Estimation of the statistical distributions of lightning current parameters at ground level from the data recorded by instrumented towers

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Outline of presentation

1. **Introduction**

   The problem

   What has been done by other Authors

2. **Numerical procedure for evaluating lightning current distributions at ground.**

   Application to the Berger's distributions and comparison with results obtained by other Authors

3. **Application of the results to the evaluation of indirect lightning performance of overhead lines (not included in Transaction paper)**

4. **Conclusions**

1.Introduction

The problem

The probabilistic approach to power insulation coordination requires the knowledge of the statistical distributions of lightning current parameters.

The lightning current distributions currently used are those derived from experimental data gathered by means of elevated instrumented towers.

The ‘*attractive radius*’ *r* of the tower tends to increase for flashes with larger currents

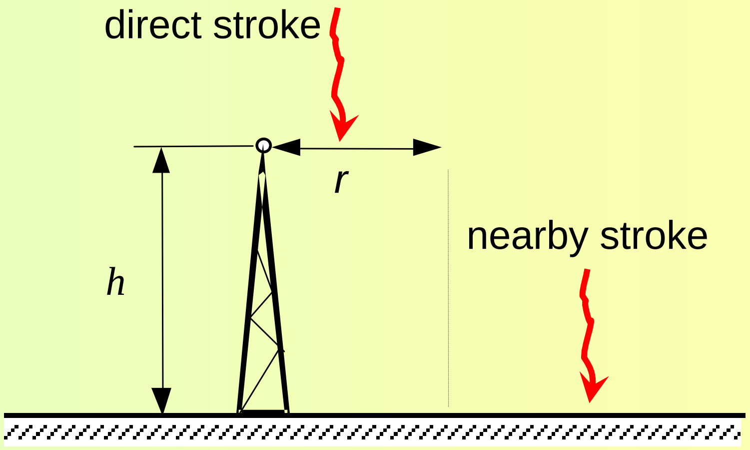
⬇

lightning current amplitudes are ‘biased’ towards higher values.

General relations between pdf of lightning peak current to a tower and at ground

$$f_t\left(I_p,h\right)=\frac{r^2\left(I_p,h\right)f_g\left(I_p\right)}{\int_0^\infty r^2\left(I_p,h\right)f_g\left(I_p\right)dI_p}$$

(Whitehead and Brown, 1969)



The problem is to determine f_g being f_t and h known

General relations between pdf of lightning peak current to a tower and at ground

$$f_t\left(I_p,h\right)=\frac{r^2\left(I_p,h\right)f_g\left(I_p\right)}{\int_0^{\infty} r^2\left(I_p,h\right)f_g\left(I_p\right)dI_p}$$

(Whitehead and Brown, 1969)

Figure 18.5: Lightning initiated by an upward-moving leader from a tower on Mt. San Salvatore near Lugano, Switzerland. Photographs of other discharges to the tower are shown in Fig. 6.1a, b. (Courtesy, Richard E. Orville, State University of New York at Albany)

We shall **disregard current reflections at tower top and base**, although they can certainly alter the measured current (e.g. *Guerrieri* et al, IEEE Trans. PWDR, 1998; *Rachidi* et al., JGR, 2003) and **we shall focus on downward discharges, assuming them perpendicular to flat ground**.

Studies performed by other Authors

The problem has been studied by several Authors, e.g:

Sargent [IEEE Trans PAS, Sept/Oct 1972], by using an attractive-radius three-dimensional electrogeometric model and on the basis of the lightning current amplitude experimental data available at that time, derived a so-called synthetic current amplitude distribution to ground level, which, as shown by ***Brown*** [IEEE Trans PAS, Sept/Oct 1972], can be approximated by a lognormal distribution with μ_g =13 kA and σ_g =0.32.

Mousa and Srivastava [IEEE Trans. PWDR,1989], have proposed a lognormal distribution of current amplitudes at ground level with μ_g =24 kA and σ_g =0.31.

Other forms of distribution have been investigated for the problem of interest by ***Chisholm*** et al. [*Proc. 1st PMAPS*, Toronto, Canada, 11-13 July 1986.

Here we shall focus on the analytical formula derived by ***Pettersson*** (see later).

Exposure of a tower to direct lightning

Lightning leader approaching ground: downward motion unperturbed unless critical field conditions develop → juncture with the nearby tower, called *final jump*.

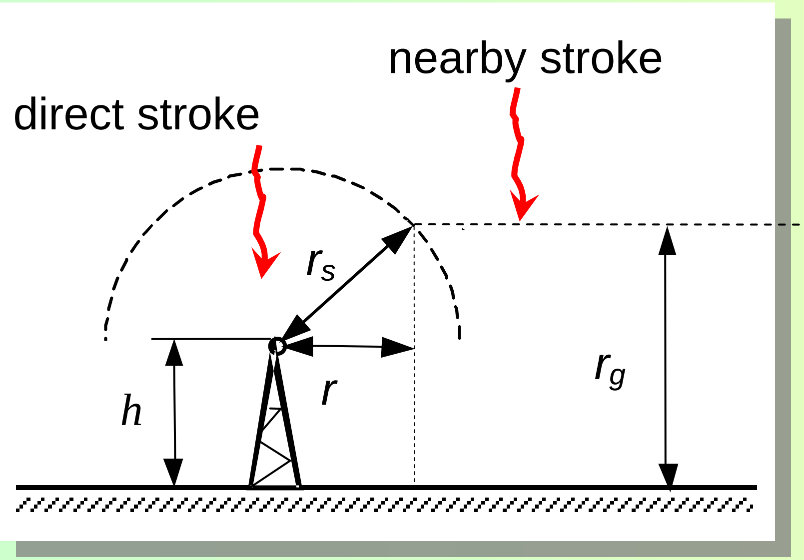
Assuming leader channel perpendicular to the ground plane → the flash will stroke the tower if its *prospective* ground termination point, lies within the *attractive radius r*.

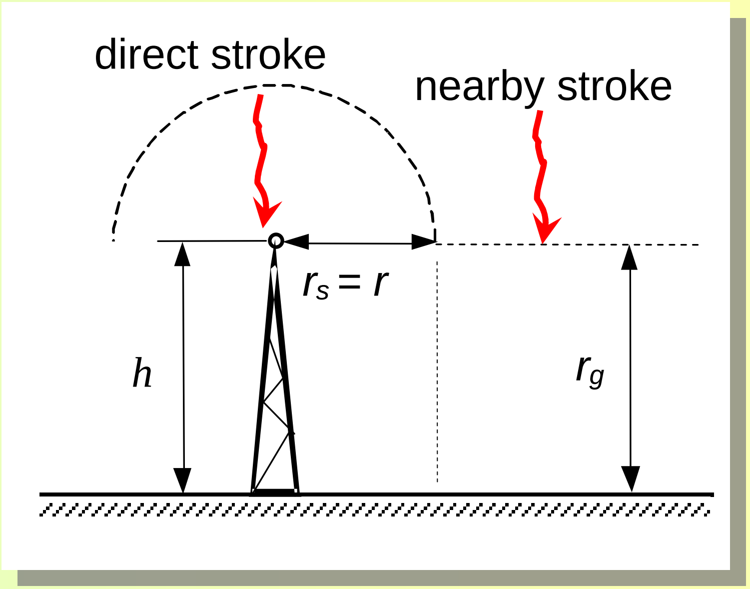
r depends on several factors, such as

- charge of the leader,
- its distance from the structure,
- type of structure (vertical mast or horizontal conductor),
- structure height,
- nature of the terrain (flat or hilly)
- ambient ground field due to cloud charges.

Several expressions have been proposed to evaluate such a radius. Some of them are based on the *electrogeometric model*.

Electrogeometrical expressions describing the exposure of a tower to direct lightning





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

$$r = r_s \qquad \text{for } h \geq r_g$$

Where r_s and r_g are the so called '*striking distances*' to the structure and to ground respectively.

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

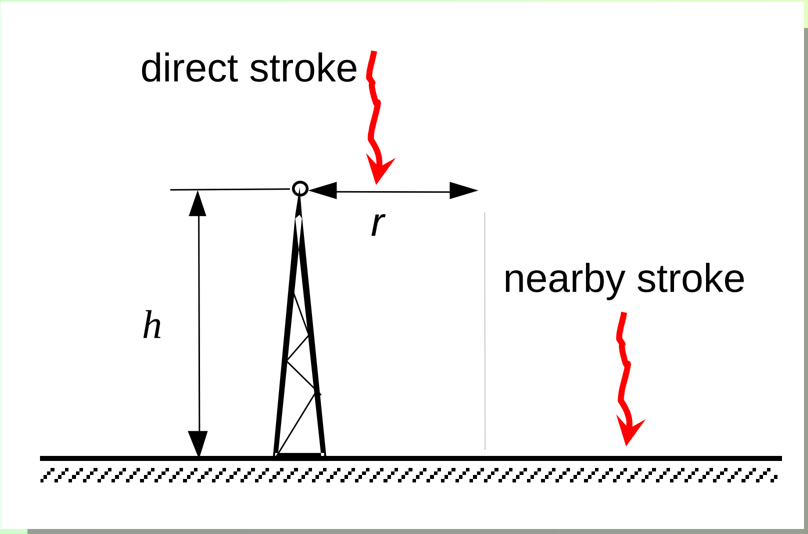
Electrogeometrical expressions describing the exposure of a tower to direct lightning

Electrogeometrical Attractive radius expression	α	β	k
Armstrong and Whitehead	6.7	0.80	0.9
IEEE	10	0.65	0.55

$$r_s = \alpha \cdot I_p^{\beta}$$

$$r_g = k \cdot r_s$$

Other expressions describing the exposure of a tower to direct lightning



They have been inferred, by regression analysis, from the results of more complex and physically-oriented models than the Electrogeometric one.

A formula of the following type can be used

$$r = c + a \cdot I_p^b$$

Model	c	a	b
Eriksson	0	0.84 $h^{0.6}$	0.76
from Rizk	0	2.83 $h^{0.4}$	0.63
from Dellera-Garbagnati *	3h0.6	0.80	0.9

* The values reported have been derived by M. Bernardi, 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

Studies performed by other Authors *Cont.*

Analytical relation between pdf of lightning peak current to a tower and at ground

We now focus on the analytical formula derived by ***Petterson*** [IEEE Trans. PWDR,1991]

1st hypothesis:

$$r\left(I_p,h\right)=a\cdot I_p^b$$

2nd hypothesis:

$$f_g\left(I_p\right)=\frac{1}{I_p\sigma_g}\frac{1}{\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{1}{\sigma_g}\ln\left(I_p/\mu_g\right)\right)^2\right]=\frac{1}{I_p\sigma_g}\phi\left[\frac{1}{\sigma_g}\ln\left(I_p/\mu_g\right)\right]$$

$$f_t\left(I_p,h\right)=\frac{r^2\left(I_p,h\right)f_g\left(I_p\right)}{\int_0^\infty r^2\left(I_p,h\right)f_g\left(I_p\right)dI_p}=\frac{a^2}{\int_0^\infty r^2\left(I_p,h\right)f_g\left(I_p\right)dI_p}I_p^{2b}\frac{1}{I_p\sigma_g}\phi\left[\frac{1}{\sigma_g}\ln\left(I_p/\mu_g\right)\right]$$

$$\exp(2b\ln I_p)$$

Studies performed by other Authors *Cont.*

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$f_t\left(I_p,h\right)$ is lognormal

$$\mu_t=\mu_g\left[\exp\left(b\cdot\sigma_g^2\right)^2\right] \qquad \sigma_g=\sigma_t$$

Pettersson's formula

2. Numerical procedure for evaluating lightning current distributions at ground.

Proposed numerical procedure for evaluating lightning current distributions at ground

I_p* minimum peak current observed
r* its attractive radius

All the strokes with perspective stroke location within $2\pi r^{*2}$ are collected by the tower

I. Generation of a population of events $I_p, t_f, \ldots$ and $x_g \in [0, r(I_p)]$
- $I_P, t_f \ldots$ are generated from the p.d.f. of strokes to the tower
- x_g are generated assuming the stroke locations be uniformly distributed (correlations are taken into account)

II. Selection of the events with $x_g < r^*$

III. Determination of the statistical distributions of the current parameters related to such events

Application to the Berger's distribution

TABLEAU 1 – *TABLE 1*

Résumé des paramètres du front
Summary of front shape parameters

Paramètre *Parameter*	N *N*	Unités *Units*	Approximation par une distribution log-normale *Approximation by log-normal distribution*			Pourcentage de cas où la valeur du tableau est dépassée *Percent of cases exceeding tabulated value*		
			μ	σ log	Test positif *Positive test*	95 %	50 %	5 %
Décharges principales *First stroke*								
T-10	80	μs	4,5	0,25	non no	1,8	4,5	11,3
T-30	80	μs	2,3	0,24	oui yes	0,9	2,3	5,8
TAN-10	75	kA/μs	2,6	0,40	non no	0,6	2,6	11,8
S-10	75	kA/μs	5,0	0,28	oui yes	1,7	5,0	14,1
S-30	73	kA/μs	7,2	0,27	oui yes	2,6	7,2	20,0
TAN-G	75	kA/μs	24,3	0,26	oui yes	9,1	24,3	65,0
PEAK-1	75	kA	27,7	0,20	oui yes	12,9	27,7	59,5
PEAK	80	kA	31,1	0,21	non no	14,1	31,1	68,5
RATIO (P-1)/P	–	–	0,9	0,10	–	–	–	–
Décharges secondaires *Subsequent strokes*								
T-10	114	μs	0,6	0,40	non no	0,1	0,6	2,8
T-30	114	μs	0,4	0,44	non no	0,1	0,4	1,8
TAN-10	108	kA/μs	18,9	0,61	oui yes	1,9	18,9	187,4
S-10	114	kA/μs	15,4	0,41	oui yes	3,3	15,4	72,0
S-30	114	kA/μs	20,1	0,42	oui yes	4,1	20,1	98,5
TAN G	113	kA/μs	39,9	0,37	oui yes	9,9	39,9	161,5
PEAK-1	114	kA	11,8	0,23	oui yes	4,9	11,8	28,6
PEAK	114	kA	12,3	0,23	oui yes	5,2	12,3	29,2
RATIO (P-1)/P	–	–	0,9	0,09				

Remarque : Dans chaque cas, les distributions sont exprimées en base 10.

Note : *In each case, the above log-normal distributions are expressed in terms of the base 10.*

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27,7

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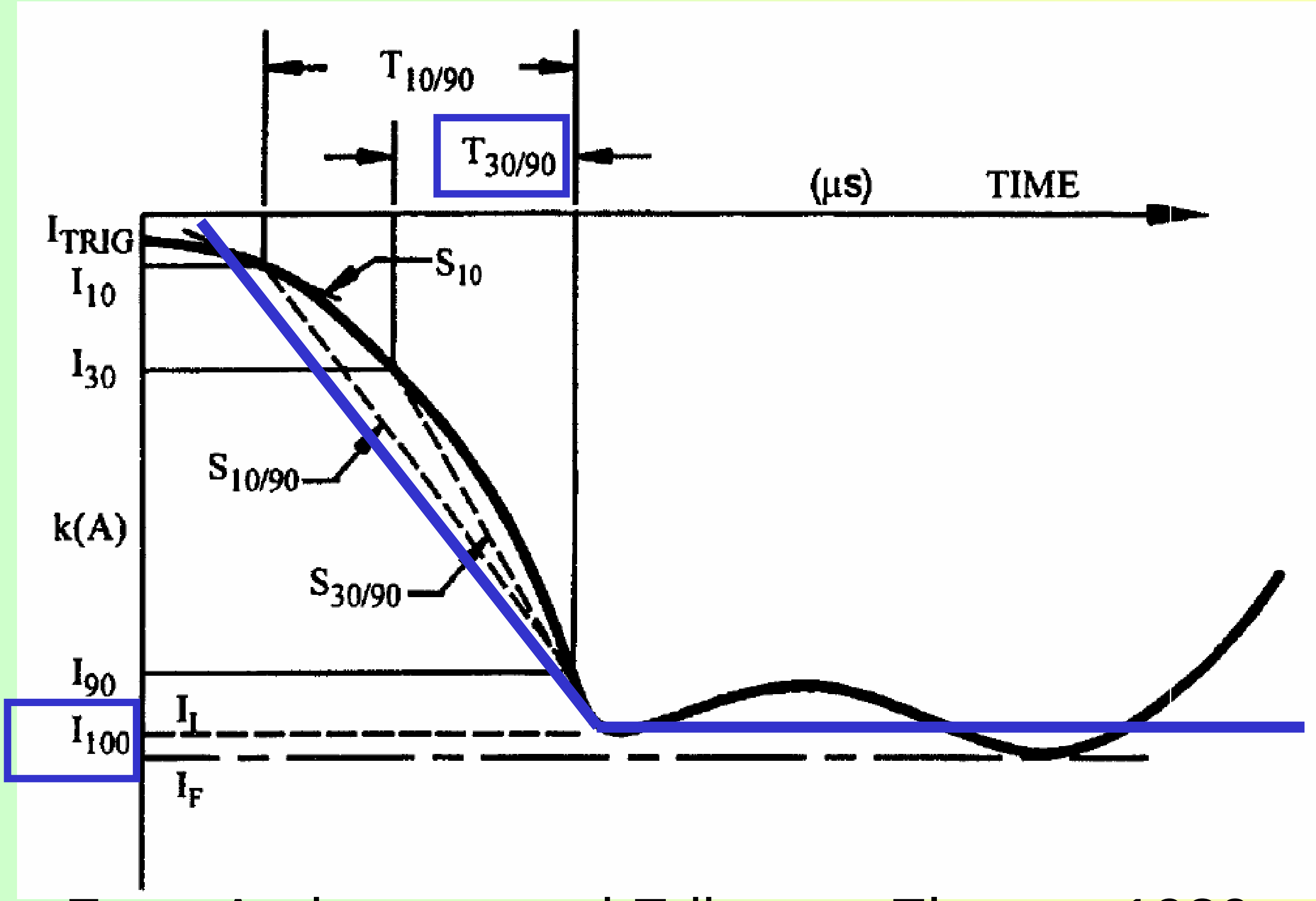
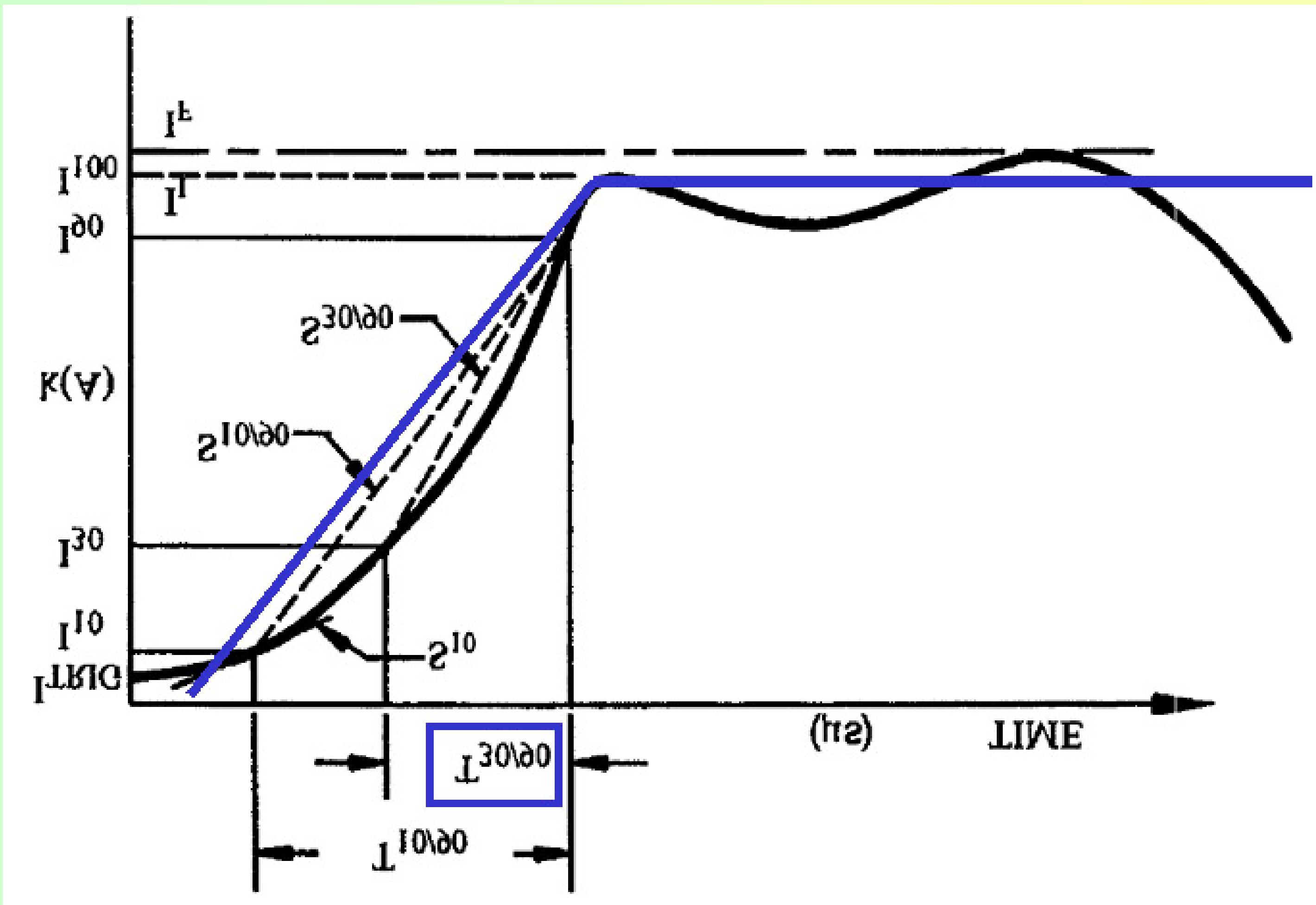
Application to the Berger's distribution *Cont*

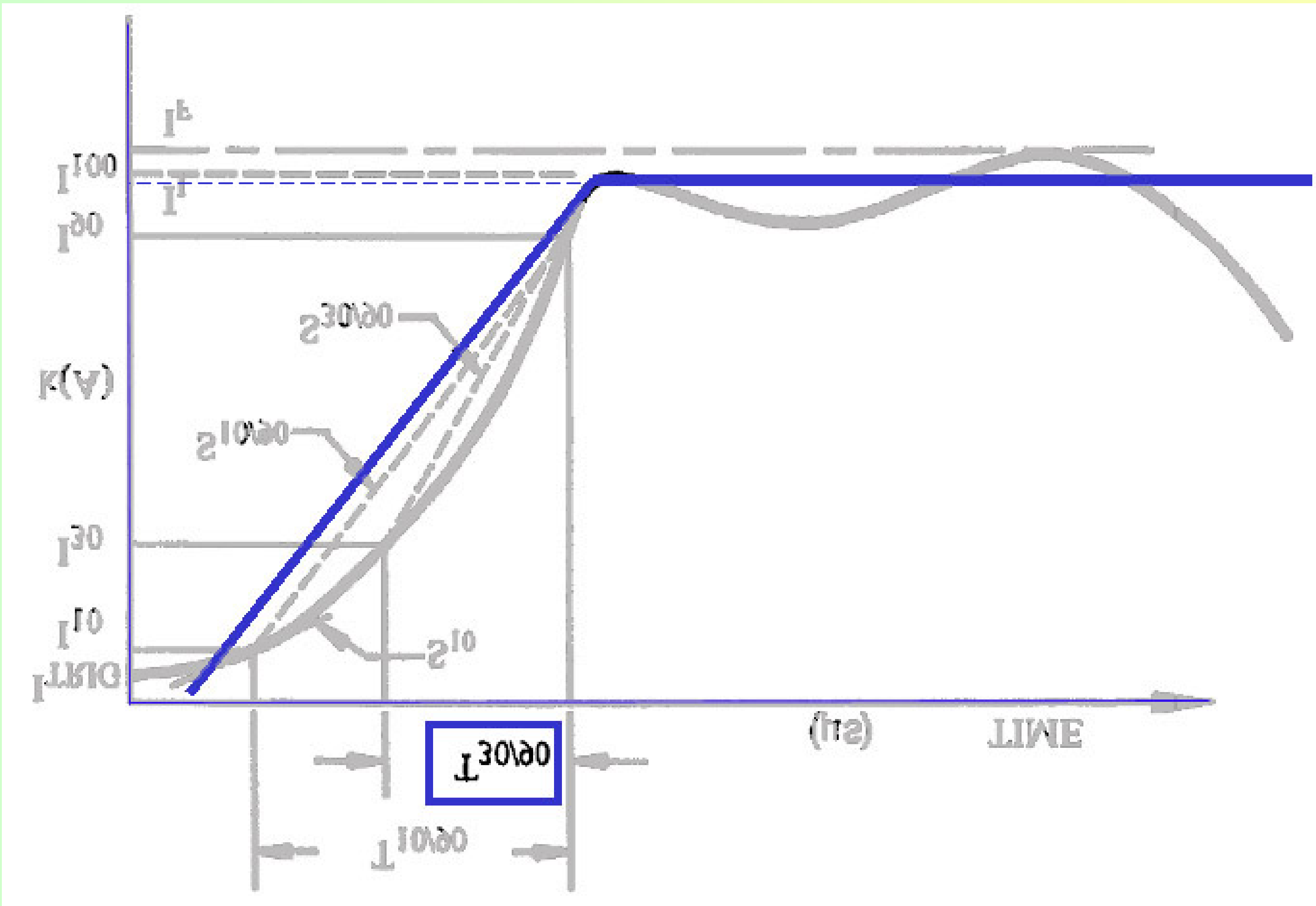


From Andersson and Eriksson, Electra , 1980

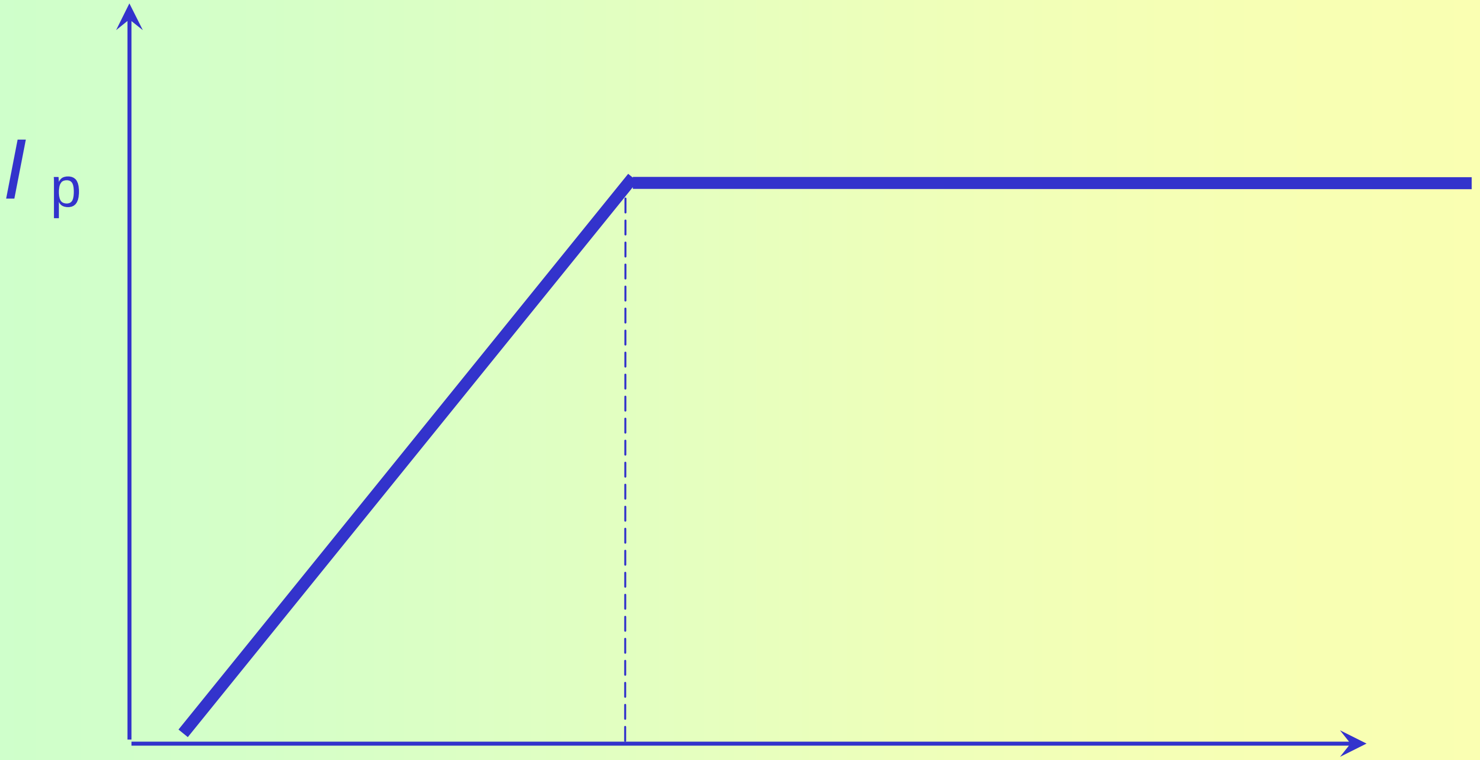
Application to the Berger's distribution *Cont*



Application to the Berger's distribution *Cont*



Application to the Berger's distribution *Cont*



$$t_f = T_{30/90} / 0.6 = \mathbf{3{,}8}$$

Application to the Berger's distribution *Cont*

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

$$\rho_t = 0.47$$

Attractive radius expression $r(I_p,h) = a \cdot I_p^b$	a	b
Eriksson	$0.84\ h^{0.6}$	0.76
Rizk	$2.83\ h^{0.4}$	0.63

Parameter		Expression	
		Eriksson	Rizk
I_p *(kA)*	μ_g	20.1	21.3
	σ_g	0.20	0.20
t_f *(μs)*	μ_g	3.2	3.3
	σ_g	0.24	0.24
	ρ_g	0.48	0.47

Application to the Berger's distribution *Cont*

Parameter	μ_t	σ_t
First Peak I_p (kA)	27.7	0.20
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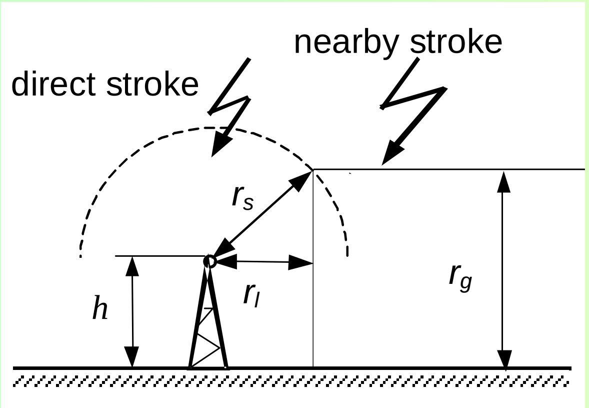
Pettersson's formula

$$\mu_t = \mu_g \left[\exp\left(b \cdot \sigma_g^2 \right)^2 \right]$$

$$\sigma_g = \sigma_t$$

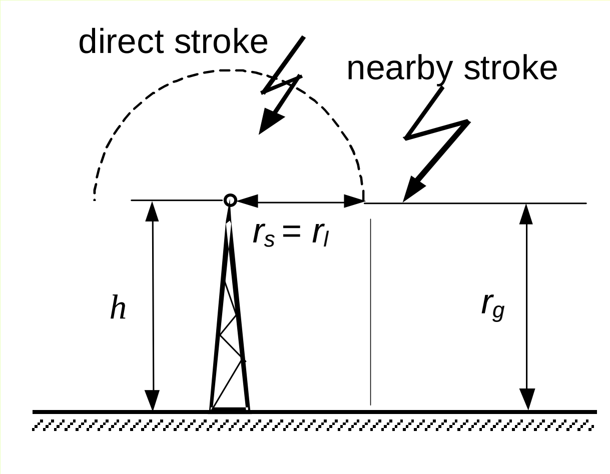
Parameter		Expression	
		Eriksson	Rizk
I_p (kA)	μ_g	20.1 20.0	21.3 21.2
	σ_g	0.20 0.20	0.20 0.20
t_f (μs)	μ_g	3.2	3.3
	σ_g	0.24	0.24
	ρ_g	0.48	0.47

Comparison with the Pettersson's formula for the case of electrogeometric expressions



$$r_s = \alpha \cdot I_p^{\beta}$$

$$r_g = k \cdot r_s$$



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

$$r = r_s \qquad \text{for } h \geq r_g$$

$$r\left(I_p, h\right) = a \cdot I_p^b$$

If $h \geq r_g$ $\Rightarrow$ $b = \beta$

or $h << r_g \quad \text{and} \quad r_g = r_s$ $\Rightarrow$ $r = \sqrt{2\alpha h} \cdot I_p^{\beta/2}$ $\quad b = \dfrac{\beta}{2}$

Application to the Berger's distribution *Cont*

Parameter	μ_t	σ_t
First Peak I_p (kA)	27.7	0.20
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$$\rho_t = 0.47$$

Electrogeometrical Attractive radius expression	α	β	k
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IEEE (1243)	10	0.65	0.55

Parameter		Expression	
		A&W	IEEE
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	σ_g	0.21	0.20
t_f (μs)	μ_g	3.2	3.3
	σ_g	0.24	0.24
	ρ_g	0.49	0.47

Application to the Berger's distribution *Cont*

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Electrogeometrical Attractive radius expression	α	β	*k*
Armstrong and Whitehead	6.7	0.80	0.9
IEEE	10	0.65	0.55

Parameter		Expression					
		A&W			IEEE		
I_p *(kA)*	μ_g	20.2	b= β /2 23.4	b=β 19.7	21.1	b= β /2 24.1	b=β 21.0
	σ_g	0.21	0.20	0.20	0.20	0.20	0.20
Probability that conditions are verified			4.2%	28.8%		0.02%	80%

Application to the Berger's distribution *Cont*

Parameter	μ_t	σ_t
First Peak I_p (kA)	27.7	0.20
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$$\rho_t = 0.47$$

Attractive radius expression $r(I_p, h) = c + a \cdot I_p^b$	*c*	*a*	*b*
From Dellera & Garbagnati	3h0.6	0.80	0.9

Parameter		Dellera & Garbagnati Expression
I_p *(kA)*	μ_g	22.1
	σ_g	0.19
t_f *(μs)*	μ_g	3.4
	σ_g	0.24
	ρ_g	0.45

Application to the Berger's distribution *Cont*

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

$$\rho_t = 0.47$$

Attractive radius expression $r(I_p, h) = c + a \cdot I_p^b$	*c*	*a*	*b*
From Dellera & Garbagnati	3h0.6	0.80	0.9

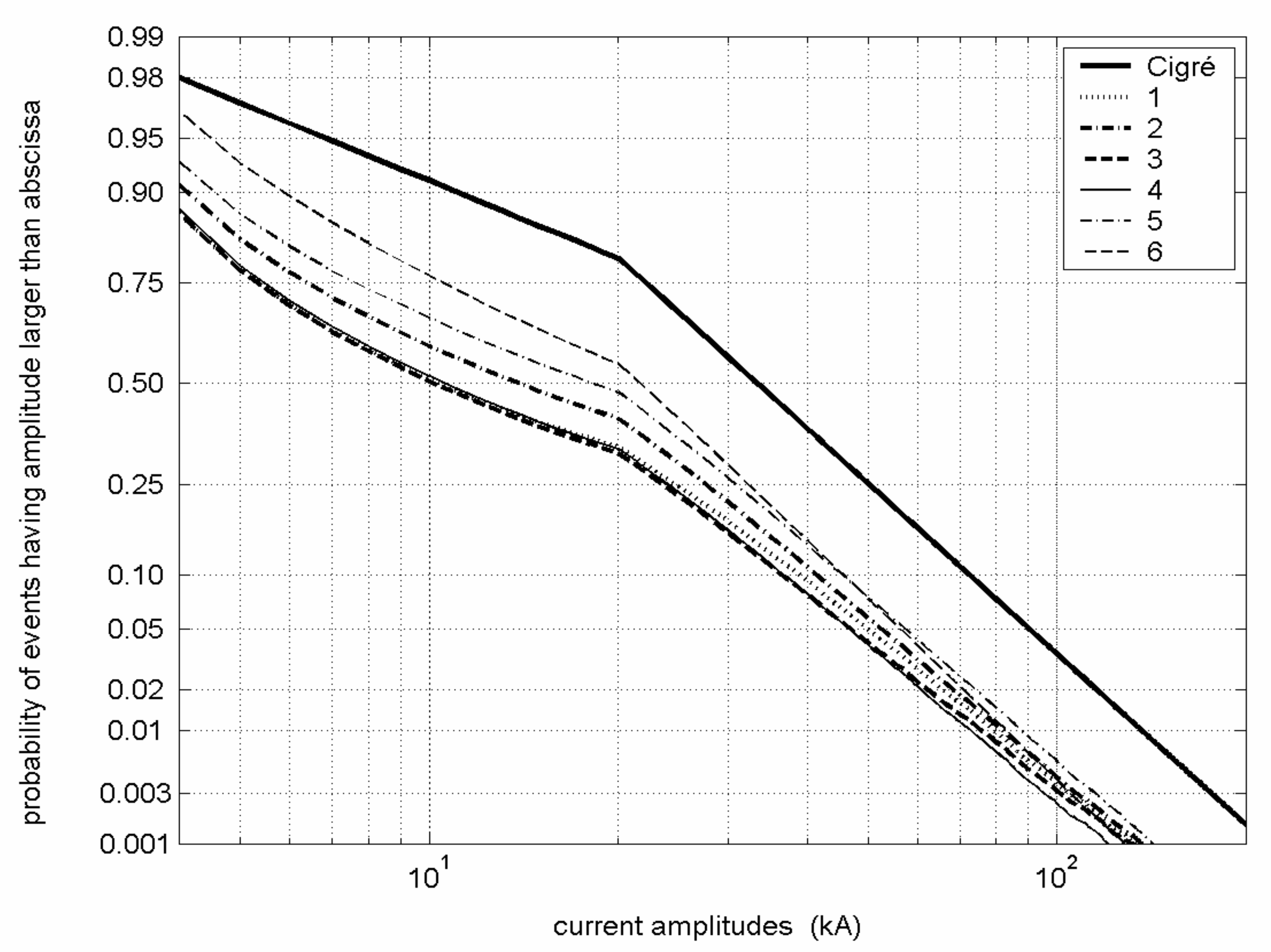
Pettersson's formula

$$\mu_t = \mu_g \left[\exp\left(b \cdot \sigma_g^2 \right)^2 \right]$$

$$\sigma_g = \sigma_t$$

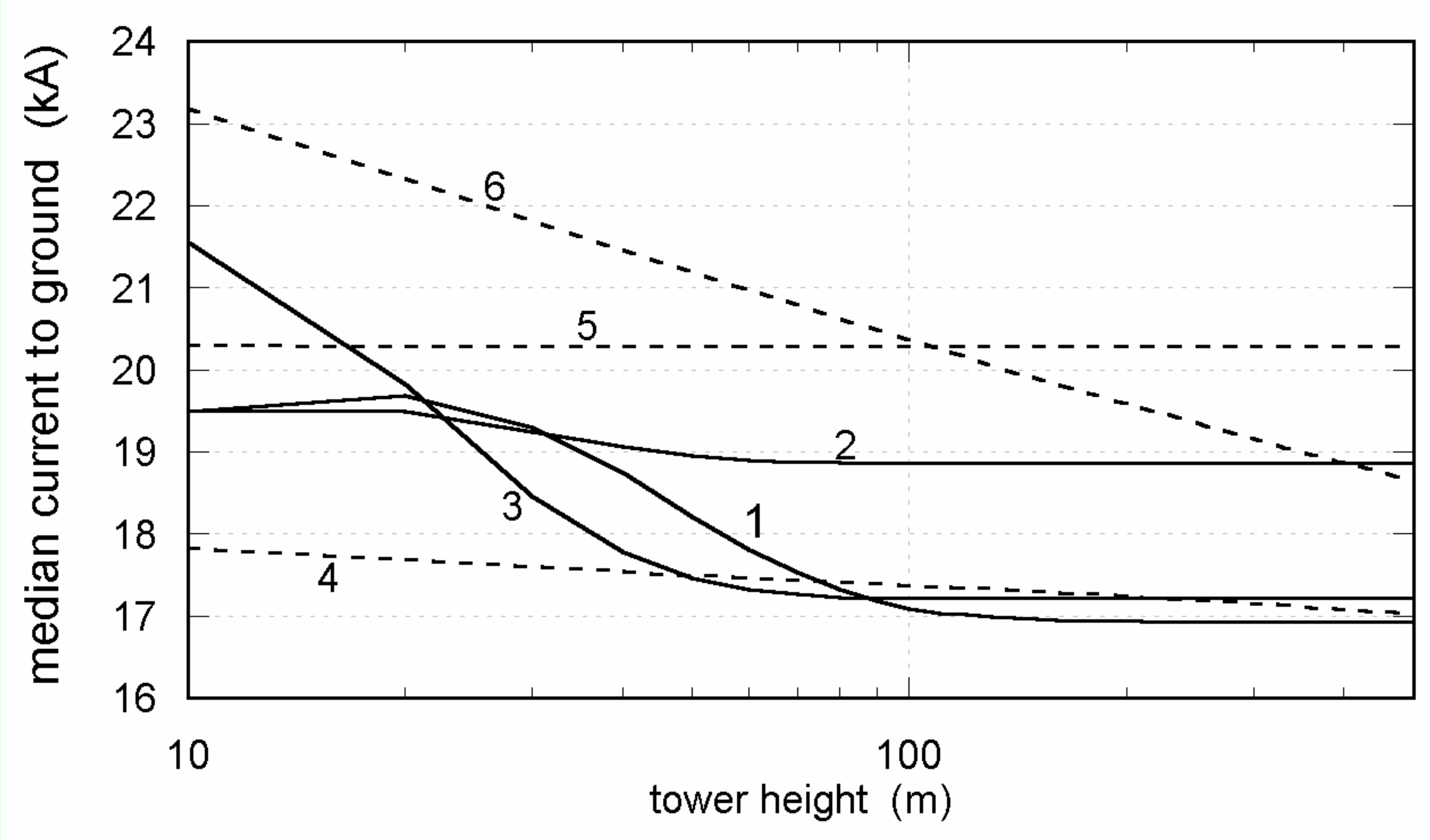
Parameter		Dellera & Garbagnati Expression
I_p *(kA)*	μ_g	22.1 18.1
	σ_g	0.19 0.20
t_f *(μs)*	μ_g	3.4
	σ_g	0.24
	ρ_g	0.45

Application to the CIGRE distribution



1: AW; 2: IEEE 4: Eriksson; 5: from Rizk; 6: from Dellera-Garbagnati

Influence of the Tower Height



1: AW; 2: IEEE 4: Eriksson; 5: from Rizk; 6: from Dellera-Garbagnati

First Conculsions

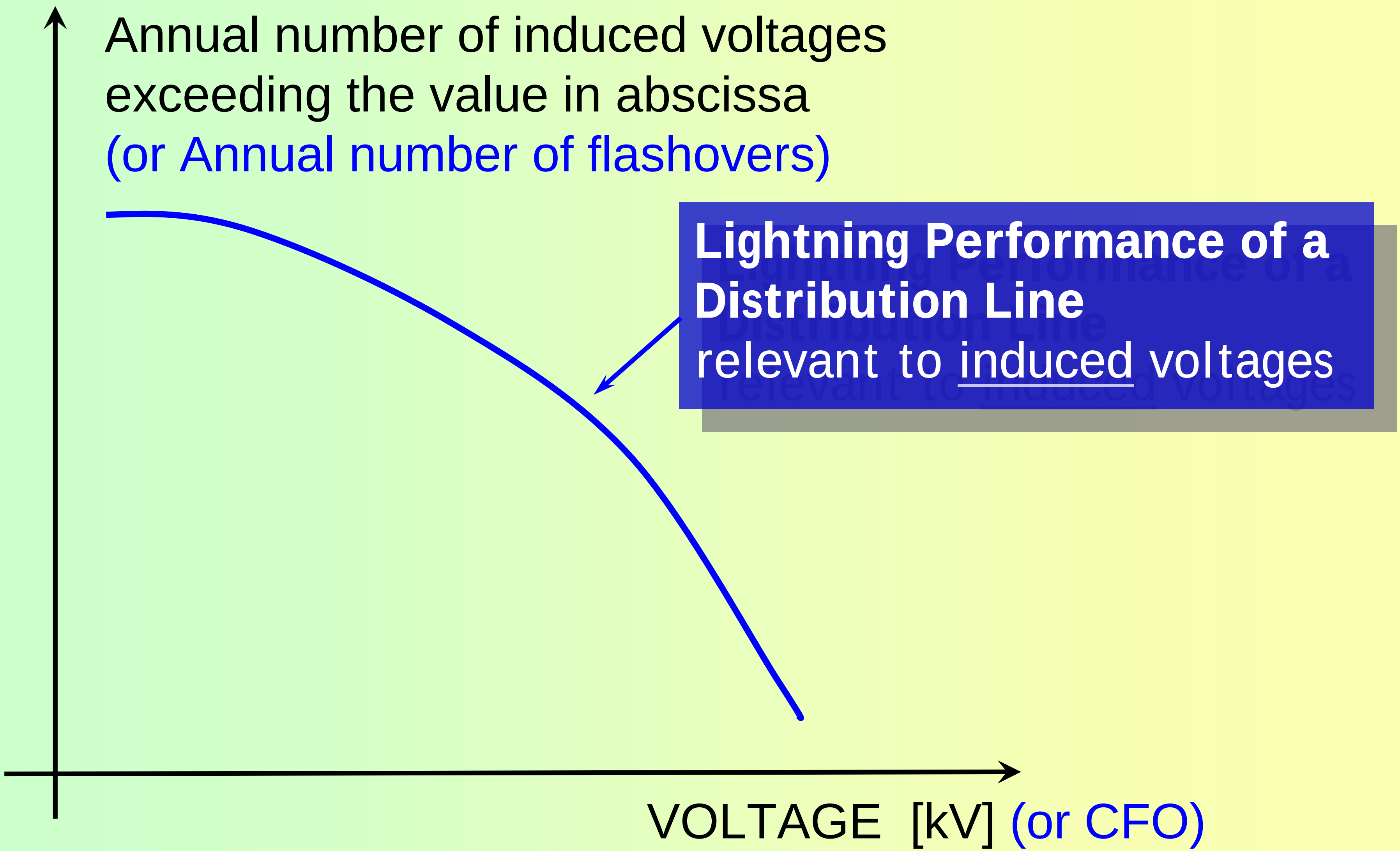
The proposed method is more general than the other proposed so far in the literature.

What are the applications?

3. Application of the results to the evaluation of indirect lightning performance of overhead lines

Application of the results to the evaluation of <u>indirect lightning performance of overhead lines</u>

The ____ is represented by the following curve:



Application of the results to the evaluation of indirect lightning performance of overhead lines *Cont.*

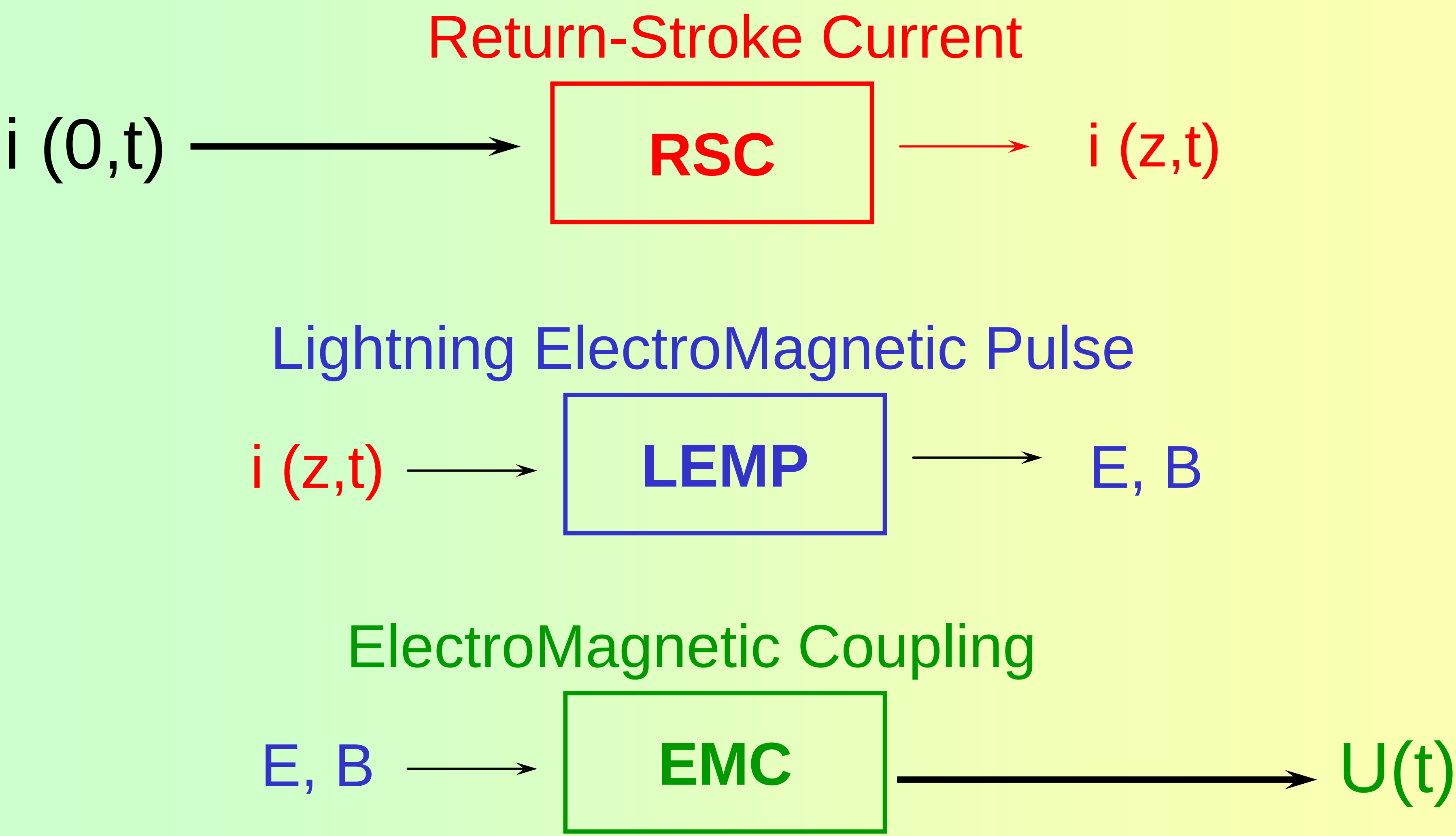
How to calculate the _____?

Application of the results to the evaluation of indirect lightning performance of overhead lines *Cont.*

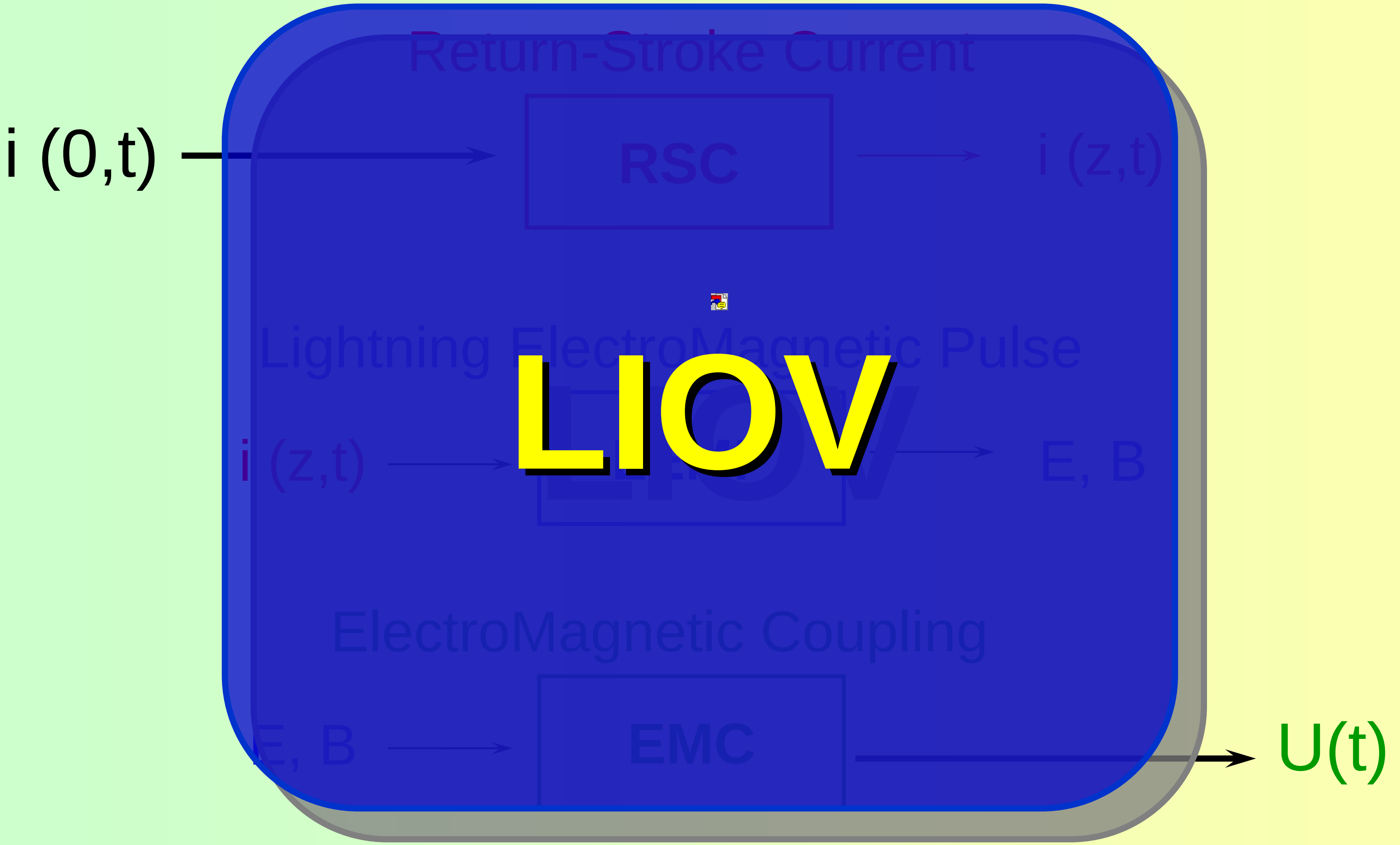
Clearly, the ___ depends on:

- models used to calculate the induced voltages
- lateral distance expression
- statistical distribution of lightning parameters

Models used to calculate the induced voltages



Models used to calculate the induced voltages



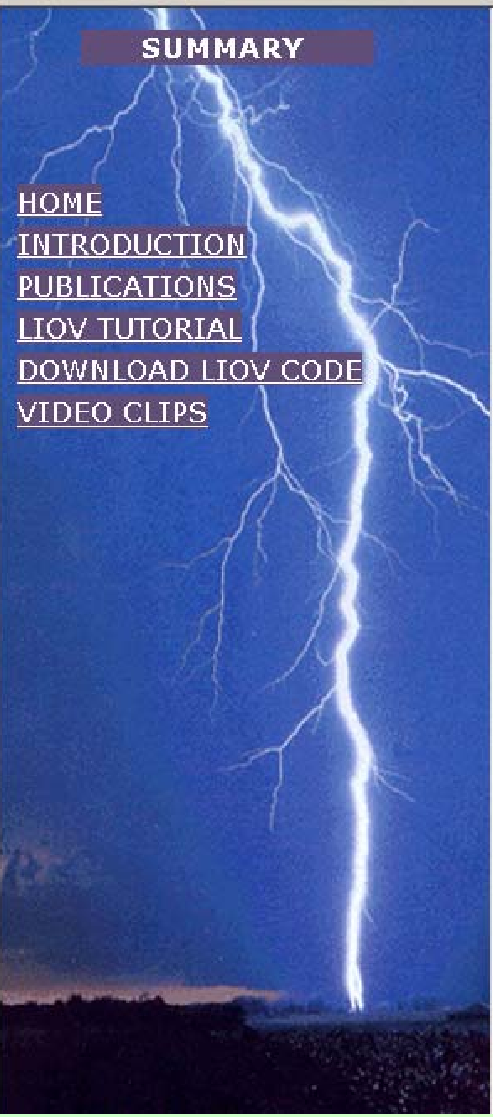
The LIOV code

LIOV web page - Microsoft Internet Explorer

File Modifica Visualizza Preferiti Strumenti ?

Indietro Cerca Preferiti Cronologia

Indirizzo http://www.ing.unibo.it/die/liov/



ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Lightning Induced Over Voltage Code

developed by

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www.ing.unibo.it/die/liov

LIOV code

Models

- Return-stroke model: MTLE (and TL)
- LEMP: Uman and McLain and Cooray-Rubinstein
- Coupling model: Agrawal extended to the case of lossy ground

This allows to take into account **more realistic line configurations** than the simplified Rusck expression

The Agrawal coupling model

$$\frac{\partial}{\partial x} v_i^s(x,t) + L'_{ij} \frac{\partial}{\partial t} i_i(x,t) + \int_0^t \xi'_g(t-\tau) \frac{\partial i(x,\tau)}{\partial \tau} = E_x^i(x,t,h)$$

$$\frac{\partial}{\partial x} i_i(x,t) + C'_{ij} \frac{\partial}{\partial t} v_i^s(x,t) = 0$$

Transmission line coupling equations

(Agrawal et al.)

Overhead line above lossy ground

The Agrawal coupling model

$$\frac{\partial}{\partial x} v_i^s(x,t) + L'_{ij} \frac{\partial}{\partial t} i_i(x,t) + \boxed{\int_0^t \xi_g^{'}(t-\tau) \frac{\partial i(x,\tau)}{\partial \tau}} = \boxed{E_x^i(x,t,h)}$$

$$\frac{\partial}{\partial x} i_i(x,t) + C'_{ij} \frac{\partial}{\partial t} v_i^s(x,t) = 0$$

The ground resistivity plays a role in

1) the calculation of the line parameters

2) the calculation of the electromagnetic field

The LIOV code

The LIOV code allows for the calculation of lightning-induced voltages along a multiconductor overhead line as a function of

- lightning current waveshape (amplitude, front steepness, and duration),
- return stroke velocity,
- line geometry (height, length, number and position of conductors), values of resistive terminations,
- ground resistivity and relative permittivity.

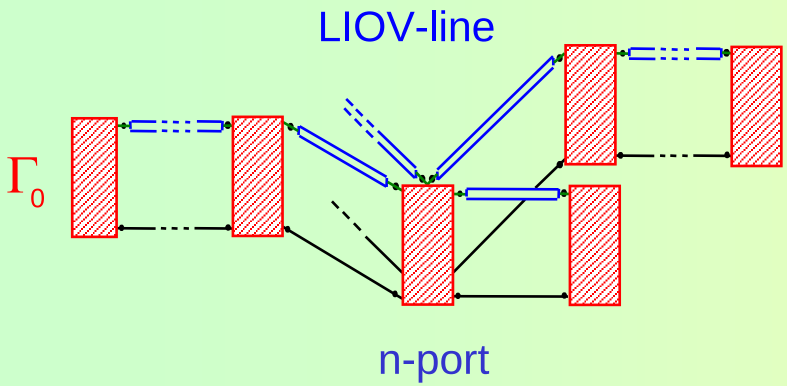
It allows also taking into account induction phenomena due to

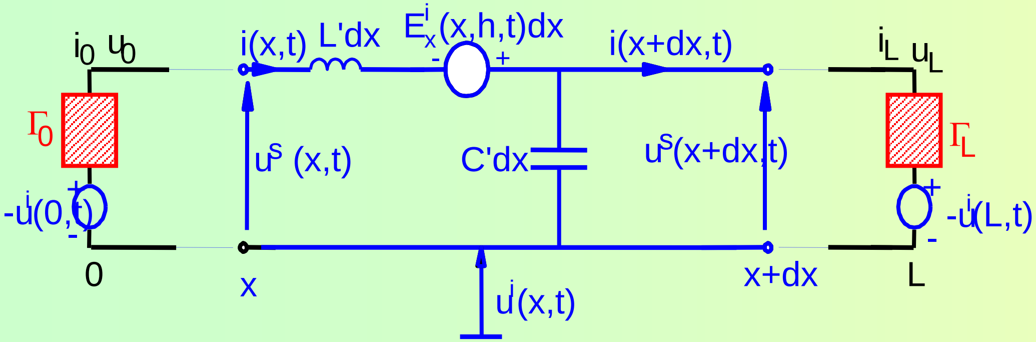
- the leader field,
- non-linear phenomena such as corona
- and the presence of surge arresters.

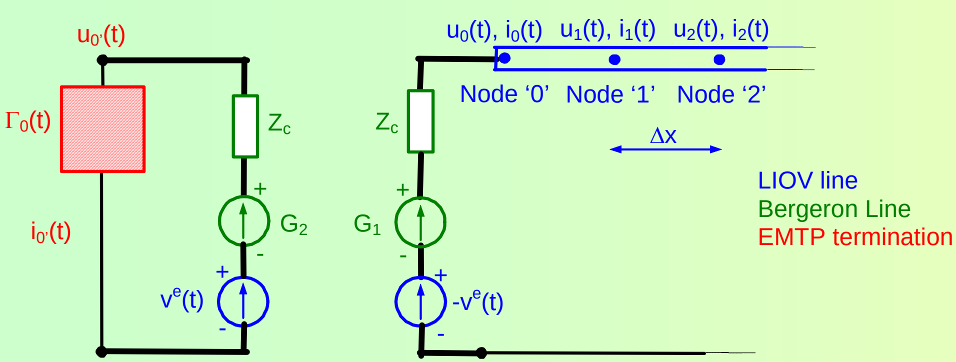
In order to take into account the presence of more complex types of terminations, as well as of line discontinuities and complex system topologies, the LIOV code has been interfaced with EMTP96.

Link of the LIOV code with EMTP96

Concept at the basis of the interface







The LIOV code calculates:

- **LEMP**
- **Coupling**

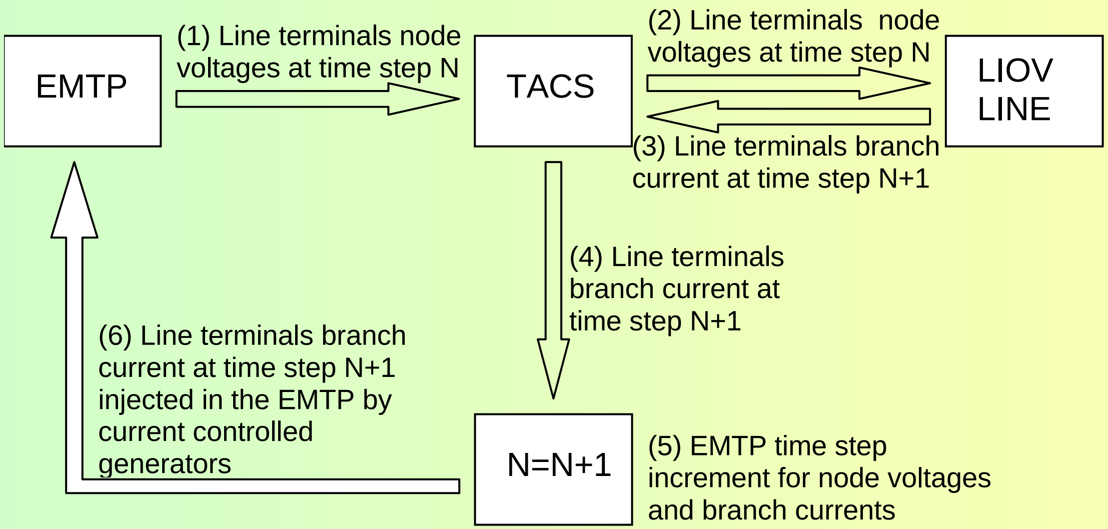
The EMTP :

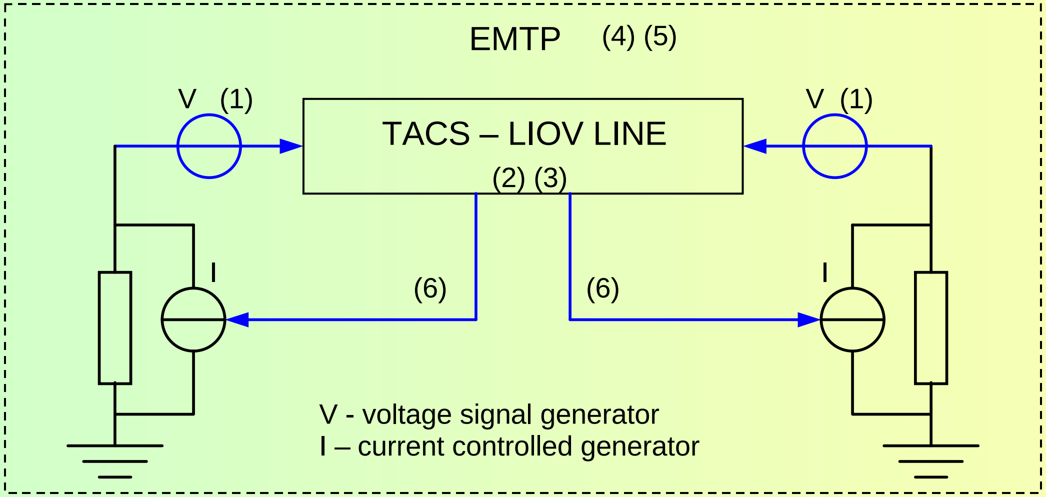
- **calculates the boundary conditions**
- **makes available a large library of power components**

Link between LIOV and EMTP

Treatment of the boundary conditions, data exchange between the LIOV code and the EMTP96:

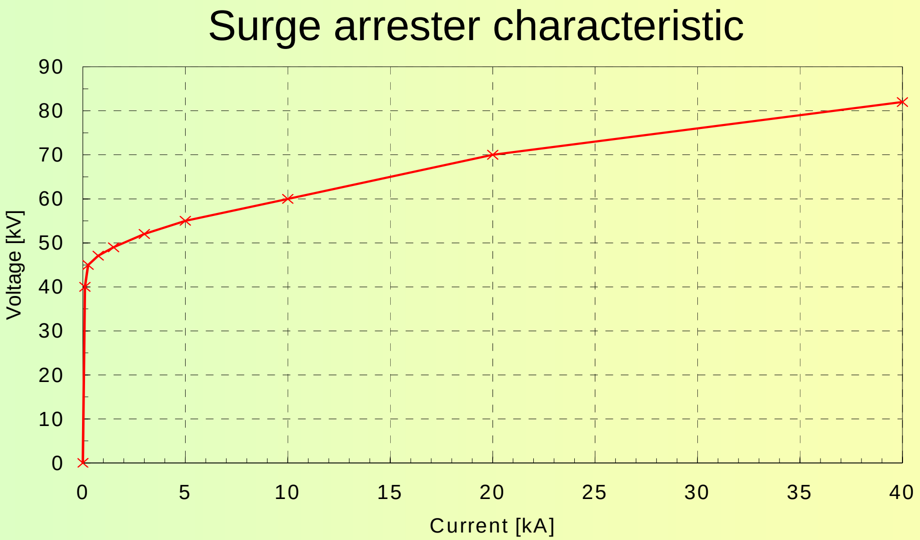
Link of the LIOV code with EMTP96



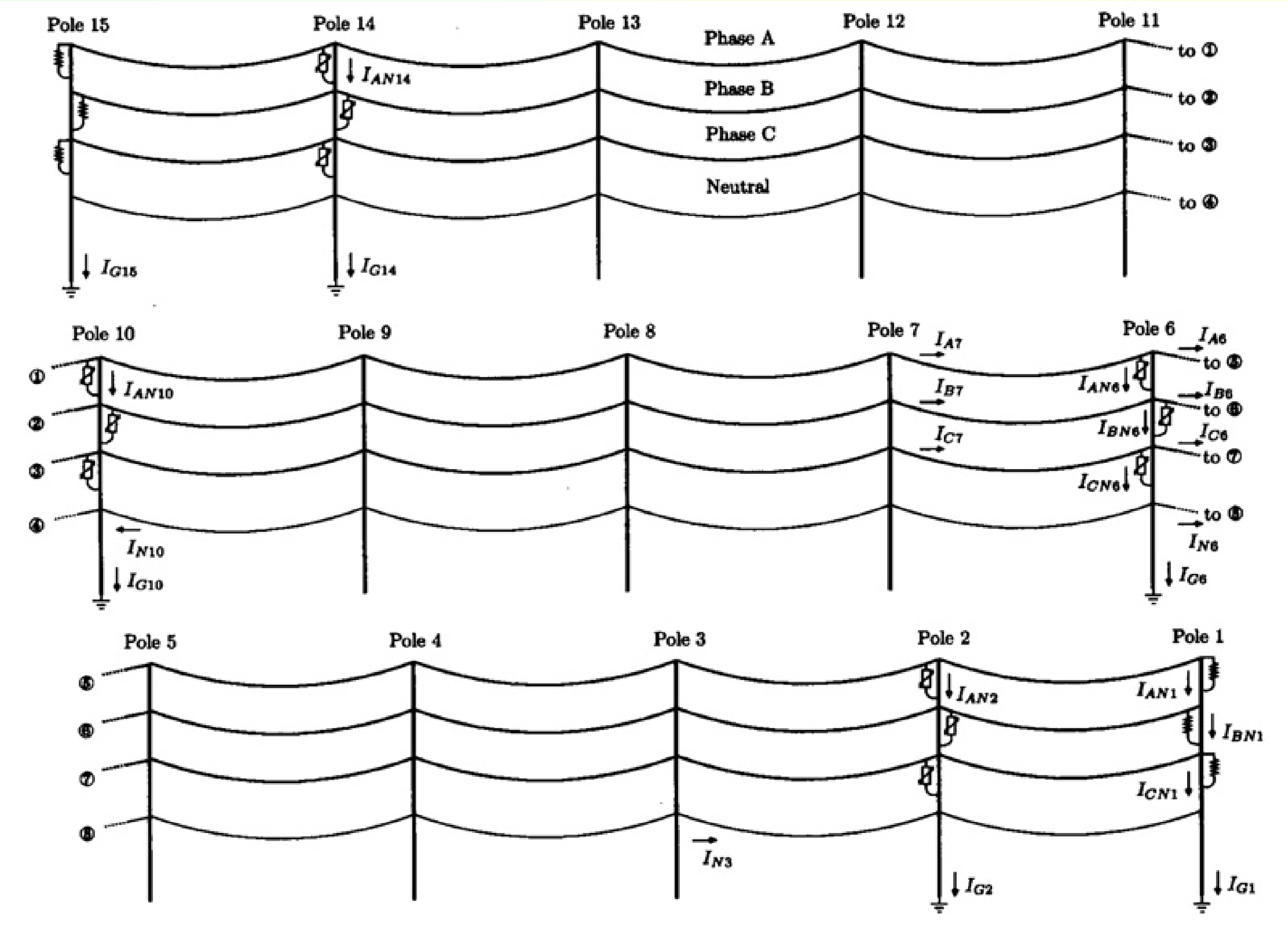


LIOV-EMTP96: simulations and comparison with experimental data *Cont.*

Comparison with data measured on real scale complex line model at the ICLRT of the University of Florida (July-August 2002/2003)

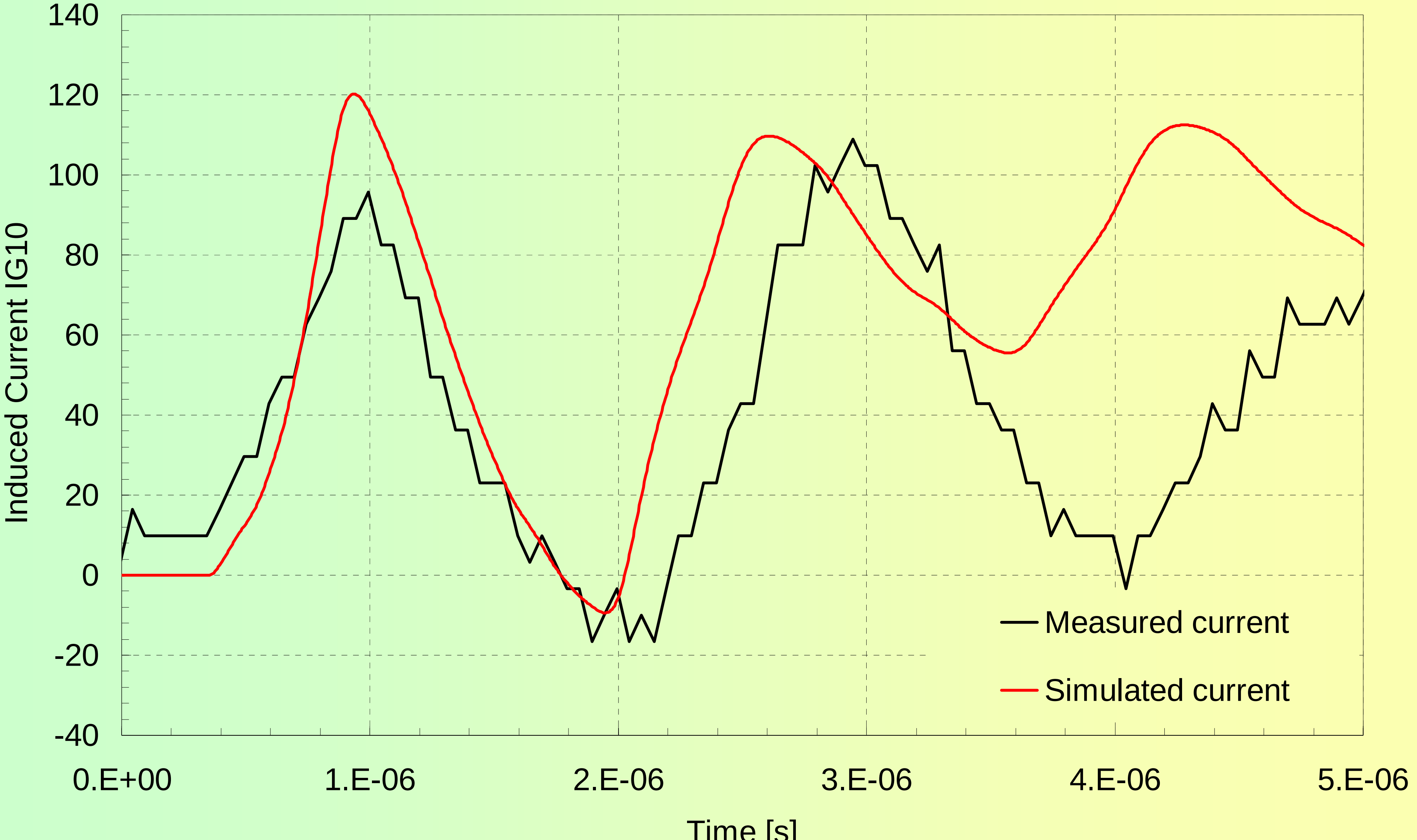


LIOV-EMTP96: simulations and comparison with experimental data *Cont.*

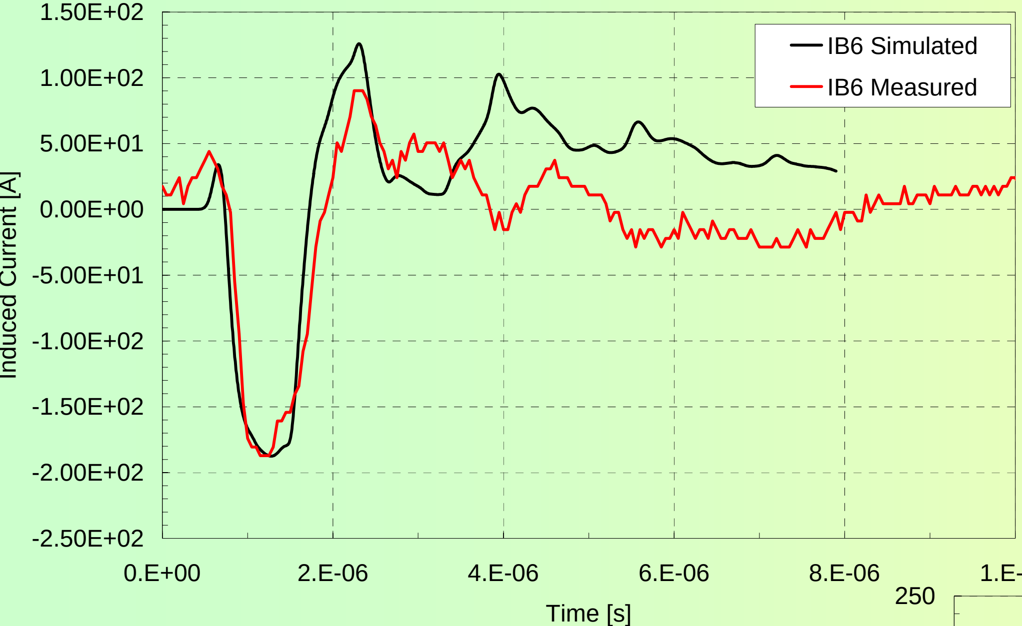


Experimental overhead distribution line installed at the ICLRT.
The indicated quantities are the measured lightning-induced currents.

LIOV-EMTP96: simulations and comparison with experimental data *Cont.*

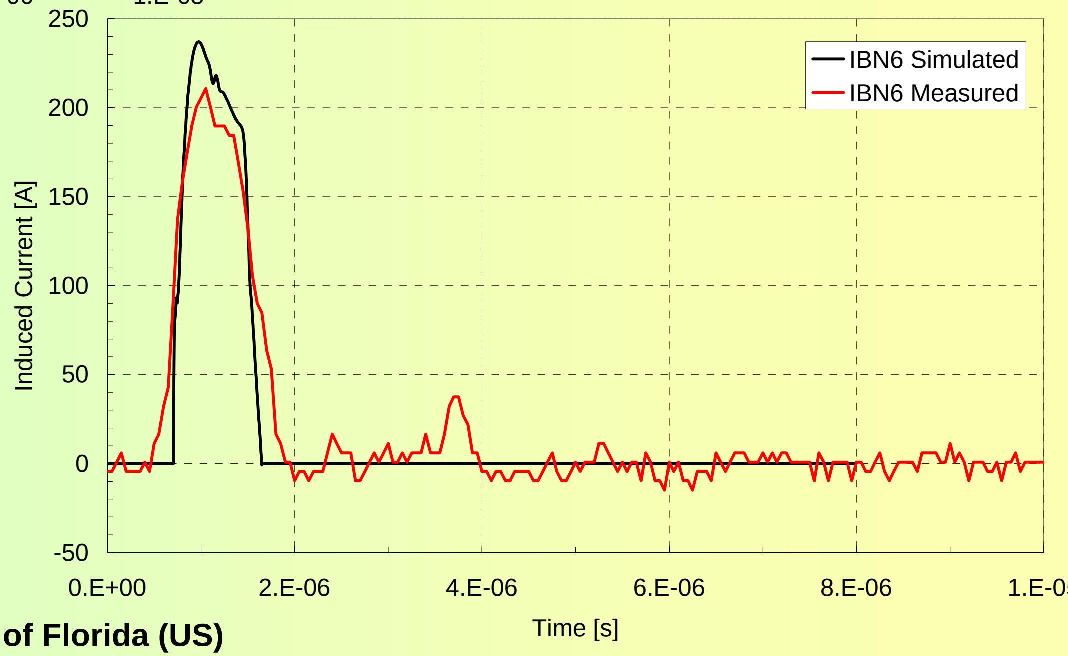


LIOV-EMTP96: simulations and comparison with experimental data *Cont.*



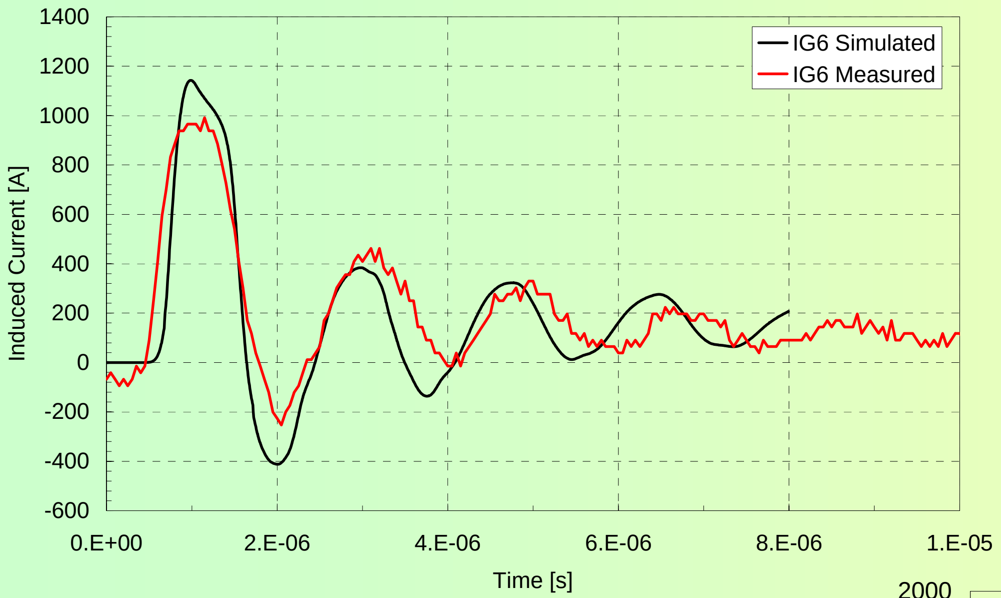
First event of 02-08-03 6th return stroke
Current flowing through the phase B conductor of pole 6

First event of 02-08-03 6th return stroke
Current flowing through the arrester located at pole 6 phase B



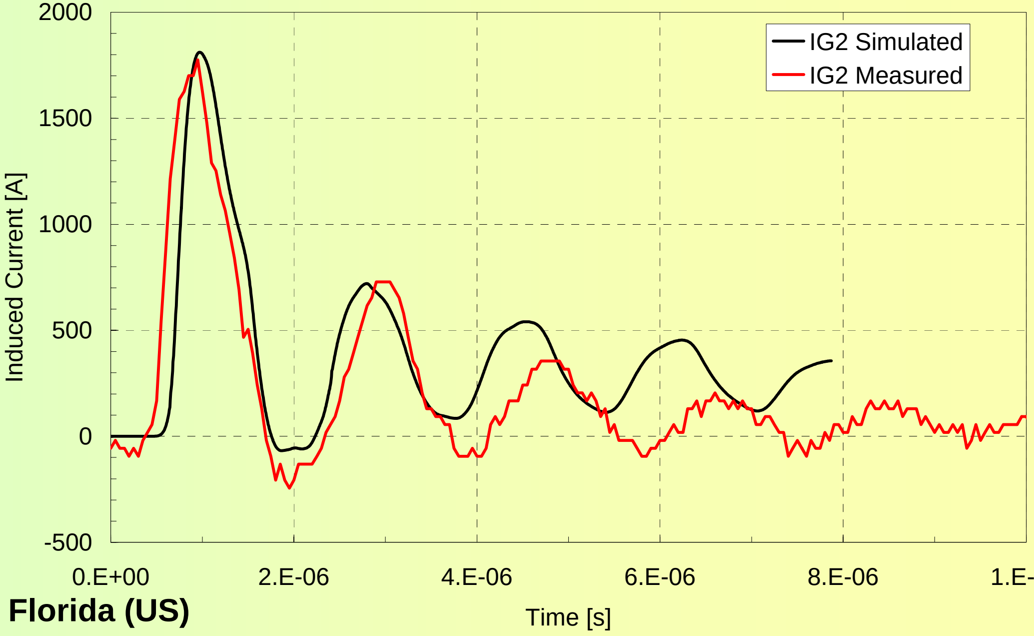
Experimental data are courtesy of ICLRT of University of Florida (US)

LIOV-EMTP96: simulations and comparison with experimental data *Cont.*



First event of 02-08-03 6th return stroke

Current flowing through the grounding of pole 6



First event of 02-08-03 6th return stroke

Current flowing through the grounding of pole 2

Experimental data are courtesy of ICLRT of University of Florida (US)

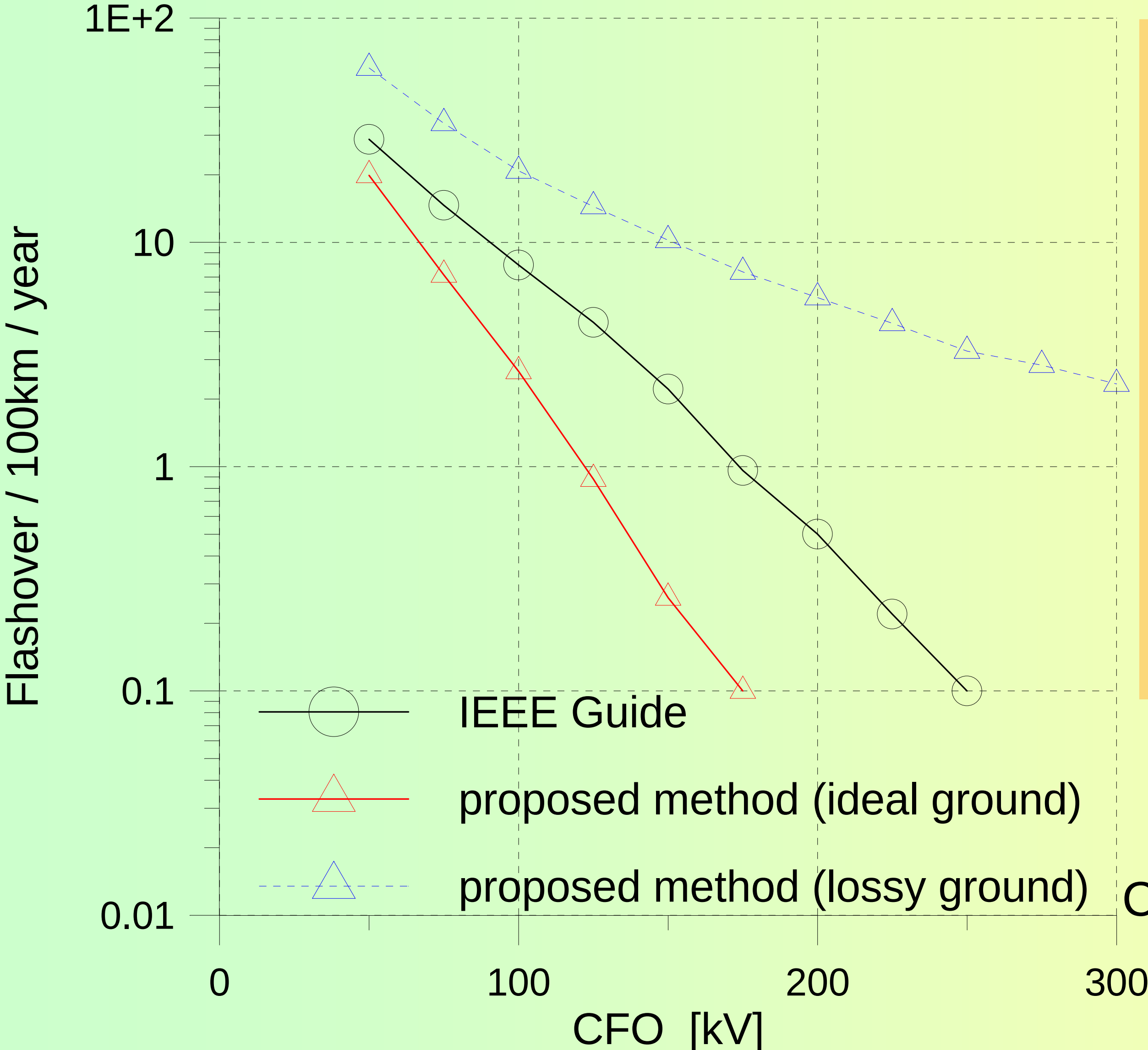
Application of the results to the evaluation of indirect lightning performance of overhead lines *Cont.*

Clearly, the ___ depends on:

- models used to calculate the induced voltages
- lateral distance expression
- statistical distribution of lightning parameters

Comparison with IEEE Std 1410-1997

Single conductor line



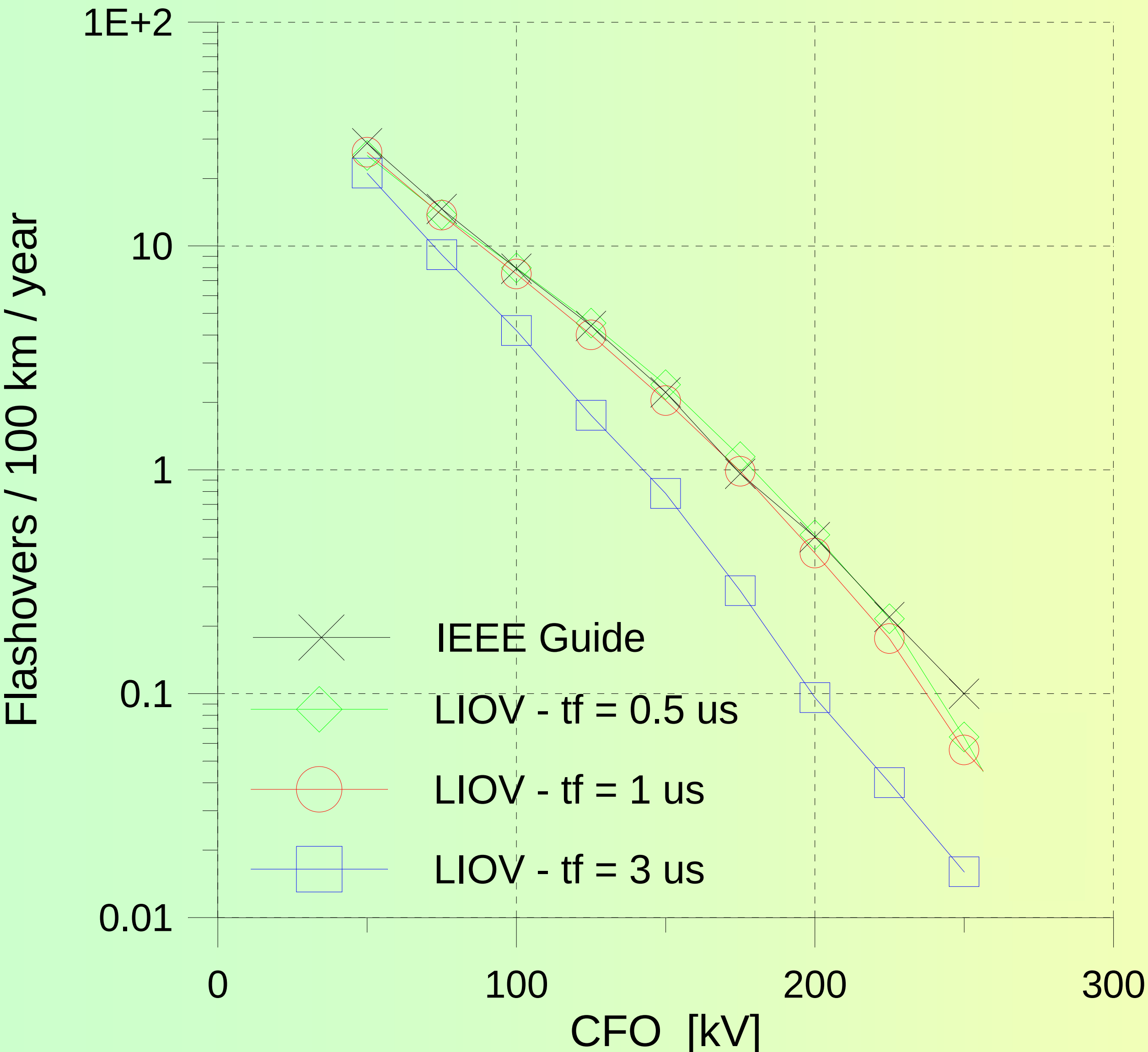
IEEE Std 1410 (solid curve)

- proposed method (ideal ground)

- proposed method (lossy ground σ_g= 0.001 S/m)

t_f is lognormally distributed with median value 3.83 μs. Correlation factor between t_f and I_P : 0.49

Comparison with IEEE Std 1410-1997



Ideal ground

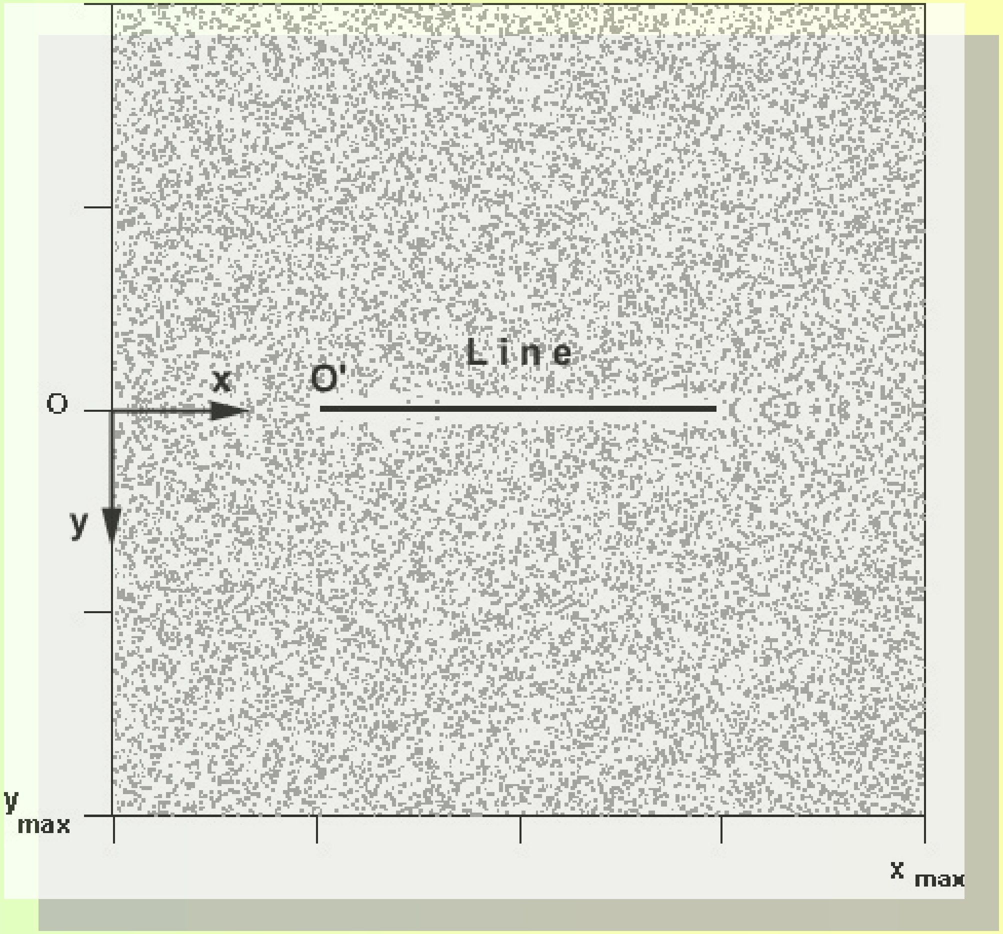
Note that with small values of t_f the two methods predict basically the same results

Application of the results to the evaluation of <u>indirect lightning performance of overhead lines</u> *Cont.*

For the calculation of the indirect lighting performance of the overhead use is made of the procedure proposed by *Borghetti and Nucci* [ICLP, 1998; Sipda, 1999] , based on the Monte Carlo method.

Each event is characterized
By 4 random variables

- peak value of the lightning current I_p
- front time t_f (correlated with I_p)
- two co-ordinates of the stroke location (x and y)



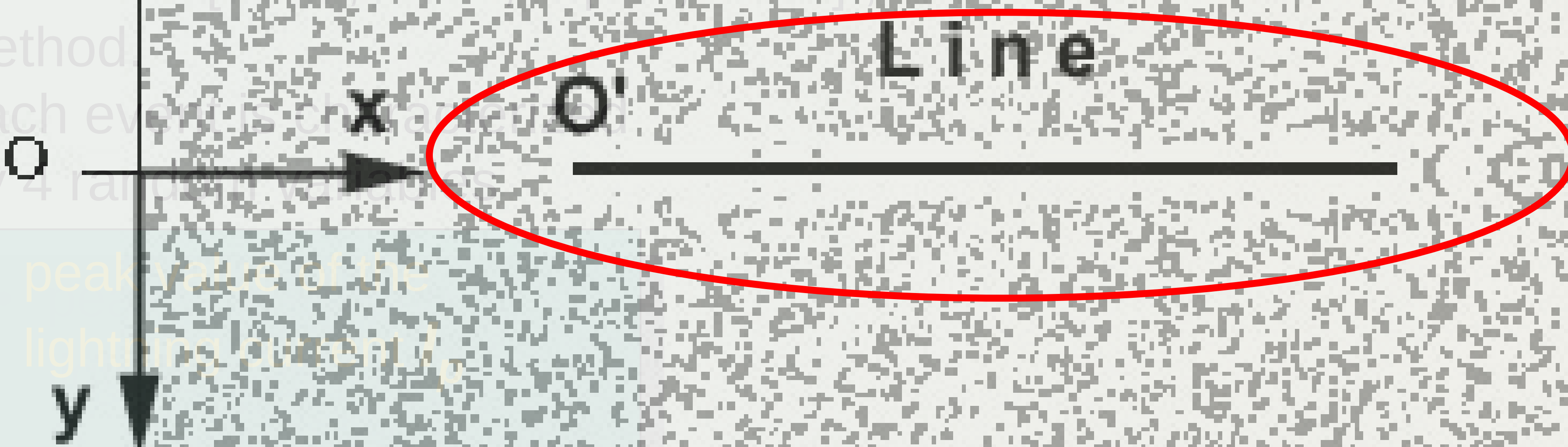
3. Application of the results to the evaluation of indirect lightning performance of overhead lines - cont.

For the calculation of the indirect lighting performance of the overhead use is made of the procedure proposed by Borghetti and Nucci [CIGRE, 1998; Sirda, 2009], based on the Monte Carlo method.

Each event is characterized

By 4 random variables:

- peak value of the lightning current I_p
- front time t_f (correlated with I_p)
- two co-ordinates of the stroke location (x and y)



Application of the results to the evaluation of indirect lightning performance of overhead lines *Cont.*

1 Inputs:
- lightning current parameters (I_p and t_f)
- return stroke velocity
- line and ground data

2 Random generation of events (I_p ; t_f : x ; y) > 20 000

3 Induced overvoltage calculation using LIOV or LIOV-EMTP96

4 Counting of the events generating overvoltages greater than 1.5 x CFO

5 Plot the graph:

No. of flashovers/100 km/year vs CFO

where **No. of flashovers/100 km/year =**

$$(n/n_{tot}) \cdot n_g \cdot S \cdot 100/L$$ (with n_g=ground flash density)

Application of the results to the evaluation of <u>indirect lightning performance of overhead lines</u> *Cont.*

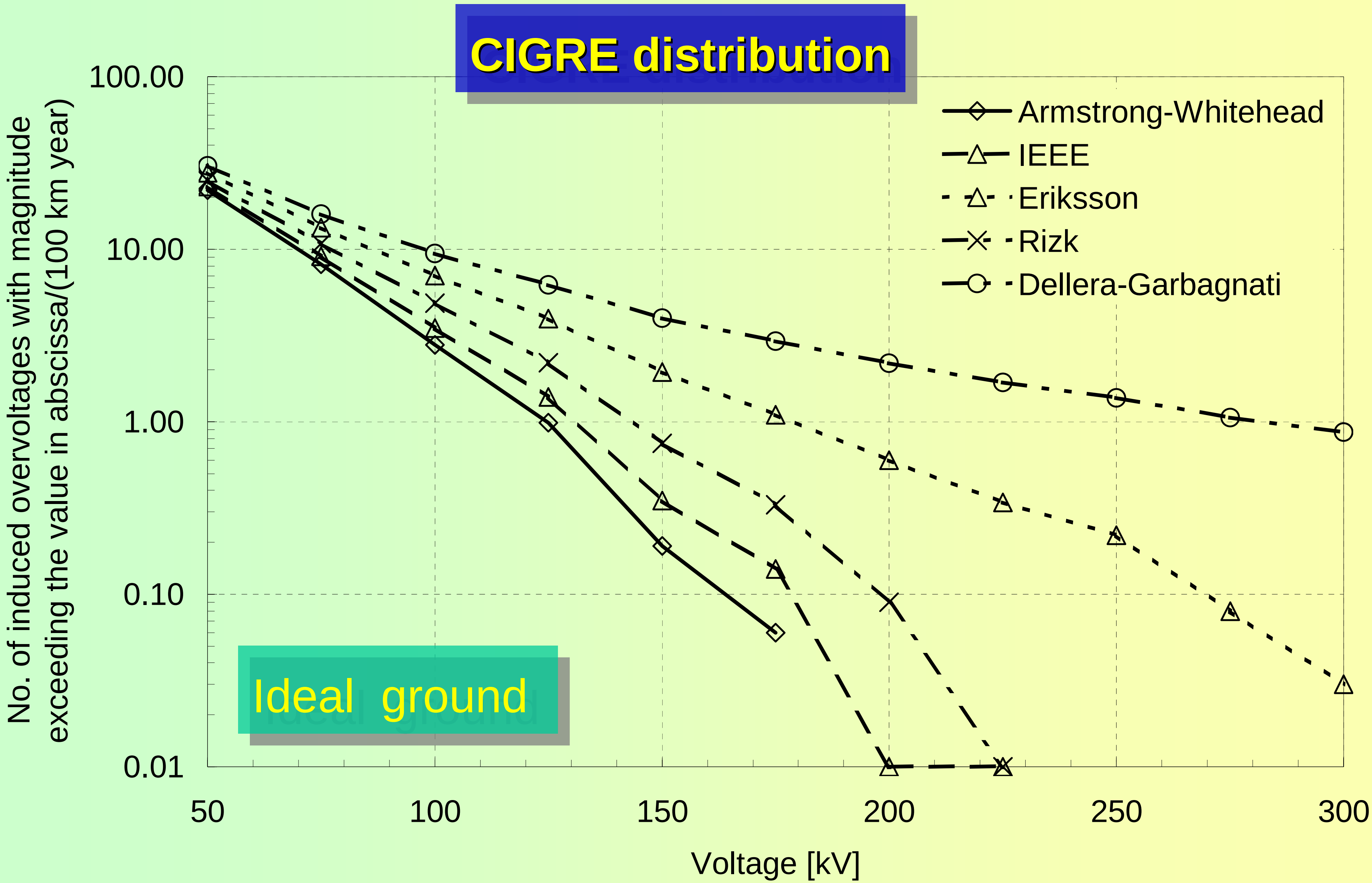
Let us now calculate the indirect lightning performance of an overhead line by using either:

- **the lightning current statistical distribution by *Berger* (CIGRE distribution) biased by the presence of the <u>tower</u>;**
- **the statistical distributions <u>at ground</u> inferred using the proposed method.**

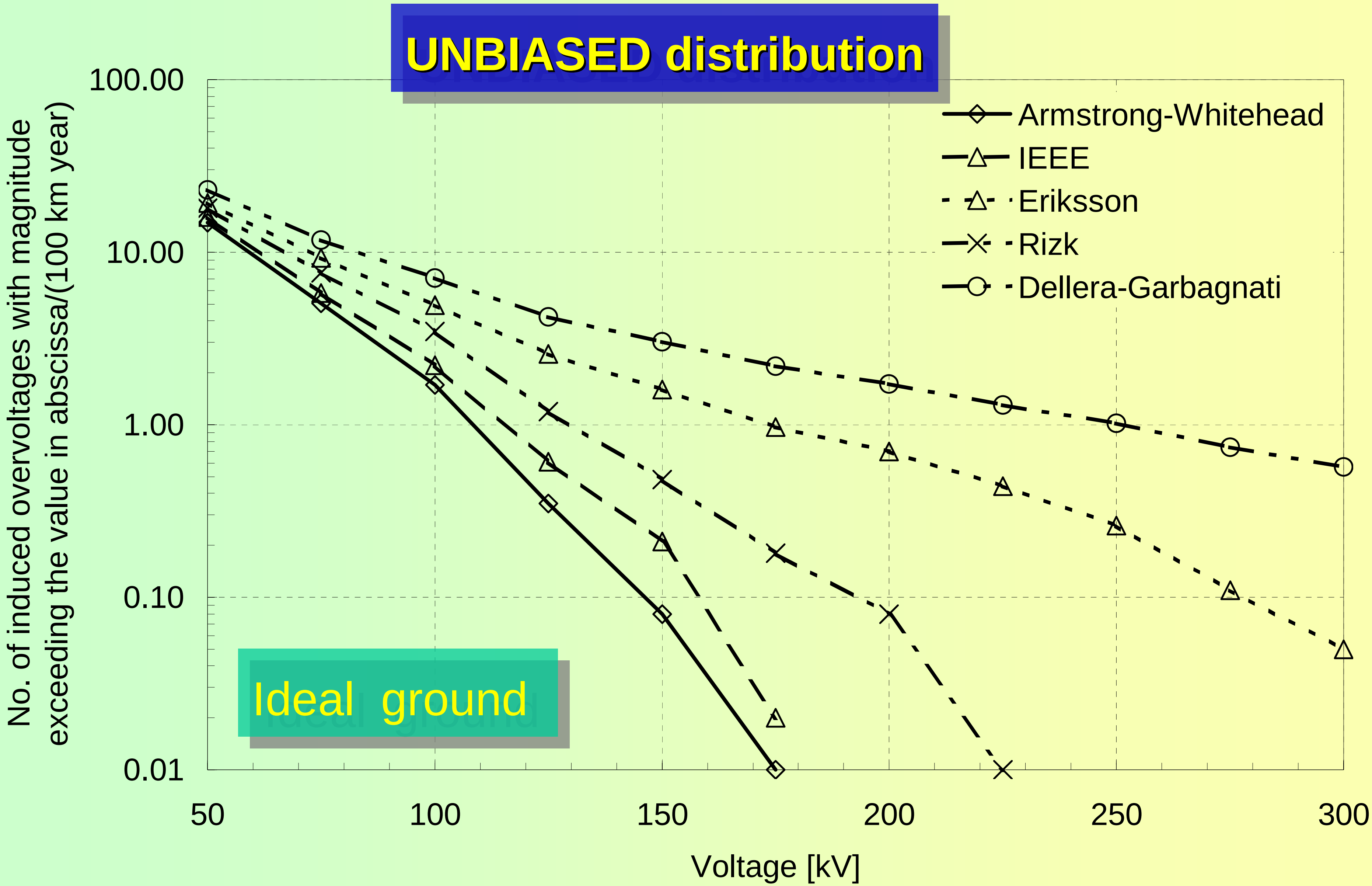
We consider a single-conductor overhead line with the following characteristics:

- **2 km long;**
- **10 m high line;**
- **'matched' at both end;**
- **"striking area" around the line about 20 km^2.**

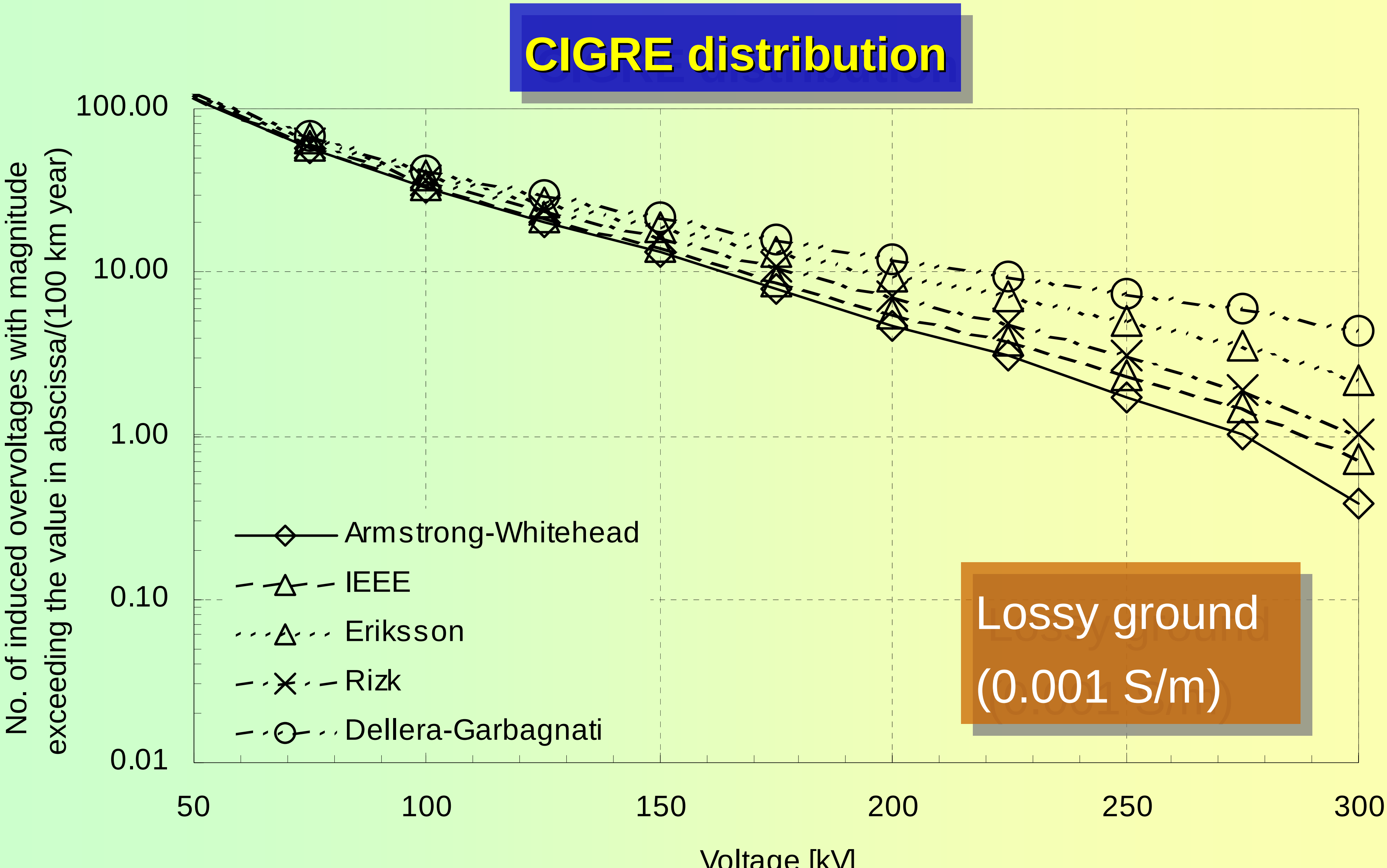
Application of the results to the evaluation of indirect lightning performance of overhead lines *Cont.*



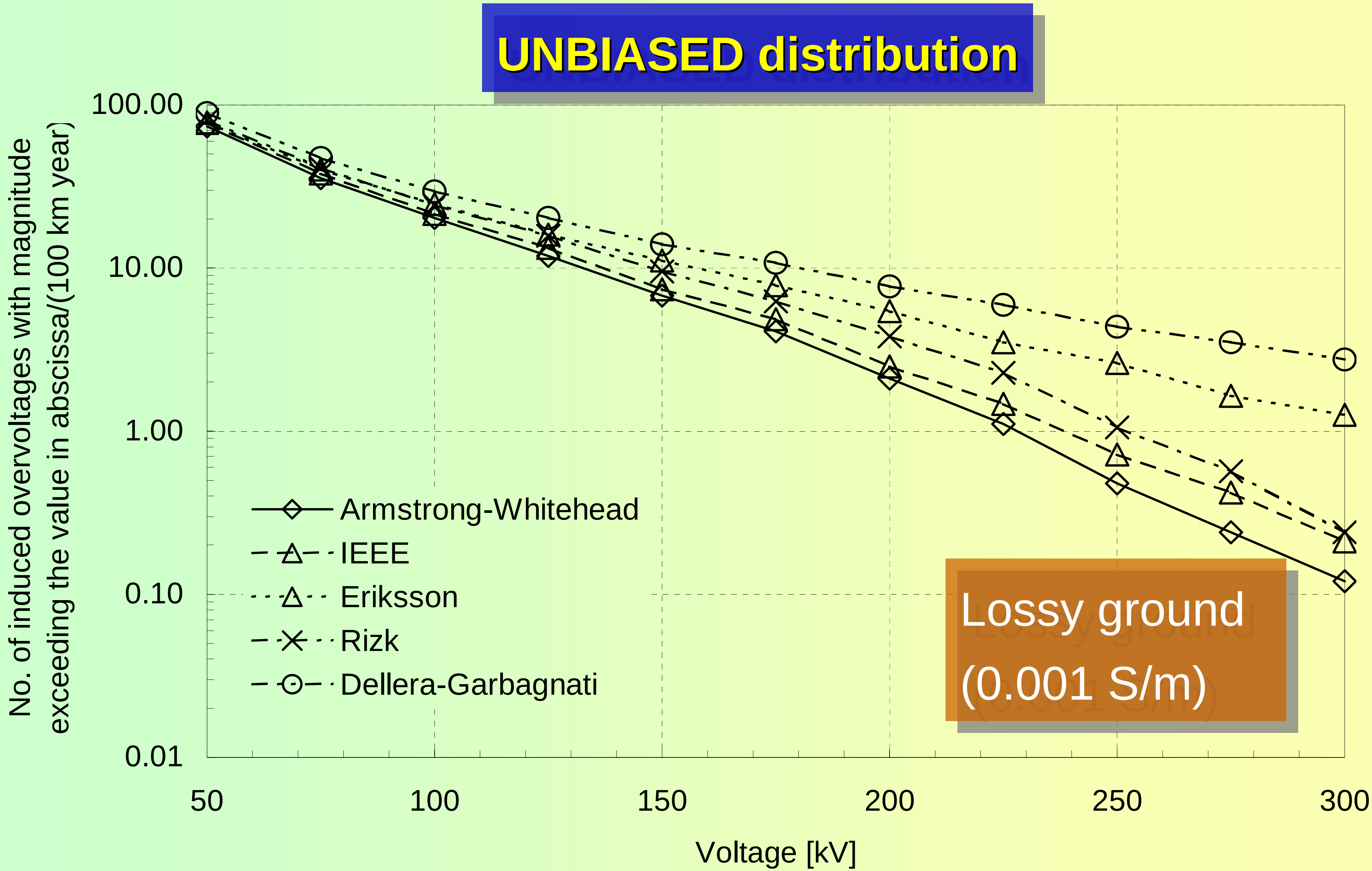
Application of the results to the evaluation of indirect lightning performance of overhead lines *Cont.*



Application of the results to the evaluation of indirect lightning performance of overhead lines *Cont.*



Application of the results to the evaluation of indirect lightning performance of overhead lines *Cont.*



Conclusions

The use of unbiased current statistical distributions results, as expected, in a better performance of the distribution line to indirect lightning, these distributions being characterized by a lower median value.

We have shown how the results vary depending on the expression adopted to evaluate the lateral distance (attractive radius).

Also, the ground resistivity acts in minimizing the difference between the line performance calculated using the biased and unbiased lightning current distributions.

Conclusions

It appears, however, that additional study on attractive radius expressions is badly needed.

The results obtained show that statistical current distributions at ground are probably characterized by lower median values than the relevant distributions gathered by means of instrumented towers.

This is in line with lower median values obtained by means of lightning location systems, although …