Effect of tall instrumented towers on the statistical distributions of lightning current parameters and its influence on the power system lightning performance assessment

A. Borghetti, C.A. Nucci, M. Paolone

Abstract—**Statistical distributions of lightning current amplitude, time-to-peak value and other lightning current parameters, used in power system insulation coordination, are based on experimental data obtained by means of tall instrumented towers. It is, however, generally accepted that these distributions are affected by the presence of the tower due to its attractive radius. Current amplitudes, in particular, are biased towards higher values with respect to those that would refer to flashes at ground. In this paper we propose a procedure, based on the Monte Carlo method, that allows to infer the statistical distributions of lightning current parameters at ground level starting from the 'classical' ones, i.e. those obtained from data measured using tall instrumented towers. The procedure is more general than others proposed in the literature for the same purpose, in that it can be applied whatever attractive radius expression is used. The procedure is applied to quantify the tower bias on the classical statistical distribution of lightning current amplitude for a number of available attractive radius expressions. Additionally, the comparison between the indirect-lightning performances of an overhead line, inferred by adopting both the classical, tower-affected, and the unaffected statistical distributions at ground of the lightning current amplitude, is given.**

Index Terms—**Power system lightning protection, Lightning statistics, Monte Carlo method, Induced overvoltages.**

I. NOMENCLATURE

Let X be a random variable with lognormal distribution; μ denotes the median value of X, which corresponds to the antilogarithm of the mean value of variable log(X); δ denotes the standard deviation of variable log(X). δ values are given with reference to common logarithm, i.e., base 10.

II. INTRODUCTION

The probabilistic approach to power system insulation coordination requires the knowledge of the statistical distributions of lightning current parameters [1]. Nowadays, the distributions adopted by power engineers are basically those derived from the experimental data gathered by means of elevated instrumented towers in the last decades [2-7]. We shall refer to these distributions as to the 'conventional' ones. There is, however, general concern on the fact that these distributions are affected by the presence of the tower; lightning current amplitudes, in particular, are 'biased' towards higher values [8-13], as the so-called attractive radius of the tower tends to increase for flashes with larger currents[1]. There are indeed several expressions for such an attractive radius [15-20], all predicting its increase with the return-stroke current.

In view of the above, the conventional distributions should not be used as such for power system insulation coordination studies. One should first eliminate the early-mentioned tower effect to obtain distributions *at ground*, and then apply the obtained distributions to the specific structure of interest (line poles, line conductors) by taking into account the relevant direct-stroke exposure model (given, in turns, by the attractive radius - or lateral distance - expression). Note, additionally, that for the case of overhead distribution lines, for which it is very important to take into account the overvoltages induced by strokes hitting the ground in their vicinity (indirect strokes), to accomplish appropriate insulation coordination the statistical distributions of interest are indeed those of the lightning current parameters at ground.

Pettersson [11] already studied the problem and proposed an analytical formula that allows obtaining the statistical distribution of the lightning current amplitude at ground starting from that obtained from elevated instrumented towers. Such a formula, which applies only when the relationship between the attractive radius and the current amplitude is exponential, and only to the current amplitude, has been afterwards applied by Sabot [12] to the Cigré lightning current amplitude distribution. In [44], Rizk has presented the relationship among the probability density functions of peak currents relevant to strokes hitting a mast, of strokes hitting a conductor, and of strokes to open ground. These relationships have been applied in [44] by Rizk to the IEEE lightning current distribution [6], having a median value of 31 kA (and assumed to be inferred only from transmission line

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[1] The lightning current parameters are also affected by the influence of the reflections at the top and at the basis of the tower (e.g. [14]). These effects are here disregarded. Also, in this paper, we focus only on downward negative flashes.

measurements), to obtain a median value for open ground equal to 23 kA. To perform this calculation the lateral distance expression proposed in [18] was applied, which is of the same exponential type assumed by Pettersson in order to derive its formula.

In order to overcome the above-mentioned limits of the Pettersson formula, and to allow for the treatment of additional lightning current parameters different from the peak amplitude, we propose here an alternative approach based on the Monte Carlo method. With it, it is possible to infer the statistical distributions of any lightning current parameter at ground starting from the 'conventional' ones, for any of the exposure models proposed in the literature. Using the proposed approach, we infer a number of statistical distributions of various lightning current parameters, and this for different attractive radius expressions. We eventually evaluate the impact of the above-mentioned tower effect on the assessment of the lightning performance of distribution overhead lines.

The different models describing the exposure of a tower and/or an overhead line to direct lightning strokes are briefly summarized in Section III where various expressions for the attractive radius (lateral distance) are summarized and reviewed. The method that we propose is described in Section IV and, in Section V, is applied to the lightning current parameter distributions of current amplitude and front duration presented in [4], obtained from the experimental records at Monte San Salvatore [21]. Section VI contains a comparison between the indirect-lightning performance of an overhead line inferred by adopting both the affected and the unaffected current statistical distributions.

III. MODELS DESCRIBING THE EXPOSURE OF AN ELEVATED STRUCTURES TO DIRECT LIGHTNING STROKES

As the lightning leader descends toward an elevated object, it reaches a point known as the striking point. At this point, it will initiate a juncture either with the object or with the ground depending on its charge, its distance from the structure, on the type (vertical mast or horizontal conductor), and height of the structure. By assuming the leader channel perpendicular to the ground plane, it is generally accepted that the flash will stroke the structure if its prospective ground termination point, i.e. its stroke location in absence of the structure, lies within the so-called "attractive radius" r_l (also called "lateral distance" for the case of horizontal conductors, as those of overhead lines).

Several expressions are available to evaluate such a distance. Some of them are based on the Electrogeometric model [22]; as shown in Fig. 1, the value r_l (in m) is determined from

$$r_l = \sqrt{r_s^2 - \left(r_g - h\right)^2} \qquad \text{for } h < r_g \qquad \text{(1a)}$$

$$r_l = r_s \qquad \text{for } h \geq r_g \qquad \text{(1b)}$$

where h is the height of the structure (in m) and r_s and r_g are the so-called critical distances (in m) to the structure and to the ground respectively. These striking distances are related to the lightning current by means of the following expressions

$$r_s = \alpha \cdot I_p^{\beta} \qquad r_g = k \cdot r_s \qquad (2)$$

where I_p is the current amplitude in kA, and the values of α, β and k are independent of I_p. Table I reports some of the values proposed in the literature on transmission line shielding. Expression 2 is an approximation of the formula proposed by Love [16] using the exponential format [6].

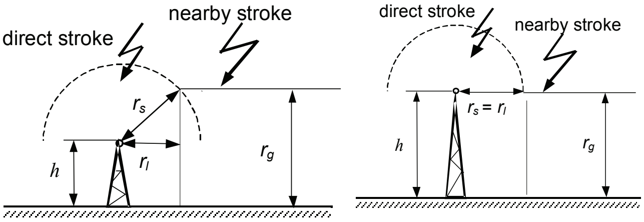

Fig. 1. Electrogeometric model: r_s and r_g are the striking distances to the structure (mast or horizontal conductor) and to ground respectively; r_l is the attractive radius (or lateral distance) of the structure.

TABLE I
VALUES OF CONSTANTS OF STRIKING DISTANCE EQUATIONS (2) PROPOSED BY DIFFERENT AUTHORS

Exposure model	α	β	k
1. Armstrong and Whitehead [15]	6.7	0.80	0.9
2. IEEE [6,16]	10	0.65	0.55* 0.9**

* adopted by IEEE Std. 1243 [22] for an average conductor height greater than 40 m.
** adopted by IEEE Std. 1410 [23] for distribution lines

Other expressions, namely those by Eriksson [17], Rizk [18], Dellera and Garbagnati [19,20] are available; they have been inferred more recently by regression analysis, from the results of more complex and physically oriented models than the Electrogeometric one. For these expressions, a formula of the following type can be used for the attractive radius

$$r_l = c + a \cdot I_p^b \qquad (3)$$

where the values of a, b and c depend on the specific expression, and are shown in Table II.

TABLE II
VALUES OF CONSTANTS OF ATTRACTIVE RADIUS AND LATERAL DISTANCE EQUATION (3) PROPOSED BY DIFFERENT AUTHORS

Exposure model	c	A	b
3. Eriksson [17]	0	$0.84\ h^{0.6}$ * $0.67\ h^{0.6}$ **	$0.7\ h^{0.02}$
4. From Rizk [18]	0	$2.83\ h^{0.4}$ * $1.57\ h^{0.45}$ **	0.63 * 0.69 **
5. From Dellera and Garbagnati [19,20]	$3\ h^{0.6}$	$0.028\ h$	1

* for towers
** for horizontal conductors.

It is worth noting that concerning the Eriksson expression, henceforth called expression 3, in [17] two lateral distance formulas are proposed, one for masts with heights up to 100 m, and another one for horizontal conductors, with an 80% reduction of parameter a (see Table II).

Concerning the Rizk expression (expression 4), in [18] an analytical formula is proposed for horizontal conductors with height range of 10 m and 50 m and for lightning currents with I_p in the range 5-31 kA. The parameters are those of Table II. For free standing structures, in [18] the two following formulas are given:

$r_l = 24.6 \cdot h^{0.40}$ for I_p=31 kA and h in the range 10-60 m,

$r_l = 12.4 \cdot I^{0.63}$ for h=40 m and I_p in the range of 5-60 kA.

From these two formulas, a first approximation for coefficient a of Table II is derived by dividing 24.6 by $31^{0.63}$, then obtaining, for different tower heights, curves similar to those shown in Fig. 5 of [18].

Concerning expression 5, the constant values have been inferred in [25] by interpolation of plots of the lateral distance of a slim structure vs. its height (in the range 5 to 100 m), calculated using the leader progression model of Dellera-Garbagnati [19,20].

IV. PROCEDURE FOR THE EVALUATION OF LIGHTNING CURRENT DISTRIBUTIONS TO GROUND

To obtain the statistical distributions of lightning parameters at ground one should be able to record the lightning currents of a large number of lightning flashes hitting the ground within a certain area. However, to accomplish that, one needs the presence of a tall instrumented tower, which, as earlier mentioned, does affect the distributions. As a matter of fact, of all the strokes that, in absence of the tower, would hit the ground in its vicinity, the tower attracts only some of them, due to the already described attractive radius concept. However, if we consider an area around the tower location, supposed circular for convenience, such that its radius is equal to the attractive radius r_l* corresponding to the minimum peak current value I_p* observed at the top of the tower, all the strokes with perspective stroke location within such an area will be collected by the tower.

The proposed approach consists of applying the Monte Carlo method to generate a population of lightning events with perspective stroke location within such an area of radius r_l*, starting from the conventional statistical distributions of the lightning currents collected by the tower, as described in what follows. We generate a significant number of lightning events (e.g. 10^6), each characterized by a number of random variables (amplitude I_p, time to peak value t_f, etc.), and perspective radial distance x_g from the tower location. For each event, the values of the various lightning current parameters are randomly selected from the corresponding statistical distributions relevant to the tower measurements. Correlation coefficients between the lightning parameters can be also taken into account by applying the inverse transform method [26], as shown for instance in [27]. The value of x_g associated to each direct lightning event is generated assuming that the stroke locations are uniformly distributed around the tower; for each lightning event, x_g is then generated from a distribution with probability density function equal to $2 \cdot x_g / r_l^2$. From the population of direct lightning events generated as above described, we select the set of stroke events having distance x_g from the tower location lower than r_l^*. The statistical distributions of the lightning parameters associated to these events are then evaluated, which, under the considered assumptions, are indeed the desired distributions of the lightning parameters to open ground, without the bias introduced by the tower.

V. APPLICATION OF THE PROPOSED PROCEDURE TO THE LIGHTNING CURRENT STATISTICAL DISTRIBUTIONS BY BERGER ET AL.

Let us now consider the statistical distributions of the lightning current parameters by Berger et al. [3], obtained from measurements on the 70 m high tower installed at the top of Monte San Salvatore in Switzerland (near Lugano, 912 m above sea level)[2]. In Table III the median μ_t and standard deviation δ_t values of the first peak and of the front duration (assumed to be lognormally distributed) as given in [4] are reported.

TABLE III
MEDIAN AND STANDARD DEVIATIONS OF FIRST PEAK AND FRONT DURATION OF NEGATIVE DOWNWARD FIRST STROKES RECORDED AT MONTE SAN SALVATORE [4]

Parameter	μ_t	δ_t
First Peak I_p (kA)	27.7	0.20
Front duration t_f (μs)	3.8	0.24

The median value and standard deviation of parameter t_f (front duration) are obtained by those of parameter T_{30}, i.e. the time interval between the 30 percent and 90 percent amplitude intercepts ($t_f = T_{30} / 0.6$) [4]. Also, a correlation coefficient $\rho_t = 0.47$ is taken into account between peak value and front duration [4].

In Table IV we report the results obtained by applying our procedure to the experimental distributions of Table III for all the models of Tables I and II describing the lightning exposure of the tower. For these calculations, the experimental data of Berger et al. have been assumed to be collected by a tower on a ground plane, assuming that the effect of the presence of the mountain can be disregarded in the expression of the attractive radius of the tower, a point that certainly requires additional investigation [4,44]. The minimum value of current peak has been assumed equal to 2 kA, for all the calculations.

The distributions at ground of current amplitude have median values ranging from 27.4% (attractive radius expression 3) to 20.2% (attractive radius expression 5) lower than the median of the original distribution. The median values of front times range from 15.8% to 10.5% lower than the median of the original distribution, due to the correlation between front time values and current amplitudes.

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[2] For a certain limited period of time, at the top of the mountain there were two towers of different height (70 and 90 m). In this paper we disregard the effect of the presence of the second tower on the statistical distributions of the lightning current parameters.

TABLE IV

MEDIAN AND STANDARD DEVIATIONS OF CURRENT PARAMETER DISTRIBUTIONS TO GROUND FOR THE ATTRACTIVE RADIUS EXPRESSIONS OF TABLES I AND II.

Parameter		Exposure model				
		1	2	3	4	5
Peak I_p (kA)	μ_g	20.2	21.1	20.1	21.3	22.1
	σ_g	0.21	0.20	0.20	0.20	0.19
Front duration τ_f (µs)	μ_g	3.2	3.3	3.2	3.3	3.4
	σ_g	0.24	0.24	0.24	0.24	0.24
	ρ_g	0.49	0.47	0.48	0.47	0.45

We now compare the results obtained with the proposed procedure with those that can be obtained by using the earlier-mentioned analytical formula derived by Pettersson [11]. Such a formula allows calculating the μ_g and σ_g values of the lognormal distribution of the current amplitudes at ground, from the corresponding μ_t and σ_t values of the conventional distribution collected by means of an instrumented tower:

$$\begin{aligned} \sigma_g &= \sigma_t \\ \mu_g &= \mu_t \cdot \exp\left(-2 \cdot b \cdot \sigma_g^2\right) \end{aligned} \tag{4}$$

where b is the exponent of the attractive radius expression assumed by Pettersson to have an exponential form – namely of type (3) with c=0 – which means that (4) can be applied to exposure models 3 and 4. For the case of the Electrogeometric model (models 1 and 2), the attractive radius assumes an exponential form only if $h>r_g$ (equation (1b)) or [28] when both $r_g=r_s$ and $h<<r_g$ [3]. In this second case, the attractive radius can be written as

$$r_l = \sqrt{2 \cdot \alpha} \cdot h^{0.5} \cdot I_p^{\beta/2} \tag{5}$$

To the best of our knowledge, equation (4) cannot be applied to exposure model 5.

Following [12] we have applied (4) to the current peak distributions by Berger et al. [3], by assuming the values of parameter b of (4) equal to the b values reported in Table II for exposure models 3 and 4. For exposure models 1 and 2 (electrogeometrical) we have applied (4) by using for coefficient b both β and β/2. We have also applied equation (4) to exposure model 5, in order to quantify the effect of parameter c, not taken into account in (4), on the results. The median values μ_g of Table V are then obtained. (Note, as earlier mentioned, that by using (4), only the parameters of the statistical distribution of lightning current amplitudes can be evaluated.)

The comparison of the results of Table IV and V shows that the proposed procedure gives practically the same results as those obtained by applying (4), when exposure models 3 and 4 are applied, which are indeed of the type assumed by Pettersson in order to derive (4). For exposure model 2, the median value predicted by (4) matches with that of the proposed approach if b is assumed equal to β; this is supported by the fact that, for model 2, the probability that r_g be larger than 70 m is greater than 90%. For the case of exposure model 1, the result of (4) differs from that of the proposed approach when b is set equal to $\beta/2$; in fact the probability that r_g be much lower than 70 m is very low (our calculations show that the probability that r_g be lower than 70/3 is only 0.02%). For this model, however, the result predicted by (4) slightly differs form our result even for b=β, as, for this case, the probability that r_g be larger than 70 m is only 28.8%.

TABLE V

MEDIAN AND STANDARD DEVIATIONS OF CURRENT AMPLITUDE DISTRIBUTION TO GROUND BY APPLYING EQ. (4) FOR THE DIFFERENT ATTRACTIVE RADIUS EXPRESSIONS (EXPOSURE MODELS) OF TABLES I AND II.

Parameter		Exposure model						
		1		2		3	4	5
Peak I_p (kA)	μ_g	23.4 *	19.7**	24.1*	21.0**	20.0	21.2	18.1
	σ_g	0.20	0.20	0.20	0.20	0.20	0.20	0.20

* from (4) using b=β/2 (r_g=r_s and $h<<r_g$)

** from (4) using b= β ($h>r_g$)

VI. APPLICATION OF THE RESULTS TO THE EVALUATION OF INDIRECT LIGHTNING PERFORMANCE OF OVERHEAD LINES

To evaluate the impact of the proposed modification of the statistical distributions of lightning current parameters at ground, in this paragraph the indirect lightning performance of an overhead line is calculated by using both the lighting current statistical parameters of Table III, affected by the presence of the tower, and those, corrected according to the proposed procedure, of Table IV.

To this purpose, we consider a 2 km long, 10 m high overhead line, matched at both end, and a "striking area" around the line, 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 (e.g. about 20 km^2). The procedure presented by the authors in [27], also based on the Monte Carlo method, is applied to generate a significant number of events (al least 10^4). Each event is characterised by four random variables: the peak value of the lightning current I_p, its front time t_f (correlated) and the two co-ordinates of the stroke location. Such events are generated, as above mentioned, assuming the statistical lognormal distributions of current peak and front time of both Table III and Table IV; the stroke locations are uniformly distributed within the earlier mentioned surface around the line (see [25,27] for further details). As we are calculating the indirect lightning performance of the line, all the events corresponding to direct strokes are disregarded.

For each event the lightning-induced voltages on the line are calculated by means the LIOV code [29-31].[4]

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[3] At least for most of lightning current amplitudes [12].

[4] The LIOV code has been developed in the framework of an international collaboration involving the University of Bologna (Department of Electrical Engineering), the Swiss Federal Institute of Technology (Power Systems Laboratory), and the University of Rome "La Sapienza" (Department of Electrical Engineering). It is based on the field-to-transmission line coupling formulation of *Agrawal* et al. [32], suitably adapted for the case of an overhead line above a lossy ground illuminated by an indirect lightning electromagnetic field; the LEMP is calculated by assuming the MTLE return-stroke engineering model [33,34] and using the Cooray-Rubinstein formula [35,36] to take into account the finite value of the ground resistivity in the

The lightning performance of the line is calculated by using the different lateral distance expressions of Tables I and II, relevant to distribution lines, in order to distinguish between direct and indirect strokes. The results obtained by using the parameters of Table III are shown in Figs. 2 and 4 and those obtained by using the parameters of Table IV are shown in Figs. 3 and 5. Results of Figs. 2 and 3 refer to the case of perfectly conducting ground plane, while those of Figs. 4 and 5 refer to the case of a ground with conductivity equal to 0.001 S/m. It can be observed that the application of the modified current statistical distributions results, as expected, in a better performance of the distribution line to indirect lightning strokes, being these distributions characterized by a lower median value. Additionally, it is shown that the results differ very much depending on the expression adopted to evaluate the lateral distance.

VII. CONCLUSIONS

In this paper we have proposed a procedure, based on the Monte Carlo method, that allows to infer the statistical distributions of lightning current parameters (peak amplitude, front time, etc.) at ground level, starting from those obtained from measurements using tall instrumented towers. The procedure is more general than others proposed in the literature for the same purpose, in that it can be applied whatever attractive radius (lateral distance) expression is assumed, and is not limited to the current peak amplitude only. The distribution of the peak amplitude at ground exhibits median values ranging from 27.4% (attractive radius expression by Eriksson) to 20.2% (attractive radius by Dellera-Garbagnati) lower than the median of the original distribution. Other exposure models (IEEE, Amstrong-Withehead and Rizk) predict median values that are within the above-mentioned range. The median values of current front times range from 15.8% to 10.5% lower than the median of the original distribution, as a consequence of the generally assumed correlation between front time values and current amplitudes.

We have also compared the indirect-lightning performance of an overhead distribution line inferred by adopting both the affected and the unaffected current amplitude statistical distributions, and have found a difference in the two cases. The performance of the line appears, however, more affected by the exposure model that is used for the determination of indirect strokes. Such a difference tends to decrease for increasing values of the ground resistivity.

The authors feel that the above conclusions should be taken into account in power systems insulation coordination practice.

VIII. ACKNOWLEDGEMENTS

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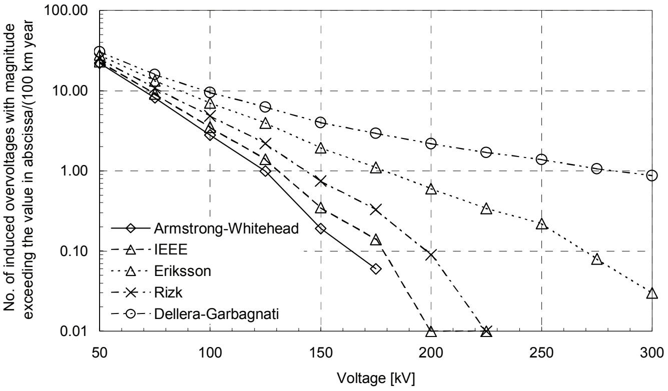

Fig. 2. Indirect-lightning performances of an overheard line above a perfectly conducting ground, by adopting the different lateral distance expression of Tables I and II and the lightning current distributions of Table III as distributions at ground.

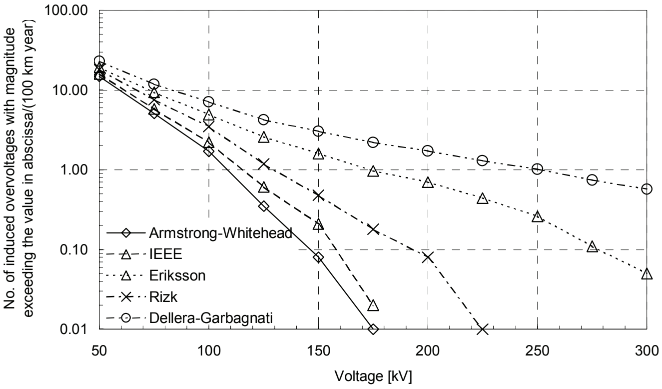

Fig. 3. Indirect-lightning performances of an overheard line above a perfectly conducting ground, by adopting the different lateral distance expression of Tables I and II and the relevant current statistical distributions at ground of Table IV.

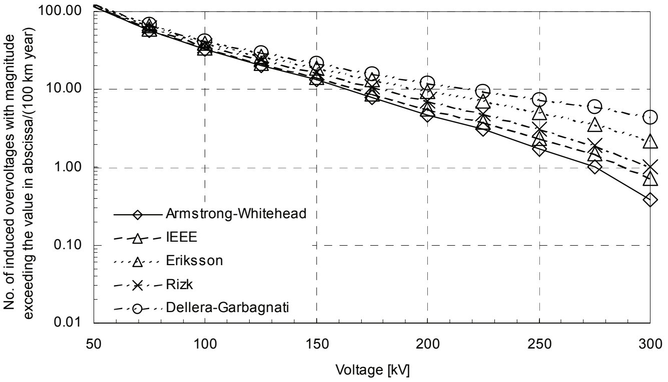

Fig. 4. Indirect-lightning performances of an overheard line above a lossy ground with conductivity equal to 0.001 S/m, by adopting the different lateral distance expression of Tables I and II and the lightning current distributions of Table III as distributions at ground.

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field calculation with correction by Cooray [37] according to the remarks by Wait [38]. Concerning the effect of the ground resistivity in the calculation of the line parameters, with particular reference to the ground transient resistance, the Carson expression [39] is used. Indeed, as in the LIOV code all above-mentioned models are implemented in the time domain, the ground transient resistance formula derived by Timotin [40] which corresponds to the Carson formula is used. Recently, the expression proposed in [41] has been introduced in the LIOV code, which corresponds to the general Sunde's expression for the ground impedance [42].

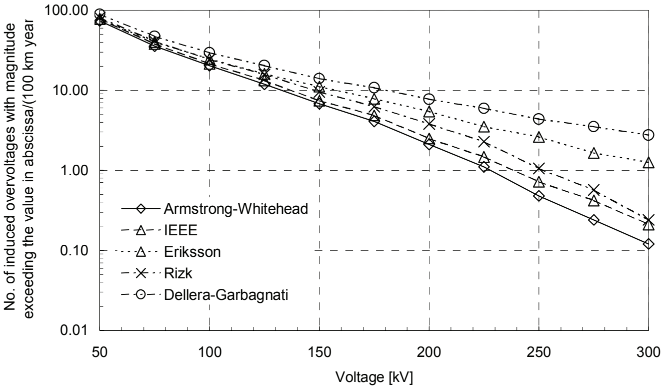

Fig. 5. Indirect-lightning performances of an overheard line above a lossy ground with conductivity equal to 0.001 S/m, by adopting the different lateral distance expression of Tables I and II and the relevant current statistical distributions at ground of Table IV.

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