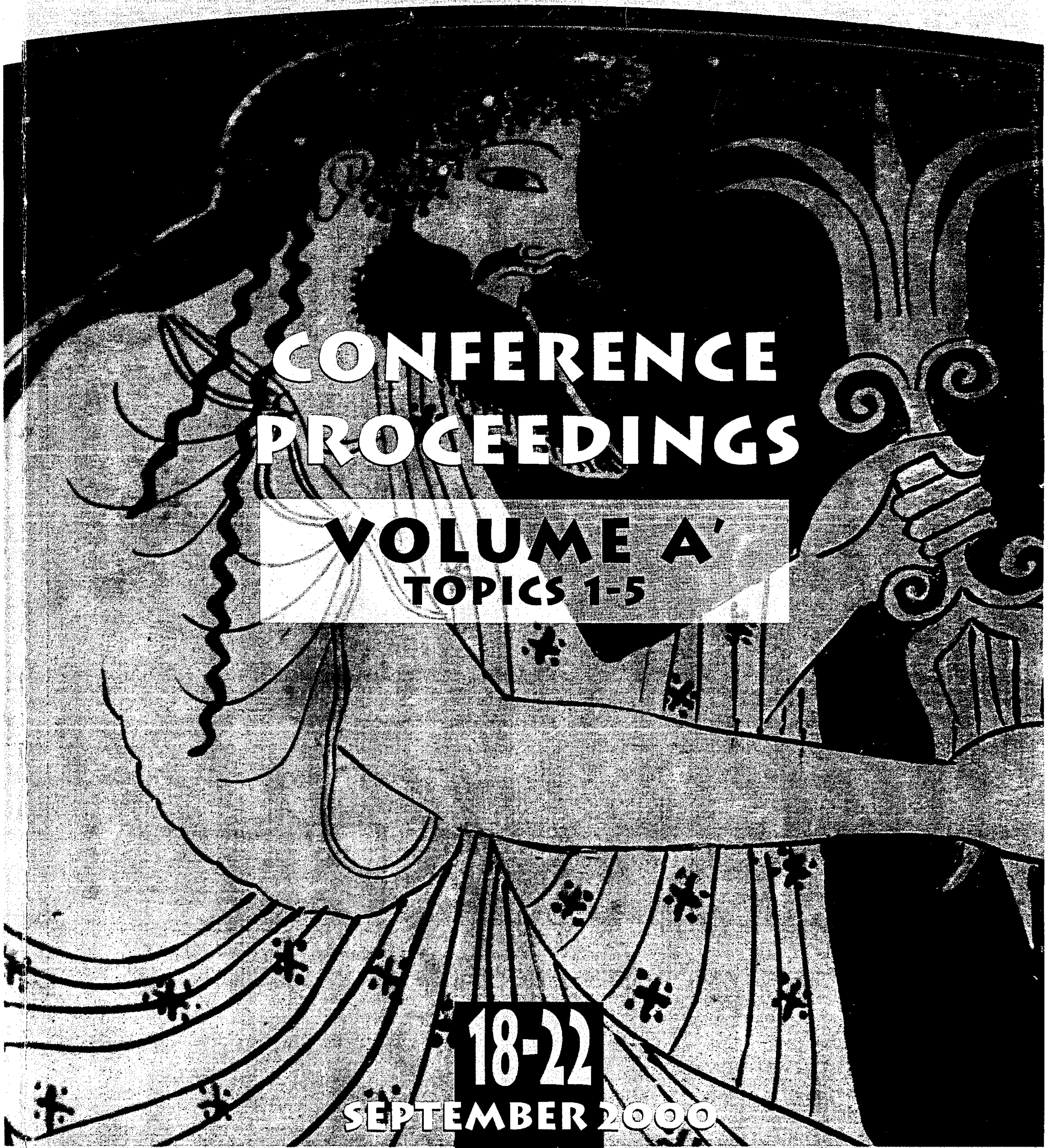

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EFFECT OF THE LATERAL DISTANCE EXPRESSION AND OF THE PRESENCE OF SHIELDING WIRES ON THE EVALUATION OF THE NUMBER OF LIGHTNING INDUCED VOLTAGES

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Abstract: The number of lightning-induced overvoltages per year that exceed the insulation level of an overhead line, given a certain ground flash density, is evaluated in the paper by means of a Monte-Carlo procedure previously presented [1]. The most popular expressions proposed for the evaluation of the so-called "lateral distance" are shown to affect considerably the results. Further, the effect of periodically-grounded shielding wires is also analysed, with particular reference to the spacing between two adjacent grounding as well as to the value of the grounding resistance.

Keywords: Flashover rate, lateral distance, striking distance, lightning-induced voltages

1. INTRODUCTION

In a previous contribution [1], a Monte Carlo-based procedure has been proposed in order to infer the number of lightning-induced overvoltages per year that exceeds the insulation level of an overhead line, given a certain ground flash density. The procedure has been applied both in [1] and [2] to carry out an investigation aimed at assessing the influence of various parameters (such as the correlation between peak current and front-time of the lightning current, the ground resistivity, the return-stroke velocity, etc.) on the number of induced voltages.

In these studies, the expression adopted by the IEEE Working Group on Lightning performance of transmission lines [3] was used for the evaluation of the so-called 'lateral distance' d_l. Such an expression, is based on the Electro-Geometric model of the last step of the lightning flash, which gives the following relation between the critical distances (the striking distances to the wire (r_s) and to ground (r_g)) and the lightning current I [3]

$$r_s = 8 \cdot I^{0.65} \qquad r_g = 8 \cdot I^{0.65} \tag{1}$$

where r_s and r_g are expressed in m and the lightning current I in kA. As shown in Fig. 1, the value d_l is then determined from

$$d_l = \sqrt{r_s^2 - (r_g - h)^2} \tag{2}$$

where h is the line height (in m).

In [1,2] further, a comparison was carried out between the results obtained using the IEEE formula and those obtained using both the older formulation of Armstrong and Whitehead for the striking distance [4] and the more recent expression proposed by Rizk [5][1]. Such a comparison has shown that the results are indeed different in the three cases.

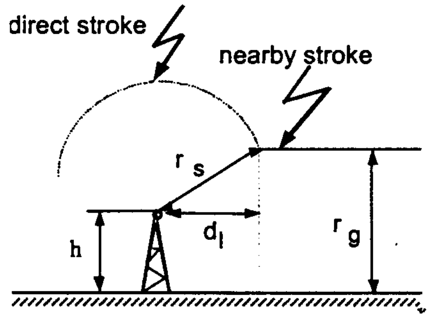

Figure 1: Striking distances to a conductor (r_s) and to ground (r_g) and lateral attractive distance (d_l) of a line. (Adapted from [10])

In this paper we shall complete the analysis started in [1,2]: in particular, we shall use the expression for the lateral distance proposed by Eriksson [6], as well as another expression that can be inferred by the leader-progression model of Dellera and Garbagnati [7,8].

Then, we shall present some results on the influence of the presence of a shielding wire (periodically grounded) on the number of induced voltages. The effects of the spacing between two adjacent groundings of the shielding wire as well as on the value of the grounding resistance will be estimated.

[1] Note that while Armstrong and Whitehead give an expression for the striking distances to the wire and ground, Rizk provides directly the expression for the lateral distance.

2. THE PROPOSED METHOD AND THE COMPUTER PROGRAM

To solve the problem of interest, basically all previous investigations have considered an infinitely long line over a perfectly ground plane [9-12]. For such a case, the desired flashover rate *vs* BIL curve is inferred by calculating the voltage at the point closest to the stroke location for a suitably large number of events. Indeed, for the theoretical case of infinitely long lines above a perfectly conducting ground, the procedure followed in [9-12] is appropriate. It becomes questionable, however, for the more realistic case of a line of finite length over a lossy ground. For such a case in fact, the maximum amplitude of the induced voltage does not necessarily occur at the point closest to the stroke location [2,13]. Stroke locations near the ideal prolongation of the line can in fact induce overvoltages along the line more severe than that at the line terminal. This means that the calculation of the induced voltages cannot be limited to a single observation point (as done, for instance, in [14]) but has to be extended, in principle, to all points along the line. A "striking area" around the line, has then to be considered, wide enough to include all the lightning events that can induce a voltage along the line with maximum amplitude greater than the considered insulation level (see Fig. 2).

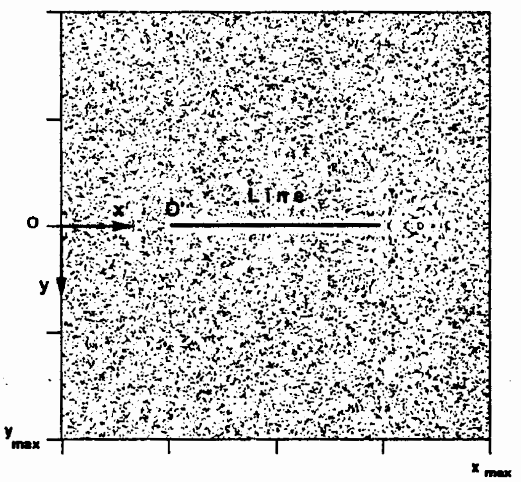

Figure 2 - Indirect stroke area to overhead line (top view).

The Monte Carlo procedure [1] is applied to generate a significant number of events (al least 10000). Each event is characterised by four random variables: the peak value of the lightning current I_p, its front time t_f ($t_f = T_{30}/0.6$, where T_{30} is the front duration expressed as the interval between the 30 percent and 90 percent amplitude intercepts [3]) and the two co-ordinates of the stroke location. We assume a correlation coefficient (ρ) between current amplitude and front duration equal to 0.47 [10] and the statistical parameters of log-normal distribution of the peak and the front time published in [15]. The stroke locations are supposed uniformly distributed within the earlier mentioned surface around the line (see [1,2] for further details). The 'striking area' we consider in our study does not include the points which distance from the line is less than the values d_l (lateral attractive distance).

For the purpose of the statistical analysis, the LIOV code [16,17][2], used for the calculation of the lightning-induced voltages, has been provided with a numerical routine that allows a fast computation of the electromagnetic field radiated by lightning, assuming a linearly-increasing flat-top waveshape of the lightning current [1].

The final goal of the calculation is a curve showing how many times per 100 km per year the maximum induced voltage amplitude along a given line will exceed the values reported in abscissa. The digital computer program to determine such a frequency of flashovers to a line has been already illustrated in [1,2]. We limit here to mention that the inputs of the program are the parameters of the lightning stroke current, the line height and length (h, L), the value of ground conductivity (σ_g) and relative permittivity (ε_r), the indirect stroke area (x_{max}, y_{max}) and the ground flash density (N_g). The parameters of the stroke current are the median value of peak $\bar{I}_p$, the log of its standard deviation $\delta_{\ln I_p}$, the median value of front time $\bar{t}_f$, the log of its standard deviation $\delta_{\ln t_f}$ and the return stroke velocity (v_{rs})[3]. The program has been recently enlarged in order to permit the analysis of multiconductor lines with periodically grounded shielding wires (see paragraph 3.2).

For the cases relevant to a perfectly conducting ground we consider a 2 km long overhead line and an indirect stroke area of 8 km^2, with x_{max} equal to 4 km, y_{max} equal to 1 km and OO' equal to 1 km (see Fig. 2). Concerning the cases of lossy ground, a larger indirect stroke area (20 km^2) is considered around a 1 km long overhead line, with x_{max} equal to 5 km, y_{max} equal to 2 km and OO' equal to 2 km, for the reasons already discussed in [2].

3. SIMULATION RESULTS

3.1. Influence of the lateral distance expression

As already, in this paper we extend the analysis previously carried out in [1,2] to include other two lateral distance expressions, namely the Eriksson one [6] and the expression inferred from the model by Dellera and Garbagnati [7,8], based on the application of the leader progression model concept.

For both these expressions, as well as for the Rizk one, we shall use a formula of the type

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[2] See also the companion paper [13].

[3] In this paper, the return stroke velocity v_{rs} is considered constant and equal to 1.5 x10^8 m/s. The influence of variation of such a parameter and possible correlation with the lightning current I_p have been studied in [2].

$$d_l = c + A \cdot I^b \tag{3}$$

where the value of constants c, A and B depends on the specific expression, as shown in table 1, below.

Table 1: Values of constant A, b and C of eq. (3).

	C	A	b	No. Direct strokes
Eriksson [6]	-	0.67 $h^{0.6}$	0.74	224
Rizk [5]	-	1.57 $h^{0.45}$	0.69	309
From Dellera and Garbagnati [7]	3 $h^{0.6}$	0.028 h	1	135

Concerning the Eriksson expression we have used the constants relevant to the simplified formula presented in [6]. On the other hand, concerning the expression relevant to the model by Dellera and Garbagnati, we have inferred it by interpolation of the lateral distance *vs* height graphics given by the leader progression model of Dellera-Garbagnati [8,18]. The lateral distance was evaluated considering a slim structure with eight in the range 5 to 100 m, exposed to lightning with current amplitude distributed as in [15]. The interpolation formula, obtained as described above, exhibits a discontinuity at the height of 10 m; this is mainly due to the major influence of the ground on the streamer tip approaching the structure. For our comparison we used the formula from 10m onwards.

For completeness, in table 2 we report also the values of constants A and b of (1), which applies to the Armstrong and Whithead [4] and IEEE WG [3] formulation of the striking distances to the wire (r_s) and to ground (r_g). Remind that, in this case, the relevant lateral distance is evaluated using equation (2).

Table 2: Values of constant A and b of eq. (1). Adapted from [19].

	r_s		r_g		No. direct strokes
	A	B	A	b	
Armstrong and Whitehead [4]	6.7	0.80	6.0	0.80	393
IEEE WG [3]	8.0	0.65	8.0	0.65	213

In both tables 1 and 2, we have reported also the number of direct strokes relevant to each formulation for the case of 10 0000 events and a striking area of 8 km².

Fig. 3 shows the results relevant to all five lateral distances considered in this study assuming the ground as a perfect conductor[4]. Fig. 4 shows the results obtained, with σ_g=0.01 (Fig. 4a) and σ_g=0.001 (Fig. 4b). The difference between the results tends to be less pronounced as the ground conductivity decreases.

[4] In this paper, as well as in [1,2], it is implicitly assumed that all induced voltages exceeding the value reported in abscissa will result in a flashover, deliberately disregarding the *V-t* characteristic of the insulator chain.

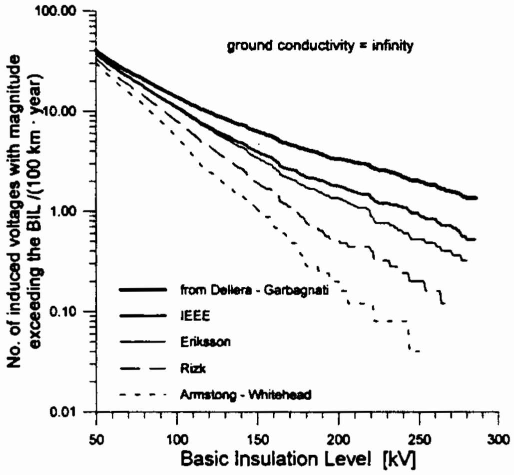

Figure 3: Influence of the lateral distance formulation. Case of perfectly conducting ground.

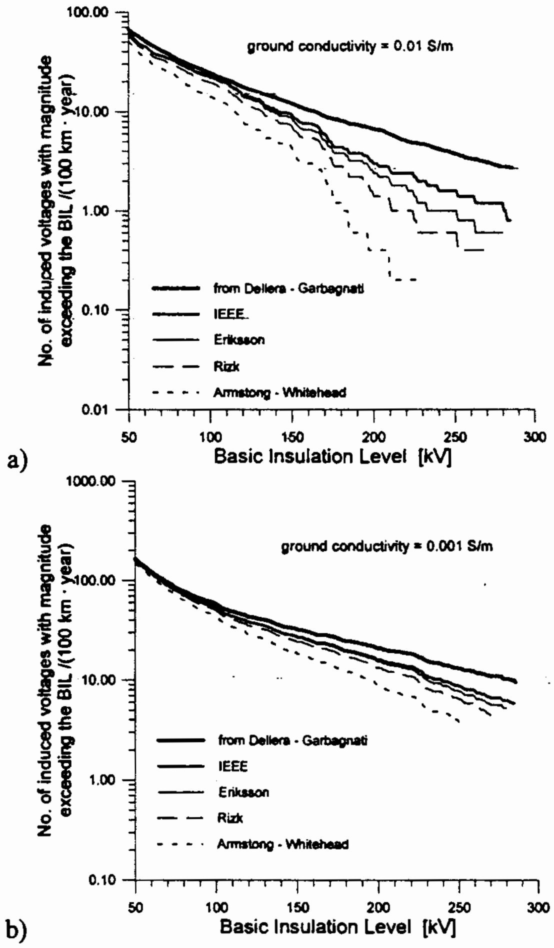

Figure 4: Influence of the lateral distance formulation: a) σ_g=0.01 S/m, b) σ_g=0.001 S/m

The largest number of induced voltages is obtained by using the formulation inferred from the model by Dellera and Garbagnati; the lowest one is obtained by using the expression by Armstrong and Whitehead. The results of figures 3 and 4 match with the number of direct strokes listed in the last column of table 1 and 2 relevant to each different formulation.

3.2. Influence of the shielding wire

We now consider a 2 km long, two-conductor line (phase conductor and shielding wire) over a perfectly conducting plane, a case similar to the one discussed in [12]. As shown in Fig. 5, the shielding wire is grounded at the line terminations and periodically grounded along the line. The spacing between two adjacent grounding (gr) is 1000 m (3 grs), or 400 m (6 grs). The simulations are carried out with the aim of evaluating the influence of the presence of the shielding wire, of its height, of the spacing between two adjacent grounding as well as the value of the grounding resistance.

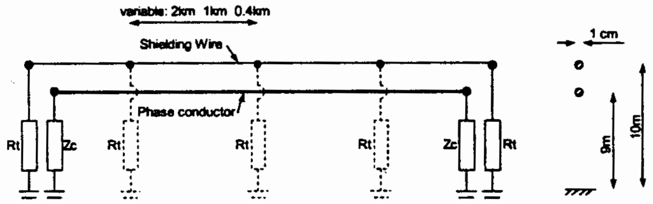

Figure 5: Line configuration with shielding wire

Fig. 6 shows the results obtained with three different shielding wire heights, namely 9.7 m, 10 m, 10.4 m. The results are indeed affected by the presence of the shielding wire, but the influence of the shielding wire height is limited for the considered cases.

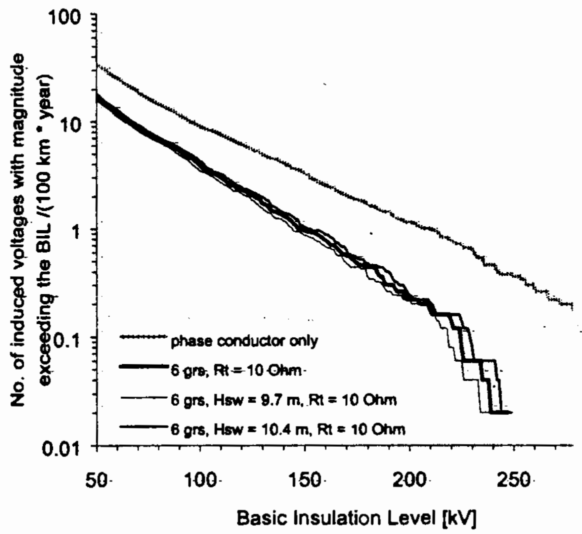

Figure 6: Influence of shielding wire height.
The spacing between to adjacent grounding is 400 m (i.e. 6 grounding overall) and the grounding resistance is equal 10 Ω.

Fig. 7 shows the influence of grounding resistance (the shielding wire in this case is at 10 m above ground). Two values of grounding resistance are considered, namely 10 and 100 Ohm. The results obtained by using the two values of grounding resistance do not differ considerably, at least when the number of grounding is low (2 and 3 grs). On the other hand, the spacing between two adjacent grounding appears to have a larger influence, as also illustrated in Fig. 8 for a value of grounding resistance of 10 Ohm and a shielding wire height of 10 m.

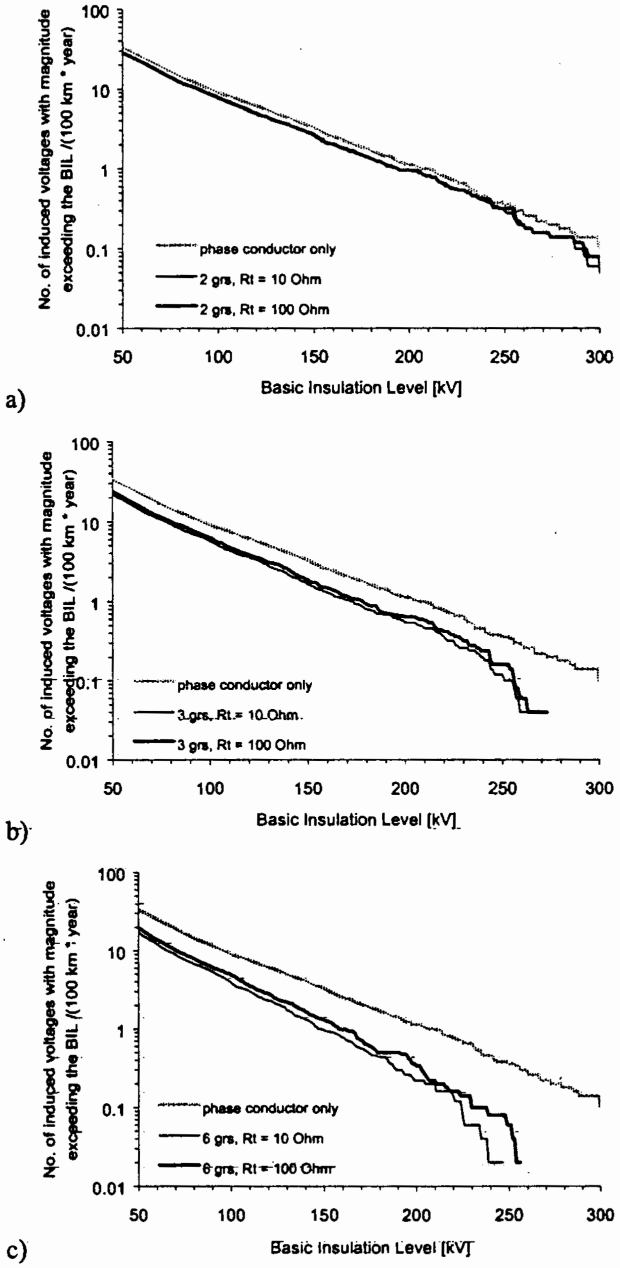

Figure 7: Influence of grounding resistance.
a) The shielding wire is grounded only at its terminations (overall 2 grs).
b) The spacing between two adjacent grounding is 1 km (overall 3 grs).
c) The spacing between two adjacent grounding is 400 m (overall 6 grs).

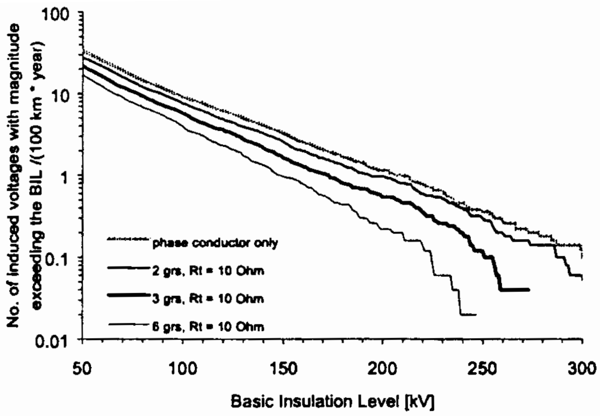

Figure 8. Influence of spacing between adjacent grounding.

4. CONCLUSIONS

The paper has presented a statistical analysis of the number of lightning induced voltages exceeding a given value, making use of a Monte Carlo procedure presented in a previous work [1].

Five different ways to evaluate the lateral distance have been adopted: the results do differ. Such a difference, however, tends to decrease as the ground resistivity increases.

The method proposed has been extended to the case of multiconductor lines with shielding wires periodically grounded. The analysis has then covered the influence of the presence of the shielding wire, of the grounding resistance as well as of the spacing between two adjacent grounding. It has been shown that the shielding wire appears to have a large influence on the performance of the distribution line; additionally, the spacing between two adjacent grounding of the shielding wire, seems to have the major impact in decreasing the number of induced voltages exceeding a given value. This represents a step ahead toward a more realistic assessment of the lighting performance of distribution lines than generally examined in previous works on the subject (infinitely long line above an ideal ground).

However, real distribution lines are characterised by topological configurations even more complexes than that examined in this paper. In this respect, it is worth noting that with the LIOV-EMTP96 code (see the companion paper [13]), statistical analysis can be carried out on a specific distribution system with any complex configuration.

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