COST P18 Training School on Lightning Physics and Effects

Sept. 4-6, 2007, Kiten, Bulgaria.

Lightning Protection of Power Systems

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Outline

- Introduction
- Lightning performance of transmission lines
- Lightning performance of distribution lines

Introduction

The designer of a power system needs to know the flashover rate of an overhead power line for a selected insulation level to meet the reliability criteria set for the system.

The lightning flashover rate (lightning performance of the line) is the sum of:
- **direct strikes** flashover rate;
- **nearby strikes** flashover rate;
- flashover rate from **failures** of protective equipment.

Only **first strokes** of **negative downward** flashes are generally taken into account in lightning performance studies:
- upward flashes occur mainly from very tall structures or mountain-top installations;
- the majority of downward flashes are of negative polarity (except for tall structures and in the few regions with frequent winter thunderstorms);
- subsequent-stroke peak current is on average about 40% of the first stroke.

Introduction

To predict the lightning performance one needs the knowledge of:

- the lightning activity (the ground flash density $\mathbf{N_g}$);
- the exposure to lightning;
- lightning consequences.

In order to evaluate the exposure to lightning, several expressions of the so-called **electro-geometric models** (**EGM**) have been developed, based on the concept of the **striking distance**: the distance between the downward leader and an object on the earth, or the earth itself, at which the point of strike becomes determined.

It was originally conceived as the distance at which a critical breakdown strength is reached (about 600 kV/m for negative lightning); to this first stage, corresponding to the initiation of an upward connecting leader, a second stage follows (the final jump) of the successful interception between the downward and upward leaders, mainly determined by the local distribution of charges.

The **leader progression model** (**LPM**) instead, simulates step by step the development of the leader channels, along the direction of maximum V gradient

Introduction *Cont.*

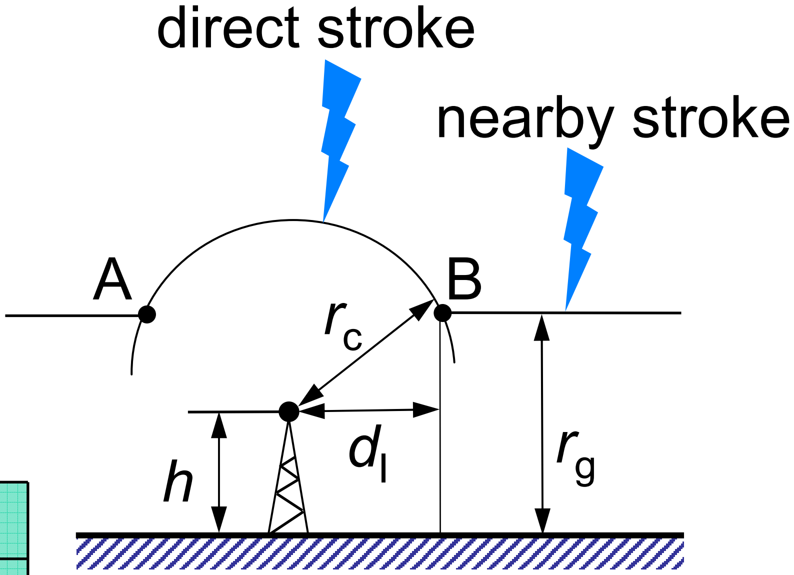
Single conductor overhead line of a given height *h*:

☐ r_c: striking distances to a conductor;

☐ r_g: striking distances to ground;

☐ d_l: lateral attractive distance of the line

$$r_c = A \cdot I^b \qquad r_g = k \cdot r_c$$



	r_c		r_g
	A	b	k
Armstrong and Whitehead	**6.7**	**0.8**	**0.9**
IEEE WG	**10**	**0.65**	**0.55**

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

Introduction *Cont.*

	A		b
	rc	rg	
Young et al	27 for h < 18m 27×444/(462-h) for h>18 m	27	0.32
Armstrong and Whitehead (CIGRE' 33.01)	6.7	6	0.8
Brown and Whitehead	7.1	6.4	0.75
Love	10	10	0.65
Anderson IEEE WG 1985	10	6.4 for UHV 8.0 for EHV 1 for others	0.65
IEEE T&D Commette 1991	8	8×22/y 4.8<rg<7.2	0.65
IEEE T&D Commette 1992 (IEEE Std 1243)	10	3.6+1.7ln(43-h) if y < 40 3.6+1.7ln(43-40) if y > 40	0.65
IEEE substation Commette 1995	8	8	0.65

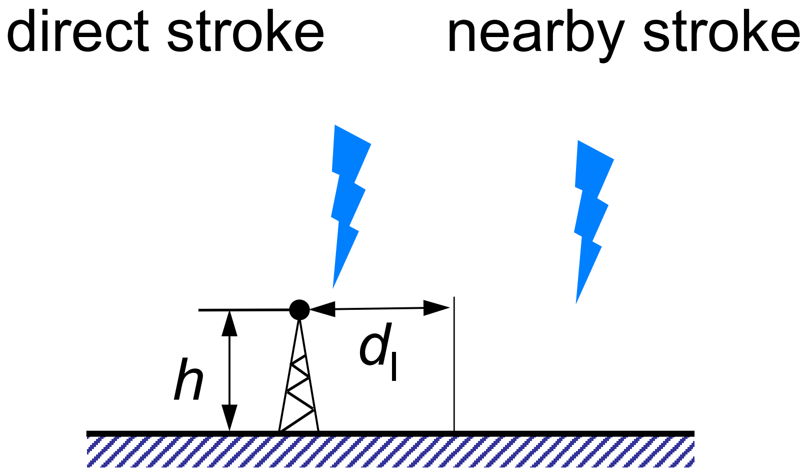
The EGM have been subjected to empirical calibration and adjustement, and are under continuos review.

In certain instances, the ratio rg/rc is reduced as structures height is increased.

Introduction *Cont.*

Simple expressions of the following type have been inferred by using the LPM, relating the attractive radius *r* and the lightning current peak *I*:

$$d_l = c + A \cdot I^b$$



	c	A	b
Eriksson	**0**	**$0.84\ h^{0.6}$**	**$0.7\ h^{0.02}$**
Rizk	**0**	**$4.27\ h^{0.41}$**	**0.55**
Dellera-Garbagnati	**$3\ h^{0.6}$**	**$0.028\ h$**	**1**

Introduction *Cont.*

The various models predict an increase of d_l as the height of the line increases, this means an increase of the median value of the peak currents striking the line →
→the probability density functions based on instrumented towers data are biased toward higher values (i.e. [Borghetti et al, 2004b]).

This has practically no implications concerning direct lightning, has some consequences concerning indirect lightning.

Flashes to unprotected phase conductors are likely to produce flashovers.
The overhead ground wire (OHGW) is placed above the phase conductors for the purpose of intercepting direct stroke and shunt the current to ground through the tower impedance and footing resistance.
Transmission lines generally are equipped with OHGW.
For distribution lines, characterized by limited height and likely to be shielded by near tall object (trees and buildings), the flashover rate reduction provided by the shielding may not justify the cost of the OHGW (and the related cost of additional insulation and greater pole height, that attracts more direct strokes).
Distribution lines lightning induced fllashover is mostly due to nearby strokes, which induce voltages usually less than 300 kV.

Introduction *Cont.*

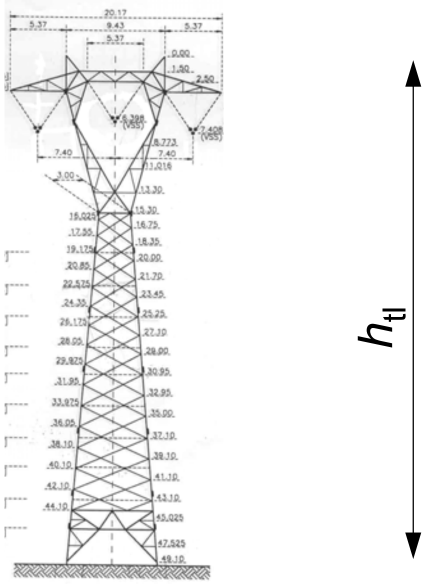
The different geometry and insulation characteristics of transmission and distribution overhead lines → direct or indirect lightning events differently concern the two line types:

- $h_{tl} >> h_{dl}$
- $CFO_{tl} >> CFO_{dl}$

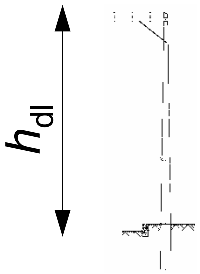
→

- **direct lightning major concern for transmission lines**
- **indirect lightning major concern for distribution lines**

Overhead transmission lines



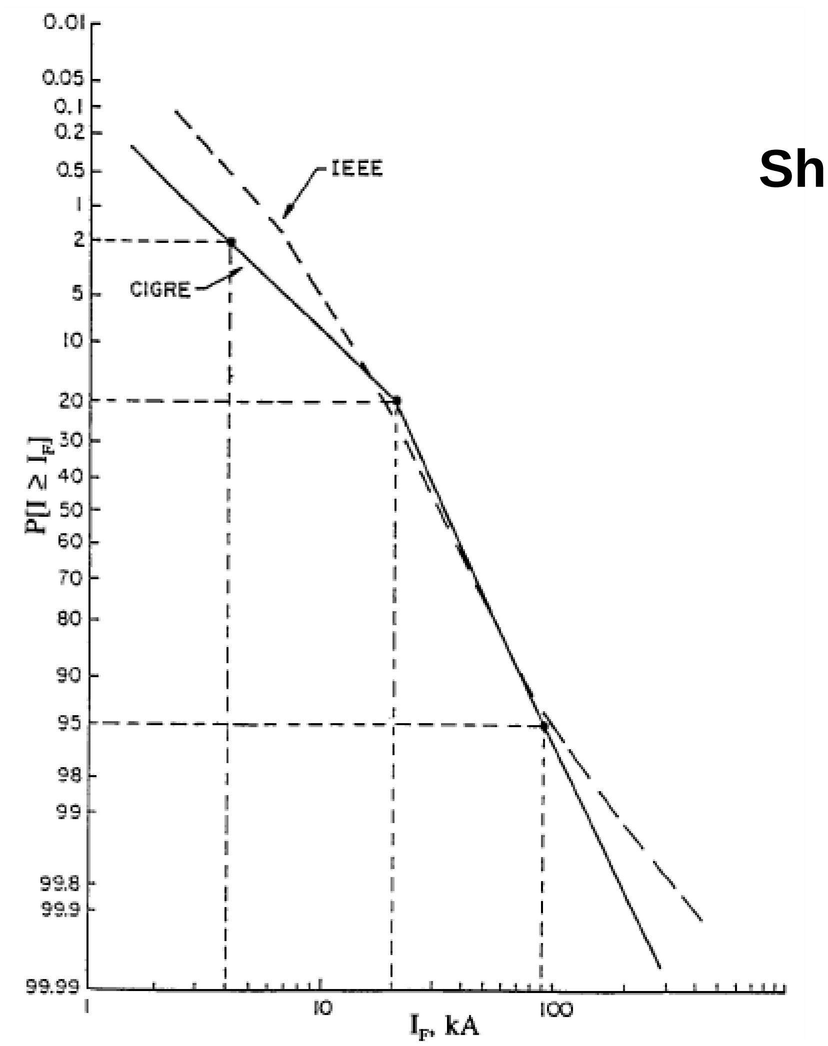
Overhead distribution lines



Outline

- Introduction
- Lightning performance of transmission lines
- Lightning performance of distribution lines

Lightning performance of transmission lines



Cigré

Shielding failure	**Backflashover**
$I_p \leq 20\text{kA}$	$I_p > 20\ \text{kA}$
$\underline{I}_p = 61.1\ \text{kA}$	$\underline{I}_p = 33.3\ \text{kA}$
$\delta_{\ln I_p} = 1.33$	$\delta_{\ln I_p} = 0.605$

IEEE

$$P(I \geq I_F) = \frac{1}{1+\left(\dfrac{I}{31}\right)^{2.6}}$$

Lightning performance of transmission lines *Cont.*

Eriksson has shown that the lightning flash collection rate for practical transmission lines is:

$$N_s = N_g \left(\frac{28h^{0.6} + b}{10} \right)$$

where h is the average ground wire height (tower height minus 2/3 of the sag)
b is the overhead ground wire separation distance
Ng is the ground flash density (flashes/km2/year)

A general formula for the lightning collection rate

Given a crest current value *I*, the number of strokes terminating on the line is

$$2N_g d_l(I)L$$

Given the current peak probability density function f(*I*):

$$P(I_1 < I < I_2) = \int_{I_1}^{I_2} f(I)dI$$

the lightning collection rate is:

$$N_s = 2N_g L \int_{I_{\min}}^{\infty} d_l(I) f(I)dI$$

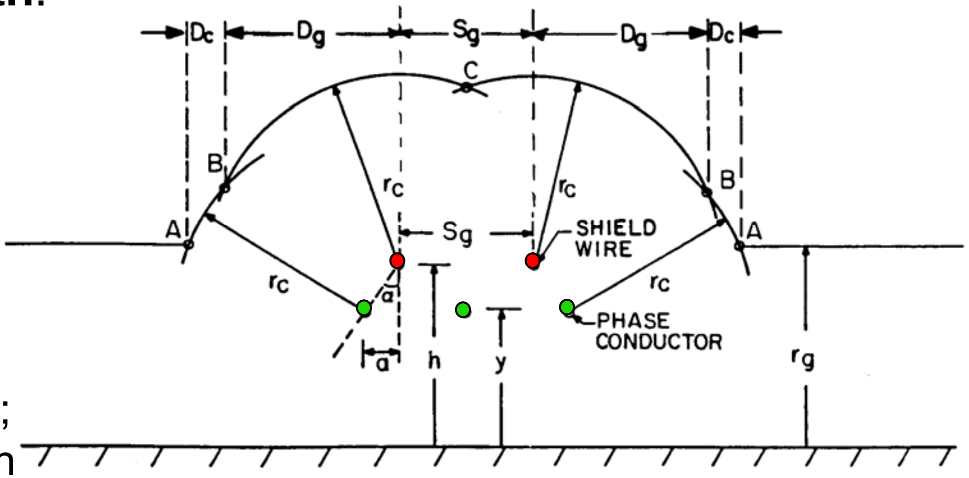
Lightning performance of transmission lines *Cont.*

Shielding failure: basic concept of the geometric model

For a specific value of stroke current, arcs of radii r_c are drawn from the phase conductors and from the shield wires with the horizontal line at a distance r_g from the earth's surface. The intersections of these arcs and the intersection of the arcs with the horizontal line are marked **A**, **B**, and **C**. **Downward leaders that reach the arc between A and B will terminate on the phase conductor. Those that reach the arc between B and C will terminate on the shield wires, and those that terminate beyond A will terminate to ground or earth**.

$$N_s = 2N_g L \int_{I_{\min}}^{\infty} [S_g/2 + D_g(I) + D_c(I)] f(I) dI$$

$$SFR = 2N_g L \int_{I_{\min}}^{I_{\max}} D_c f\left(I\right) dI$$



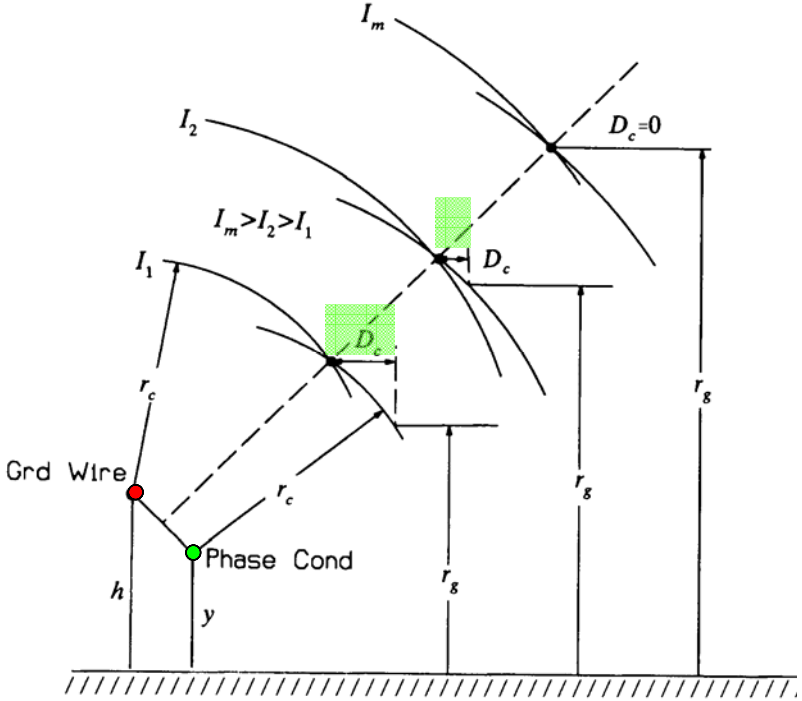
Where:

- $I_{\min}$ is the minimum lightning current (2 or 3 kA);
- $I_{\max}$ is the maximum current at and above which no strokes will terminate on the phase conductor.

Lightning performance of transmission lines *Cont.*

Note: determination of I_{max}

By redrawing the previous geometric model for higher and higher lightning currents, as the current increases D_c decreases until a point is reached at which all three striking distances meet and D_c becomes zero. This point define I_{max}:



Lightning performance of transmission lines *Cont.*

Note: determination of I_{max}

$$\alpha >> \beta$$

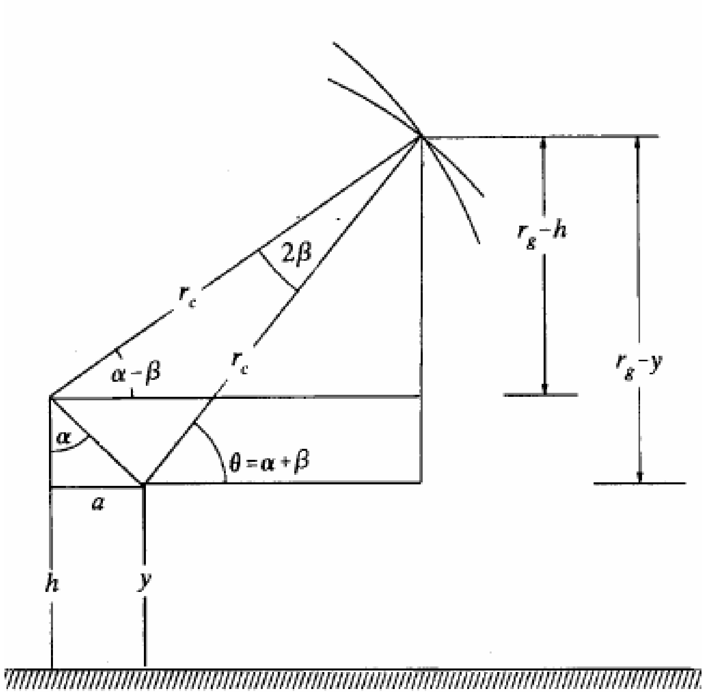
$$r_{gm} - \frac{h+y}{2} = r_{cm}\sin\alpha$$

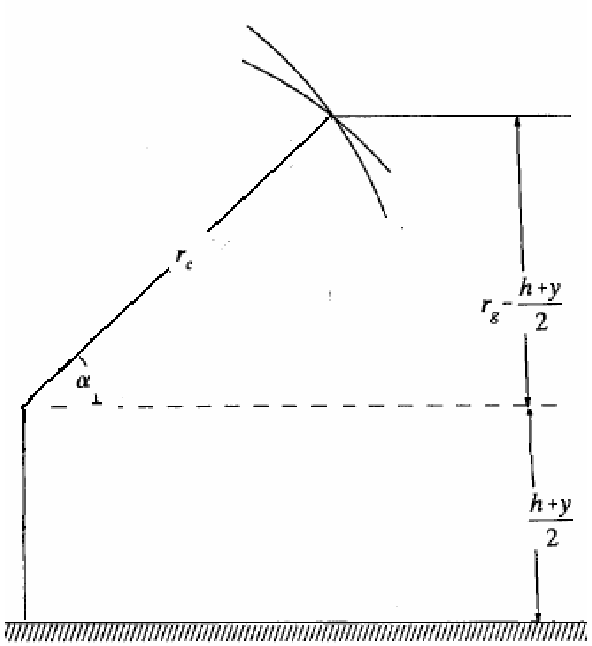
$$r_{gm} - \frac{h+y}{2} = \gamma r_{gm}\sin\alpha$$

$$r_{gm} = \frac{h+y}{2(1-\gamma\sin\alpha)}$$

$$r_g = AI^b$$

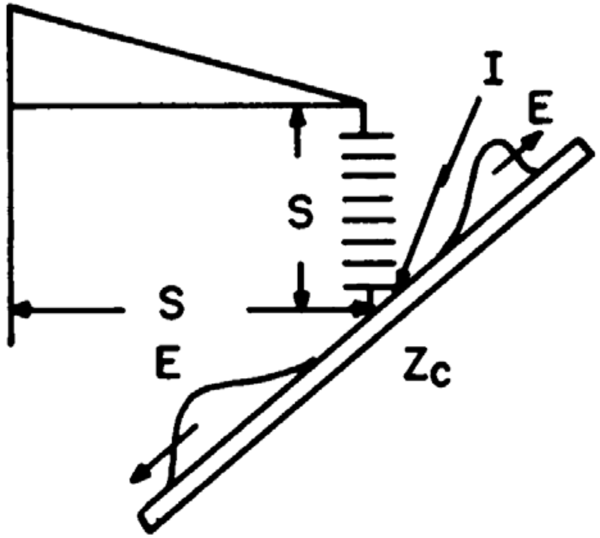
$$I_{max} = \left[\frac{r_{gm}}{A}\right]^{\frac{1}{b}}$$





Lightning performance of transmission lines *Cont.*

Shielding failure flashover rate: SFFOR



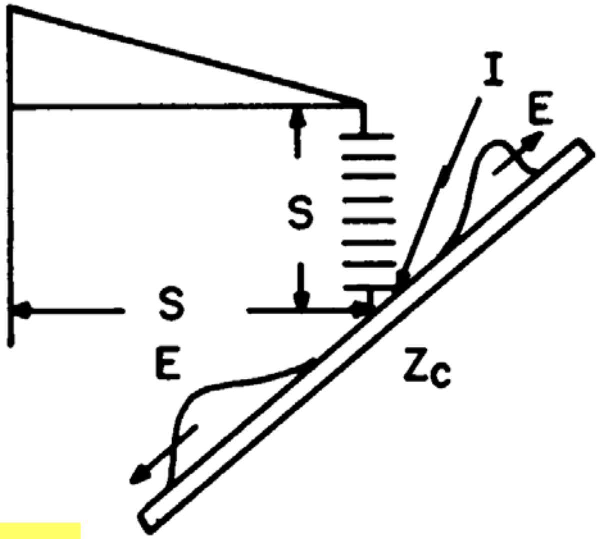
The SFR is the number of strokes that terminate on the phase conductor. Not all of these will result in flashover. However, if the voltage produced by a stroke to the conductor exceeds the CFO, flashover occurs. **Thus the SFR includes both the strokes that cause flashover and those that do not**. To determine the flashover rate, is necessary to determine the voltage on the conductor and across the line insulation *E*:

$$E = I\frac{Z_c}{2}$$

Where Z_c is the surge impedance of the phase conductor.

Lightning performance of transmission lines *Cont.*

Shielding failure flashover rate: SFFOR



If the voltage *E* is set to the *CFO*, negative polarity, then the **critical current**, at and above which flashover occurs, is:

$$I_c = \frac{2CFO}{Z_c}$$

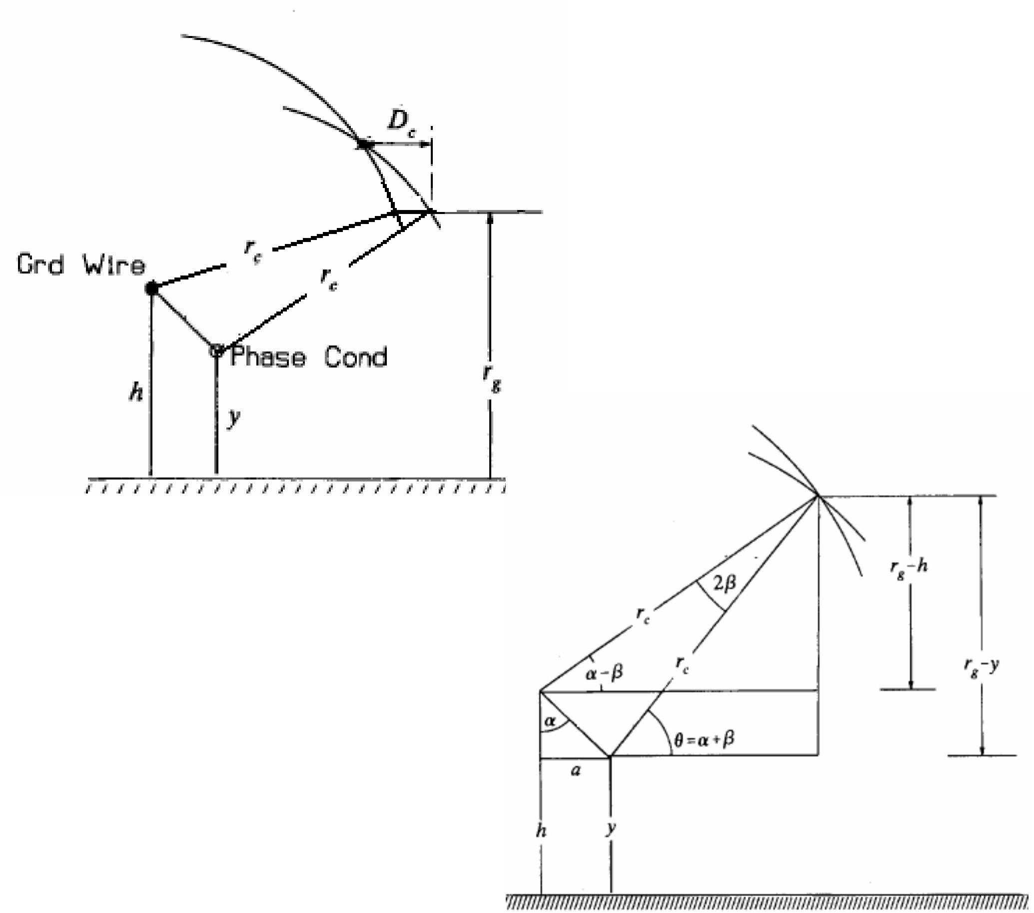
Therefore SFFOR is:

$$SFFOR = 2N_g L \int_{I_c}^{I_{\max}} D_c f(I) dI$$

Note: the impulse waveshape produced by the stroke is the same as that of the stroke current. Although the time to half value of this surge exceeds that of the standard lightning impulse, and thus the *CFO* for this surge would be less than the standard lightning impulse *CFO*, **the *CFO* employed is usually assumed as the standard *CFO*, negative polarity, which is typically assumed equal to 605 kV/m times the strike distance *S*.**

Lightning performance of transmission lines *Cont.*

Note: determination of α_p



$$I_c = \frac{2CFO}{Z_c}$$

$$r_{gc} = A_g (I_c)^b$$

$$r_{cc} = A_c (I_c)^b$$

$$r_{gc} - h = r_{cc}\sin(\alpha-\beta)$$

$$r_{gc} - y = r_{cc}\sin(\alpha+\beta)$$

$$\alpha = \frac{(\alpha-\beta)+(\alpha+\beta)}{2}$$

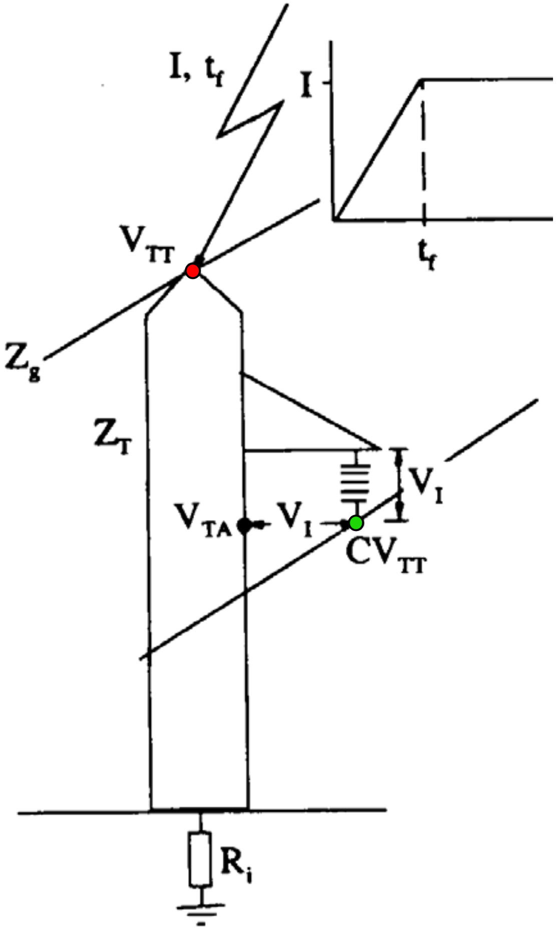
$$= \frac{\sin^{-1}\left(\frac{r_{gc}-h}{r_{cc}}\right) + \sin^{-1}\left(\frac{r_{gc}-y}{r_{cc}}\right)}{2}$$

Lightning performance of transmission lines *Cont.*

Backflashover: basic concepts

In the previous section, the overhead shield wires have been located to minimize the number of lightning strokes that terminate on the phase conductors. Then, the remaining and the vast majority of strokes terminate on such shielding wires. A stroke that terminates on such a wires forces currents to flow down the tower and out on the shielding wires. Thus voltages are built up across the line insulation. **If these voltages equal or exceed the line CFO, flashover occurs**.
This event is called a **backflash** and the corresponding lightning current **critical current I_c**

Cross-arm impedance is here disregarded.



Lightning performance of transmission lines *Cont.*

Backflashover: basic concepts on tower modeling

When lightning strikes a transmission tower, the potential of the tower top rises. Then back flashover occurs at arcing horn, and the surge propagates into the power line. Therefore, the **tower model – including the earth electrode, – which is related to the tower top potential rise, affects greatly the lightning surge analysis results**.

Front times of 1-4 μs are long with respect to typical line heights, so most models assume that tower response is dominated by TEM wave.

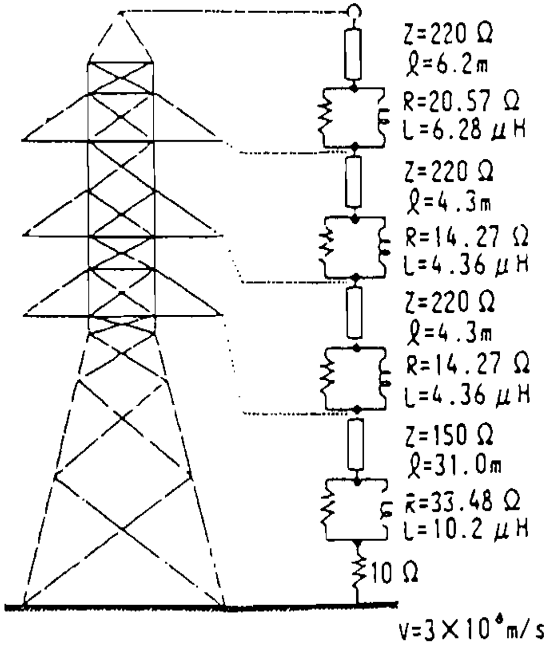
Tower is a vertical conductor to the ground, thus cannot be modeled as distributed parameter circuits in a strict sense. For instance, to carry out an analysis by EMTP-like programs, this has to be modeled as distributed parameter circuits and/or lumped circuits. To do this, models, which can be treated by using the traveling wave theory, and methods to calculate the parameter values of these models have been studied.

Lightning performance of transmission lines *Cont.*

Backflashover: basic concepts on tower modeling

As a detailed transmission tower model, a four story model is widely used (e.g. [Eriksson, 1987; Ishii et al, 1991]) This model, as represented in figure below, consists of four **distributed parameter lines** divided by arm parts, and RL paralleled circuits which represent **tower impedance time-variation and wave distortion**.

Finally, in most of models for these studies, the **transmission tower is approximated with a cylinder or a cone using electromagnetic theory**, and the surge impedance (here, this means the ratio of voltage and current at the tower top) is calculated as a function of its height and radius (e.g. [Ametani et al., 1994]).



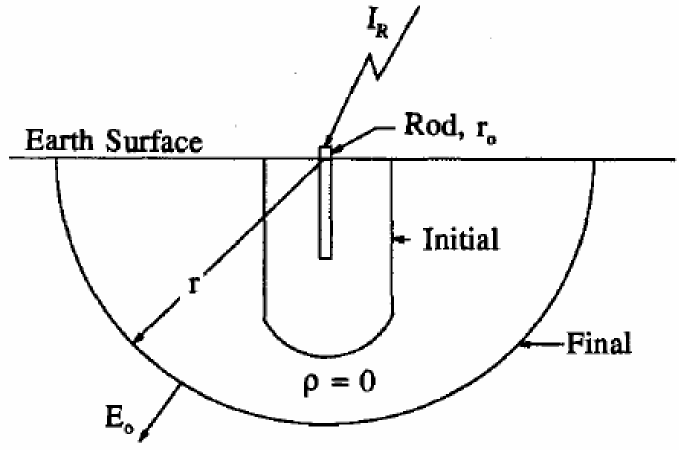
Lightning performance of transmission lines *Cont.*

Backflashover: soil ionization, variation of grounding resistance

The purpose of this section is to present simplified equations to estimate the impulse or high-current resistance of concentrated grounds.
For high currents, representative of lightning, when the gradient exceeds a critical gradient E_0, breakdown of soil occurs. In general this soil breakdown can be viewed as **increasing the diameter and length of the rod** as shown below, which shows the initial limit or area. As the ionization increases, the shape of the zone becomes more spherical.

For an hemispherical electrode of radius r_0, the current required to achieve the gradient E_0 (≈400 kV/m) is denoted as I_g and is determined by the equation:

$$I_g = \frac{1}{2\pi}\frac{\rho E_0}{R_0^2}$$

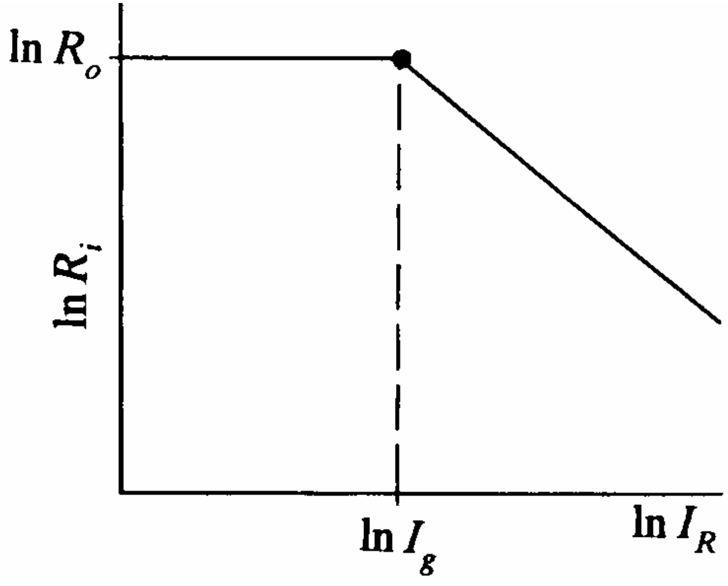


Lightning performance of transmission lines *Cont.*

Backflashover: soil ionization, variation of grounding resistance

For currents greater than I_g, breakdown of soil continues and expands, reaching a radius *r*. As a first approximation we can consider that within this area, the soil resistivity can be considered zero, the soil being a perfect conductor. Thus the resistance under high currents is simply the resistance of a hemisphere of radius *r*. Therefore, the resistance R_i becomes:

$$R_i = \frac{R_0}{\sqrt{I_R / I_g}}$$



Note: since the dimensions of the rod permit the gradient E_0 to be achieved essentially instantaneously, the decrease in resistance also occurs instantaneously. However, this decrease is not rapid until the streamer and arcing zones approximate an hemisphere. This can be approximated with the equation: $R_i = \frac{R_0}{\sqrt{1+(I_R/I_g)}}$

Lightning performance of transmission lines *Cont.*

Backflashover: soil ionization, variation of grounding resistance

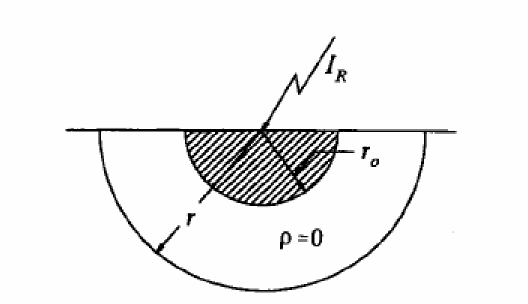
$$R_0 = \frac{\rho}{2\pi r_0}$$

$$J = \frac{I}{2\pi r^2}$$

$$E = \rho J = \frac{\rho I}{2\pi r^2}$$

$$\begin{cases} E_0 = \dfrac{\rho I_g}{2\pi r_0^2} \\ R_0 = \dfrac{\rho}{2\pi r_0} \end{cases} \Rightarrow \begin{cases} I_g = \dfrac{2\pi r_0^2 E_0}{\rho} \\ r_0 = \dfrac{\rho}{2\pi R_0} \end{cases} \Rightarrow I_g = \frac{2\pi E_0}{\rho}\left(\frac{\rho}{2\pi R_0}\right)^2 = \frac{E_0 \rho}{2\pi R_0^2}$$

$$E_0 = \frac{\rho I_R}{2\pi r^2} \Rightarrow r = \sqrt{\frac{\rho I_R}{2\pi E_0}}$$



$$R_i = \frac{\rho}{2\pi r} = \frac{\rho}{2\pi}\sqrt{\frac{2\pi E_0}{\rho I_R}} = \sqrt{\frac{\rho E_0}{2\pi I_R}}$$

$$\begin{cases} I_g = \dfrac{\rho E_0}{2\pi R_0^2} \\ R_i = \sqrt{\dfrac{\rho E_0}{2\pi I_R}} \end{cases} \Rightarrow R_i = R_0 \sqrt{\frac{I_g}{I_R}}$$

$$R_i = \frac{R_0}{\sqrt{1 + \dfrac{I_R}{I_g}}}$$

Lightning performance of transmission lines *Cont.*

Estimation of the backflash rate: use of the Electromagnetic Transient Program

The calculation of I_c by means of EMTP-like programs allows to take in account:

- ☐ waveshape of the current source;
- ☐ flashover criteria in the form of volt-time characteristics or integral formulas are approximate;
- ☐ transmission line models including all line conductors (em-coupling);
- ☐representation of the soil ionization;
- ☐ frequency dependent grounding models;
- ☐ surge arresters;
- ☐ representation of all the power system components.

Appendix – Backflashover *Cont.*

Additional remarks

The backflash rate BFR is the probability of exceeding the critical current multiplied by the number of flashes to the line N_L. **However, since the crest voltage and the CFO_{NS} are both functions of the time-to-crest t_f of the lightning current, the critical current previously determined is variable. Therefore, the BFR considering all the possible time-to-crest values is:**

$$BFR = 0.6 \cdot N_L \int_0^{\infty}\int_{I_c}^{\infty} f\left(\frac{I}{t_f}\right) f\left(t_f\right) dI dt_f \left[\frac{fl}{100km \cdot yr}\right]$$

Where $f(I/t_f)$ is the conditional probability density function of the stroke current given the time-to-crest and $f(t_f)$ is the probability function of the time-to-crest.

Note: in order to obtain the BFR for strokes to the tower and stroke and to the spans, the BFR obtained for strokes to the tower is multiplied by a coefficient, equal to 0.6 [Hileman]

Appendix – Backflashover *Cont.*

Additional remarks

As reported in [Ametani et al. 1994], the BFR resulting from the application of the previous equation, can be obtained by using of an **equivalent time-to-crest value T_e**. Such a value is **approximately the median fronts for the critical currents**. Since a single equivalent front is used, the BFR is reduced to:

$$BFR = 0.6 \cdot N_L \int_{I_c}^{\infty} f(I)dI = 0.6 \cdot N_L P(I_c)\left[\frac{fl}{100km \cdot yr}\right]$$

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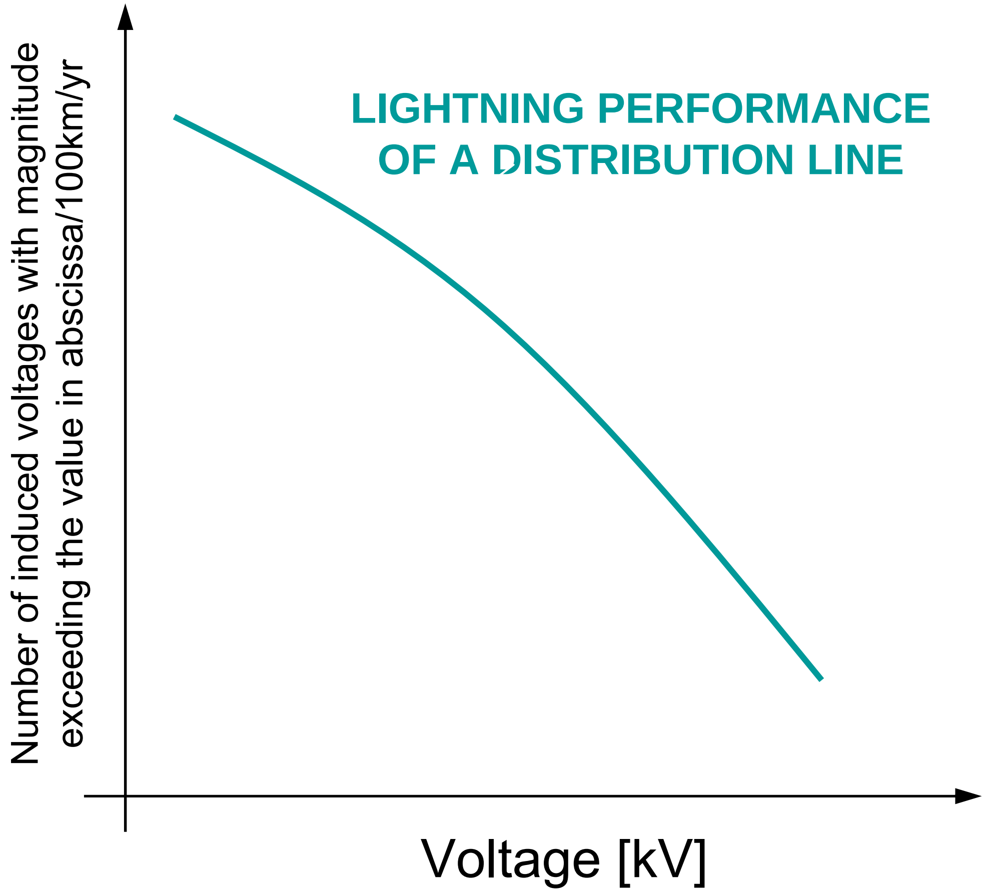
Lightning performance of distribution lines

Distribution systems insulation coordination →

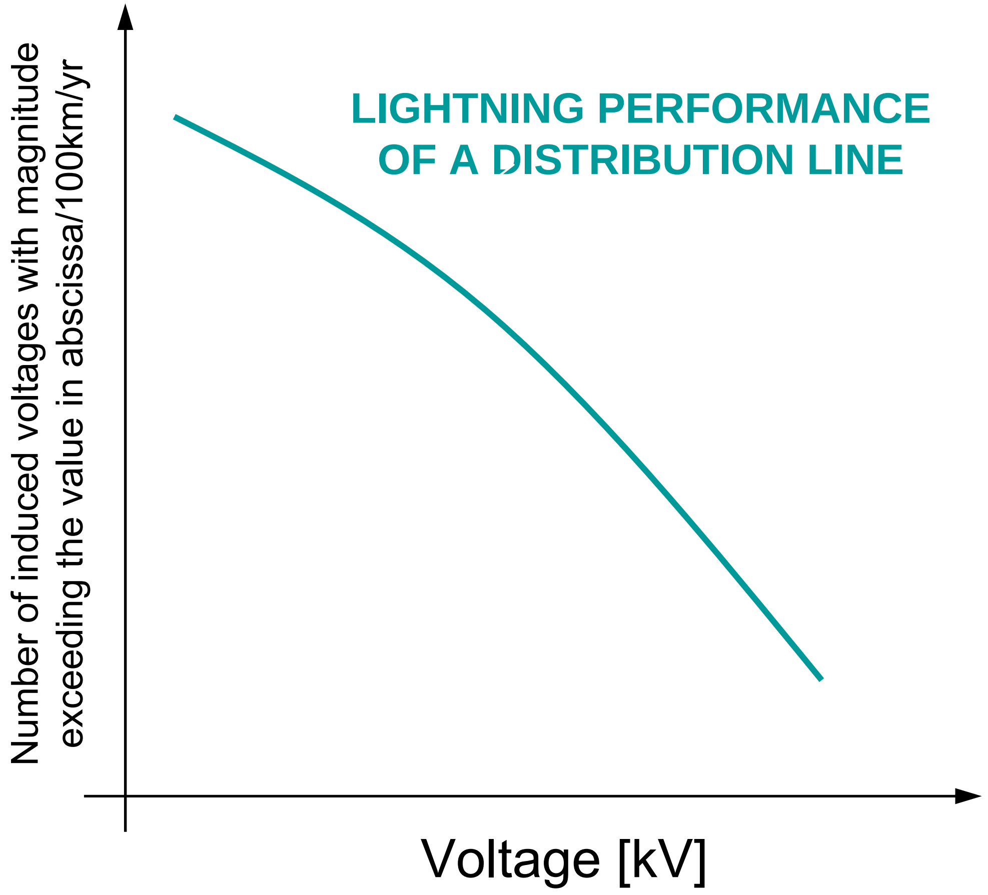
evaluation of the number of annual faults due to **indirect lightning** that a distribution overhead line may experience, as a function of **insulation level** and line **construction design**.



Lightning performance of distribution lines

Distribution systems insulation coordination →

The lightning performance of overhead lines is generally represented by means of curves reporting how many lightning flashovers per year a distribution line may experience as a function of their insulation levels



Lightning performance of distribution lines *Cont.*

Example: **Rusck** formula

$$U_{max} = \frac{Z_0 I_0 h}{y}\left(1 + \frac{1}{\sqrt{2}}\frac{v}{c}\frac{1}{\sqrt{1 - \frac{1}{2}\left(\frac{v}{c}\right)^2}}\right)$$

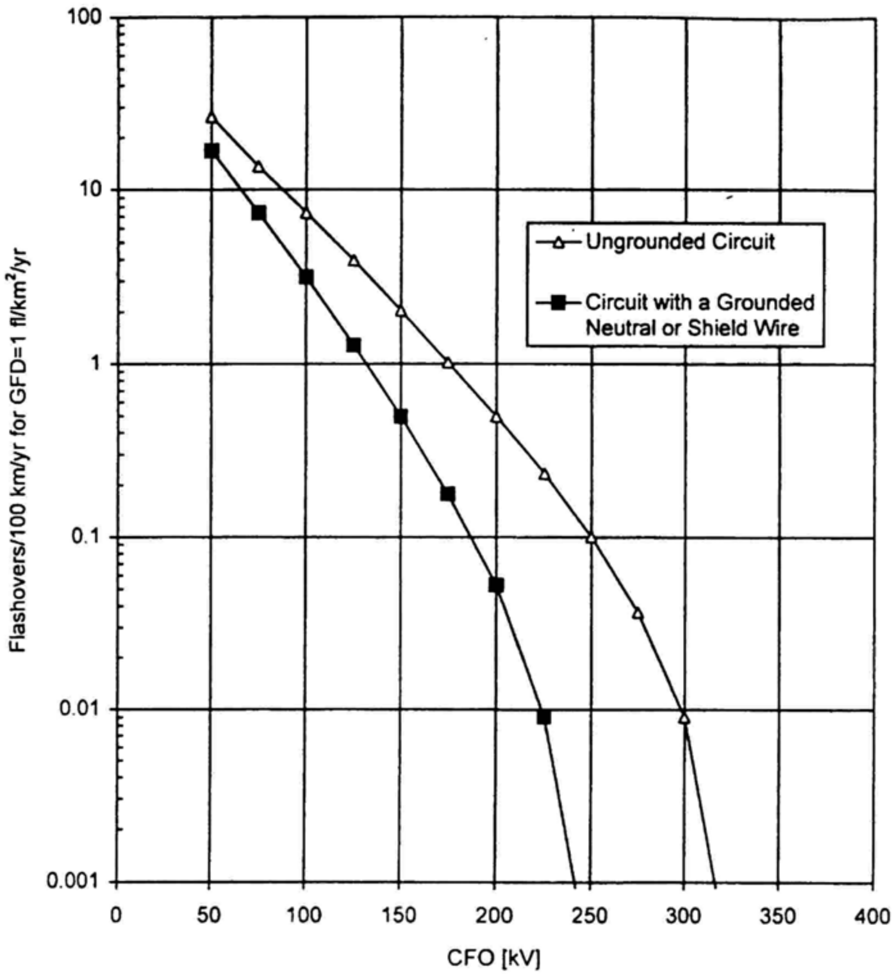
v return stroke velocity

$$Z_0 = 1/4\pi\sqrt{\mu_0/\varepsilon_o} = 30\Omega$$

Assumptions:

1. **single-conductor**
2. **infinitely long lines above a**
3. **perfectly cond. ground**
4. **step current waveshape**

From: "IEEE Std 1410-2004.



Lightning performance of distribution lines *Cont.*

Rusck developed another formula to estimate the shielding effect; it has been obtained by assuming the grounded wire as a non-illuminated conductor and with continuous grounding connections:

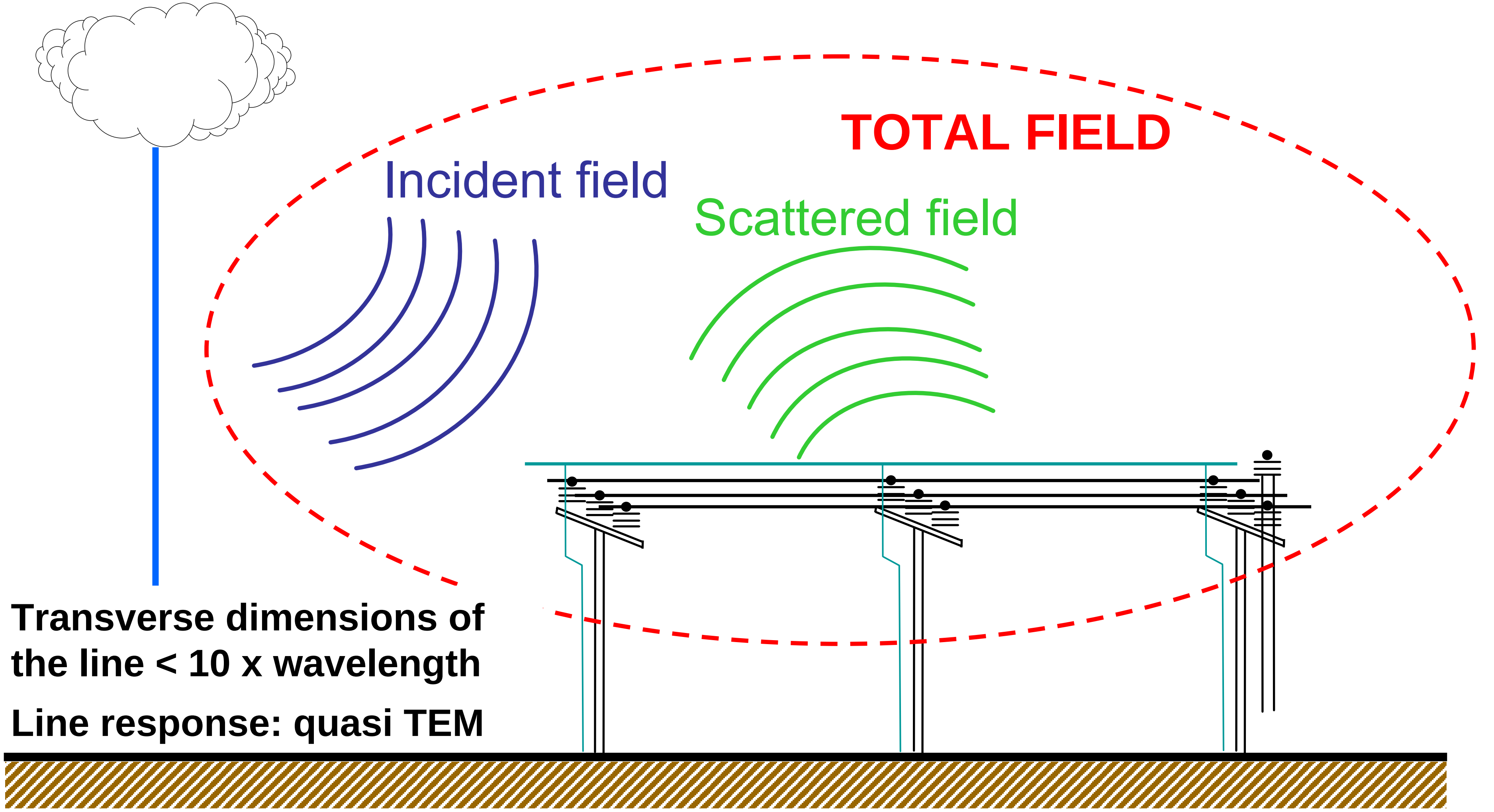
$$\eta = \frac{U'_i}{U_i} = 1 - \frac{h_{sw}}{h_i} \cdot \frac{Z_{sw-i}}{Z_{sw} + 2R_g}$$

where:

- ❑ U'_i is the lightning induced voltage of conductor *i* in presence of the shielding wire;
- ❑ U_i is the lightning induced voltage of conductor *i* in absence of the shielding wire;
- ❑ h_{sw} is the height of the shielding wire;
- ❑ h_i is the height of the conductor I;
- ❑ Z_{sw-i} is the mutual surge impedance between the shielding wire and the conductor *i*;
- ❑ Z_{sw} is the surge impedance of the shielding wire;
- ❑ R_g is the grounding resistance.

Adapted from A. Rusck, "Induced lightning overvoltages on power transmission lines with special reference to the overvoltage protection of low voltage networks", Trans. of the Royal Institute of Technology, Stockholm, 120 (1958).

Lightning performance of distribution lines *Cont.*



- **Transverse dimensions of the line < 10 x wavelength**
- **Line response: quasi TEM**

Lightning performance of distribution lines *Cont.*

Transmission line Coupling equations by Agrawal et al.

(homogeneous lossless multi-conductor line along the x-axis)

$$\frac{\partial}{\partial x}\left[v_i^s(x,t)\right]+\left[L'_{ij}\right]\frac{\partial}{\partial t}\left[i_i(x,t)\right]=\left[E_x^e(x,h_i,t)\right]$$

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

where:

- ❑ [L_{ij}’]: per-unit-length inductance matrix of the line;
- ❑ [C_{ij}’]: per-unit-length capacitance matrix of the line;
- ❑ [$E_x^e(x,h_i,t)$]: vector of the horizontal component of the exciting (or incident) electric field along the x axis at the i_{th} conductor’s height h_i;
- ❑ [$i_i(x,t)$]: vector of the line currents;
- ❑ [$v_i^s(x,t)$]: vector of the scattered voltage.

Lightning performance of distribution lines *Cont.*

$$\left[v_i(x,t)\right]=\left[v_i^s(x,t)\right]+\left[v_i^e(x,t)\right]=\left[v_i^s(x,t)\right]-\left[\int_0^{h_i} E_z^e(x,z,t)dz\right]$$

where:

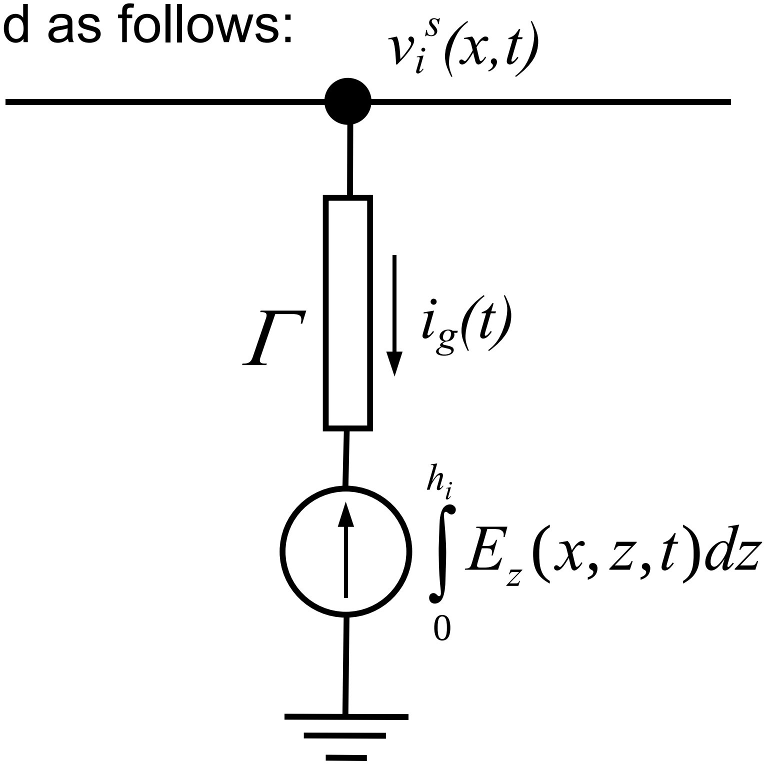
- ❑ $[v_i^e(x,t)]$: vector of the **exiting** (or incident) voltage, due to the exciting (or incident), vertical component of the electric field;
- ❑ $[v_i(x,t)]$: vector of the **total** voltage;

Adapted from M. Paolone, C.A. Nucci, E. Petrache, F. Rachidi, "Mitigation of Lightning-Induced Overvoltages in Medium Voltage Distribution Lines by Means of Periodical Grounding of Shielding Wires and of Surge Arresters: Modelling and Experimental Validation", IEEE Trans. on PWDR, Vol. 19, Issue 1, Gennaio 2004, pp. 423-431.

Lightning performance of distribution lines *Cont.*

The scattered voltage, at the node in which an **arbitrary impedance is connected to the ground**, can be expressed as follows:

$$v_i^s = \Gamma\,(\,i_g\,) + \int_0^{h_i} E_z^e(x,z,t)dz$$



Γ is an integro-differential operator, which describes the voltage drop across the impedance as function of current i_g ($\Gamma = R\,i_g$ for a simple resistance).

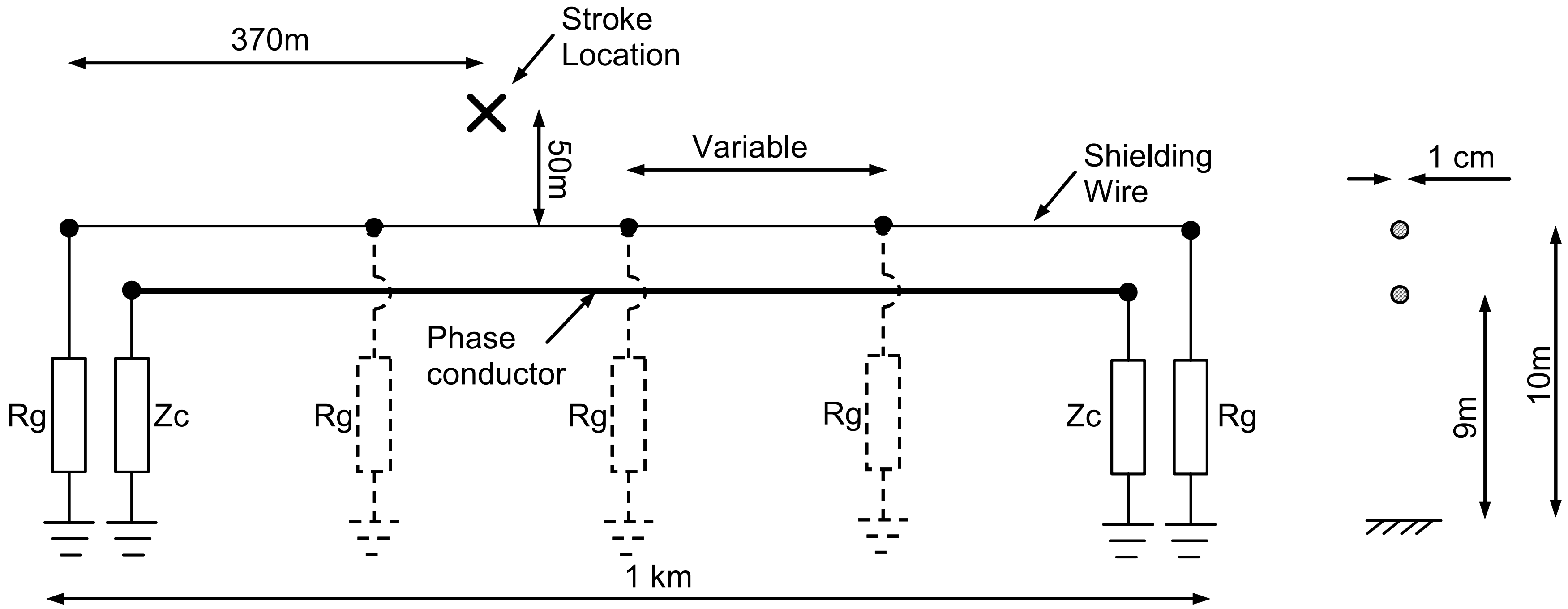
Adapted from M. Paolone, C.A. Nucci, E. Petrache, F. Rachidi, "Mitigation of Lightning-Induced Overvoltages in Medium Voltage Distribution Lines by Means of Periodical Grounding of Shielding Wires and of Surge Arresters: Modelling and Experimental Validation", IEEE Trans. on PWDR, Vol. 19, Issue 1, Gennaio 2004, pp. 423-431.

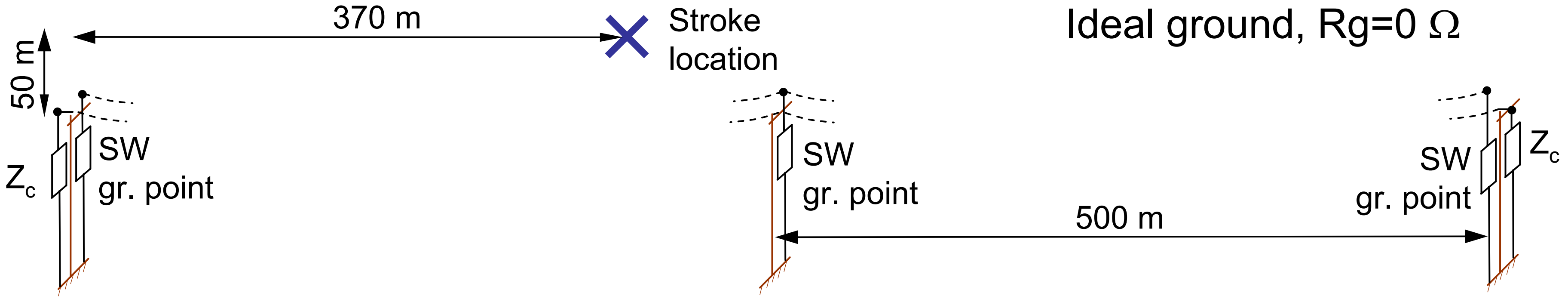
Lightning performance of distribution lines *Cont.*

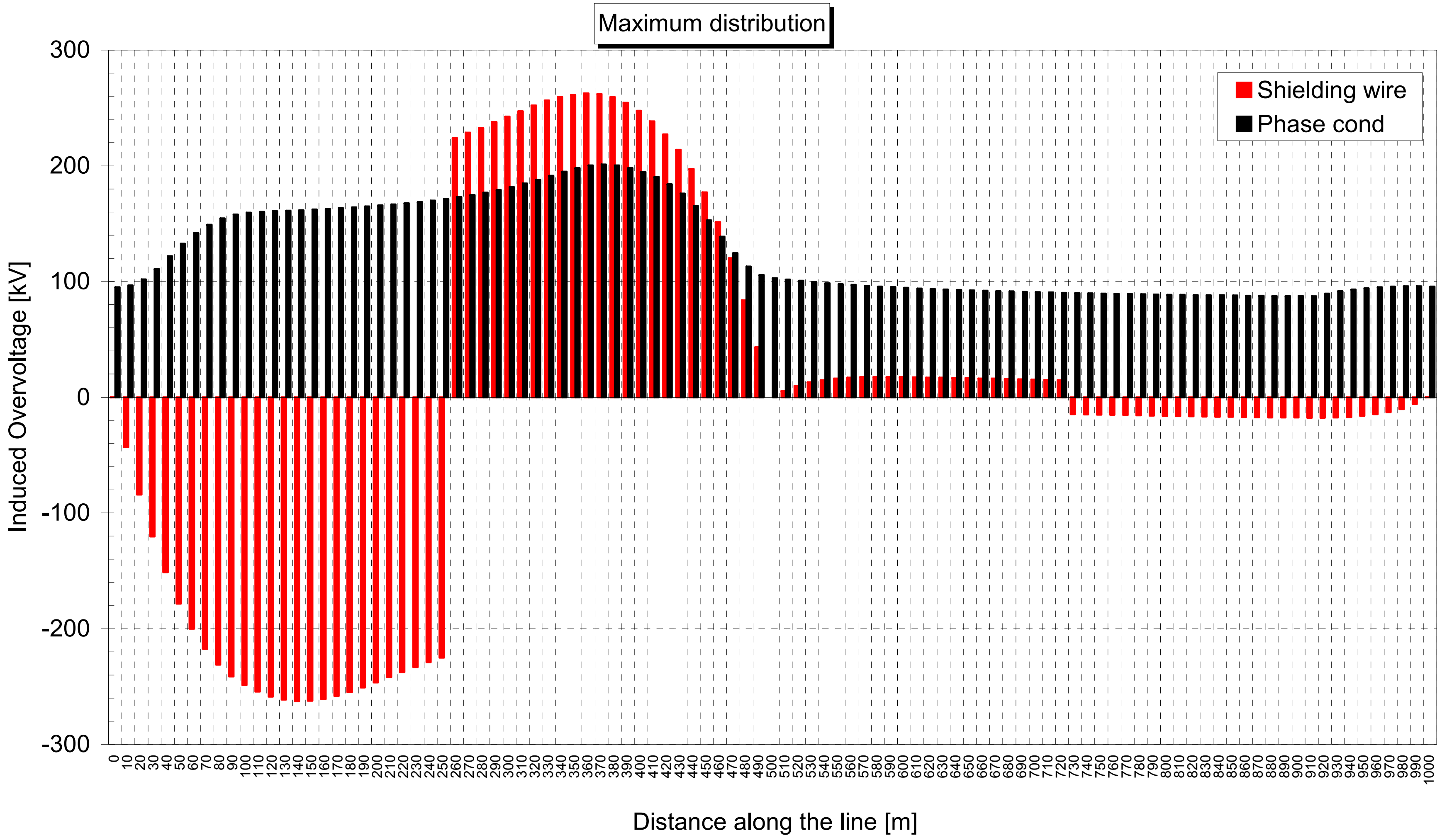
To better assess the effect of the number of the multiple groundings of the shielding wire, let assume a stroke location which does not “face” any of the grounding point.

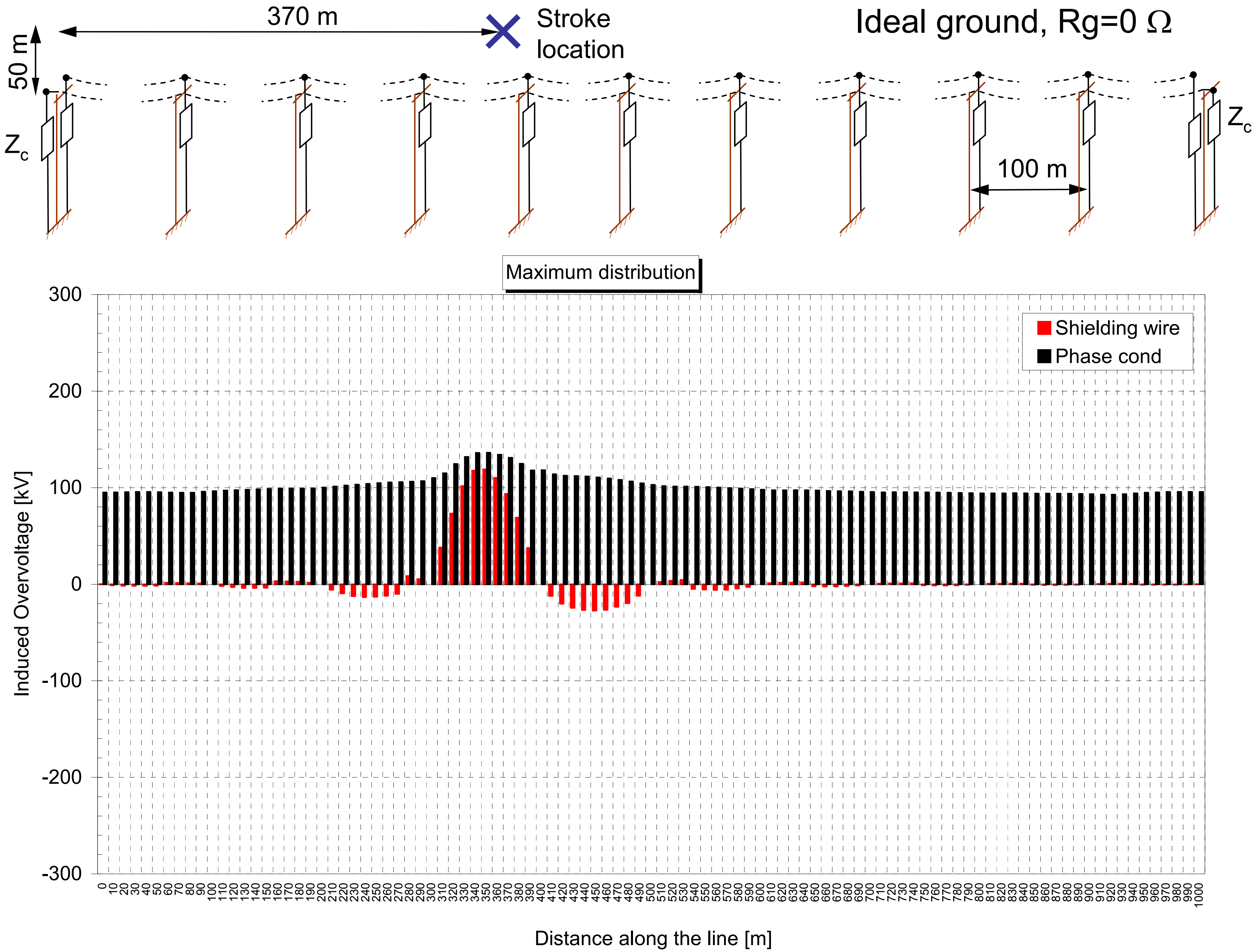
Lightning current with:

- ☐ 30 kA peak value;
- ☐ 100 kA/μs max time derivative.




370 m
50 m
Stroke
location
Ideal ground, Rg=0 Ω
SW
gr. point
Z_c
SW
gr. point
500 m
SW
gr. point
Z_c


Maximum distribution
🟥 Shielding wire
■ Phase cond
Induced Overvoltage [kV]
300
200
100
0
-100
-200
-300
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260 270 280 290 300 310 320 330 340 350 360 370 380 390 400 410 420 430 440 450 460 470 480 490 500 510 520 530 540 550 560 570 580 590 600 610 620 630 640 650 660 670 680 690 700 710 720 730 740 750 760 770 780 790 800 810 820 830 840 850 860 870 880 890 900 910 920 930 940 950 960 970 980 990 1000
Distance along the line [m]


370 m
Stroke
location
Ideal ground, Rg=0 Ω
50 m
Z_c
Z_c
100 m
Maximum distribution
Shielding wire
Phase cond
300
200
100
0
-100
-200
-300
Induced Overvoltage [kV]
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260 270 280 290 300 310 320 330 340 350 360 370 380 390 400 410 420 430 440 450 460 470 480 490 500 510 520 530 540 550 560 570 580 590 600 610 620 630 640 650 660 670 680 690 700 710 720 730 740 750 760 770 780 790 800 810 820 830 840 850 860 870 880 890 900 910 920 930 940 950 960 970 980 990 1000
Distance along the line [m]

Lightning performance of distribution lines *Cont.*

An alternative to IEEE method: LIOV & Monte Carlo (LIOV-MC)

1. Inputs:
   - lightning current parameters
   - return stroke velocity
   - line and ground data
2. Random generation of events ($\overbrace{\mathbf{I_p} \quad \mathbf{t_f}}^{\textbf{correlated}} \quad x \quad y$) (e.g. > 10 000)
3. Selection of indirect lightning events by using a lightning incidence model
4. Induced overvoltage calculation using LIOV (or LIOV-EMTP) code
5. Counting of the *n* events generating overvoltages greater than the insulation level (e.g. 1.5·CFO)
6. 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 = annual ground flash density, S = striking area, L=line length)

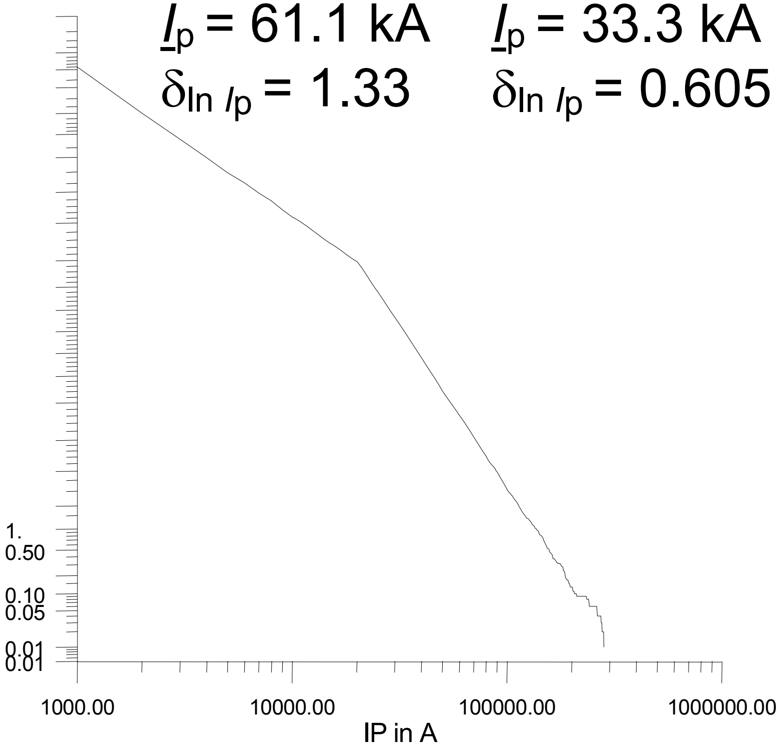
Lightning performance of distribution lines *Cont.*

Lightning performance of distribution lines: effects of shielding wires

Current amplitude

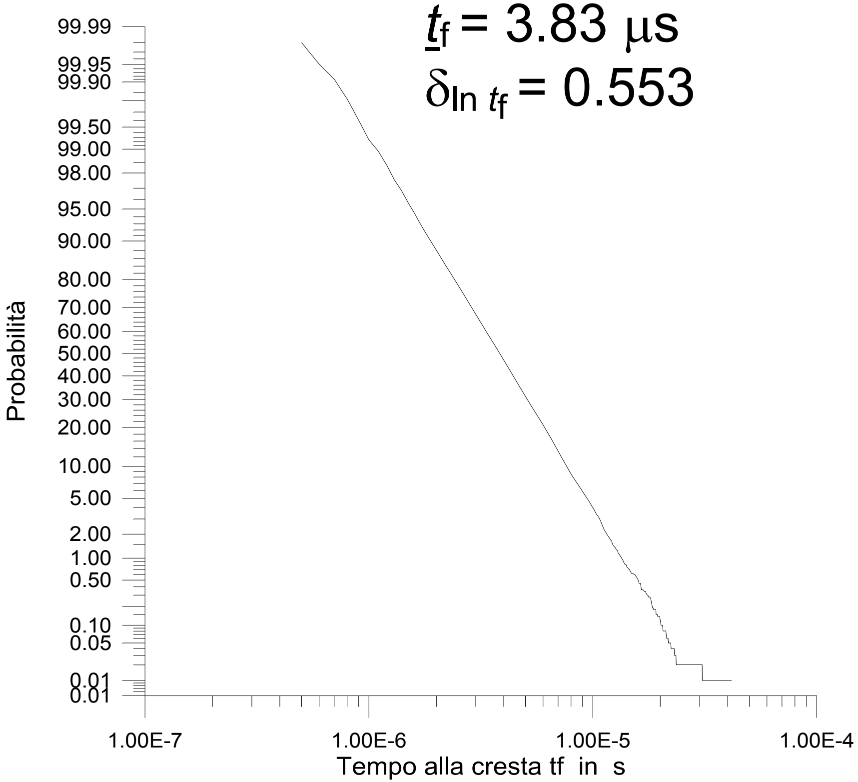
$I_p \le 20$kA
$\underline{I}_p = 61.1$ kA
$\delta_{\ln I_p} = 1.33$

$I_p > 20$ kA
$\underline{I}_p = 33.3$ kA
$\delta_{\ln I_p} = 0.605$

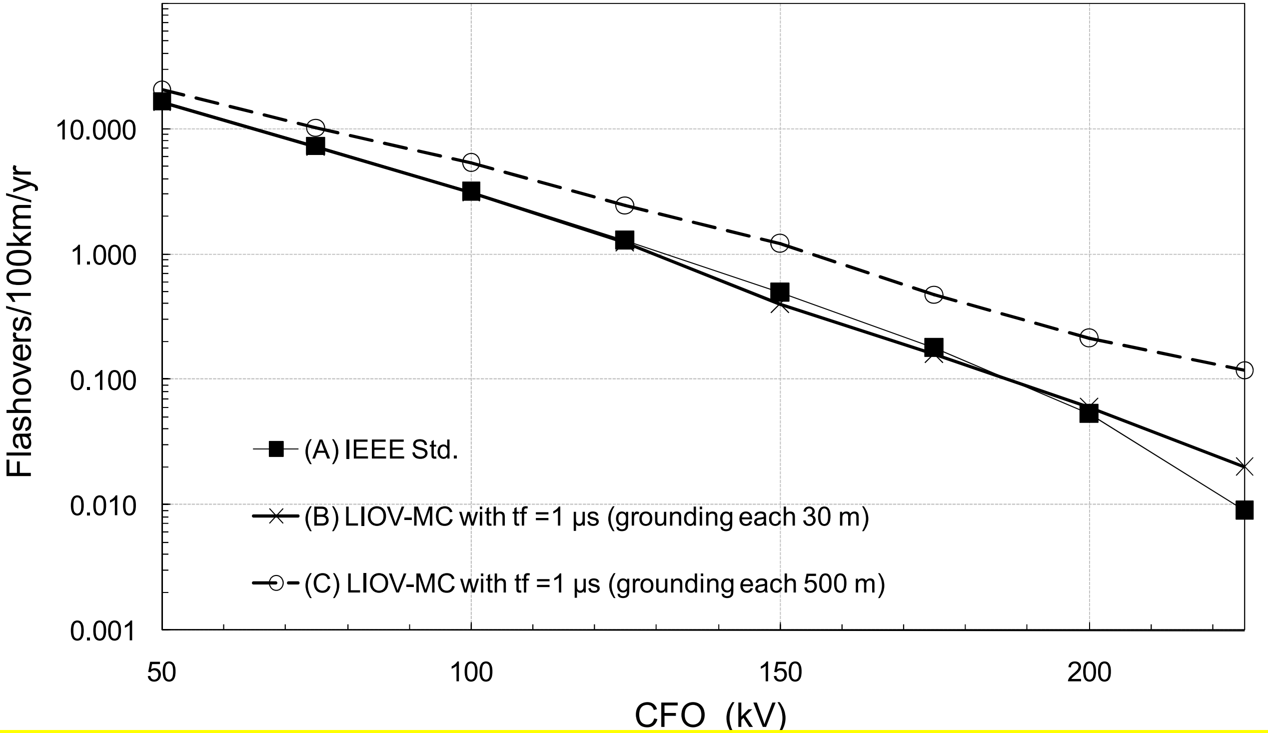


Time to crest

$\underline{t}_f = 3.83$ µs
$\delta_{\ln t_f} = 0.553$



Lightning performance of distribution lines *Cont.*



Comparison between the line flashover rate curve of IEEE Std. 1410 (A) and those obtained by using LIOV-MC, enforcing *tf* = 1 μs for each event, for the case of two different shielding wire grounding spacing, namely 30 m (B), and 500 m (C).

(Flashovers are assumed to occur only from the phase conductor to ground)

Lightning performance of distribution lines *Cont.*

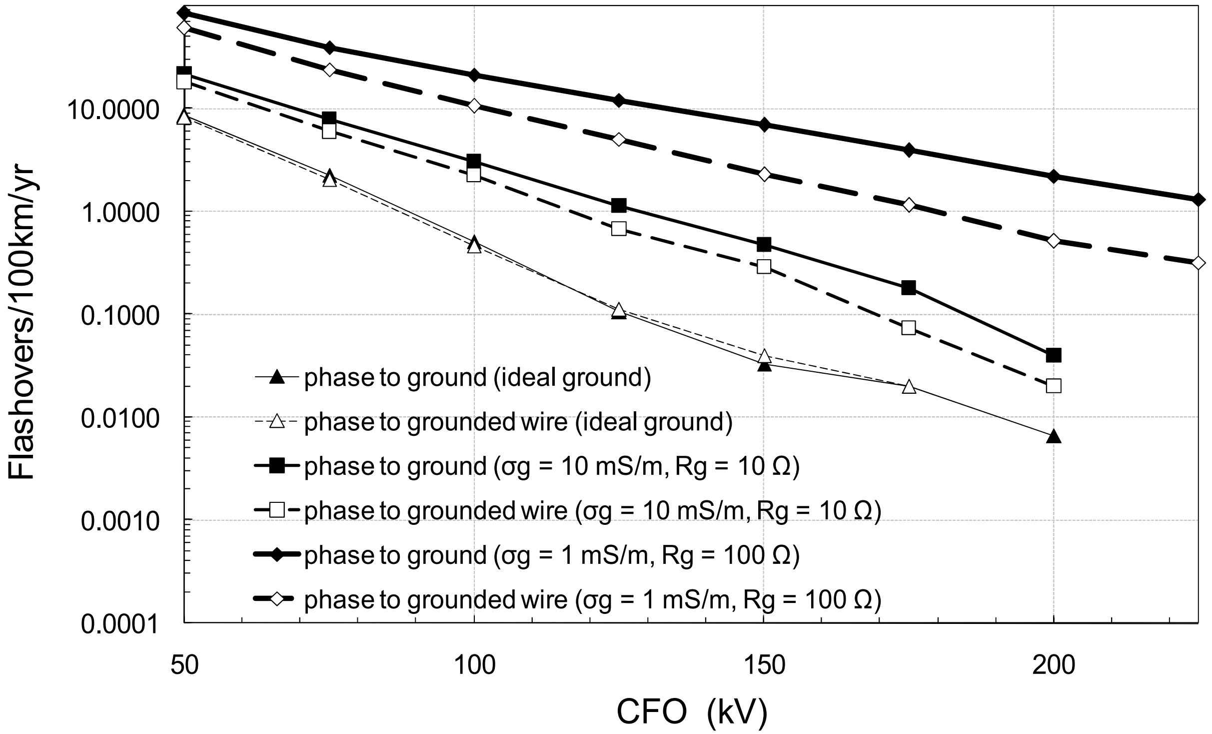
For purpose of comparison with the IEEE Std. 1410, the results of the previous slide have been obtained by assuming the **flashover occurring only from the phase conductor to ground**, as specified in the figure caption.

In principle, however, the line could experience flashovers **between the phase conductor and the grounded conductor too**.

The next slide shows the flashover rates calculated by considering the **two different flashover paths, namely the phase–to-ground path and the phase-to-grounded wire one**.

Note that the results of next slide must be interpreted by keeping in mind that the **two different flashover paths are characterized by different CFOs especially for wooden poles and crossarms**.

Lightning performance of distribution lines *Cont.*



Comparison between phase-to-ground and phase-to-grounded-wire flashover rate curves calculated for different ground conductivity σ_g and grounding resistance R_g.

(Shielding wire grounded each 200 m. A linear model is assumed for the grounding impedance of the neutral or shielding wire)

Lightning performance of distribution lines *Cont.*

The results show clearly that the mitigation effect of the shielding wire depends, in general, more on the **spacing between two consecutive groundings** rather than on the value of the grounding resistance.

This differs from the case of direct stroke for transmission lines for which the effectiveness of the shielding wire depends strongly on the grounding resistance (BFR value).

Additionally results show that it is only when the **grounding resistance becomes poor (100 Ω or larger), that it starts to affect in a more significant way the distribution of the induced voltage along the line**.

Lightning performance of distribution lines *Cont.*

According with preliminary studies*, simulations performed with LIOV-EMTP96 code shows that **an important reduction of the induced overvoltages on typical distribution overhead lines can be achieved only with a large number of surge arresters namely 1 surge arrester every 200 m**.

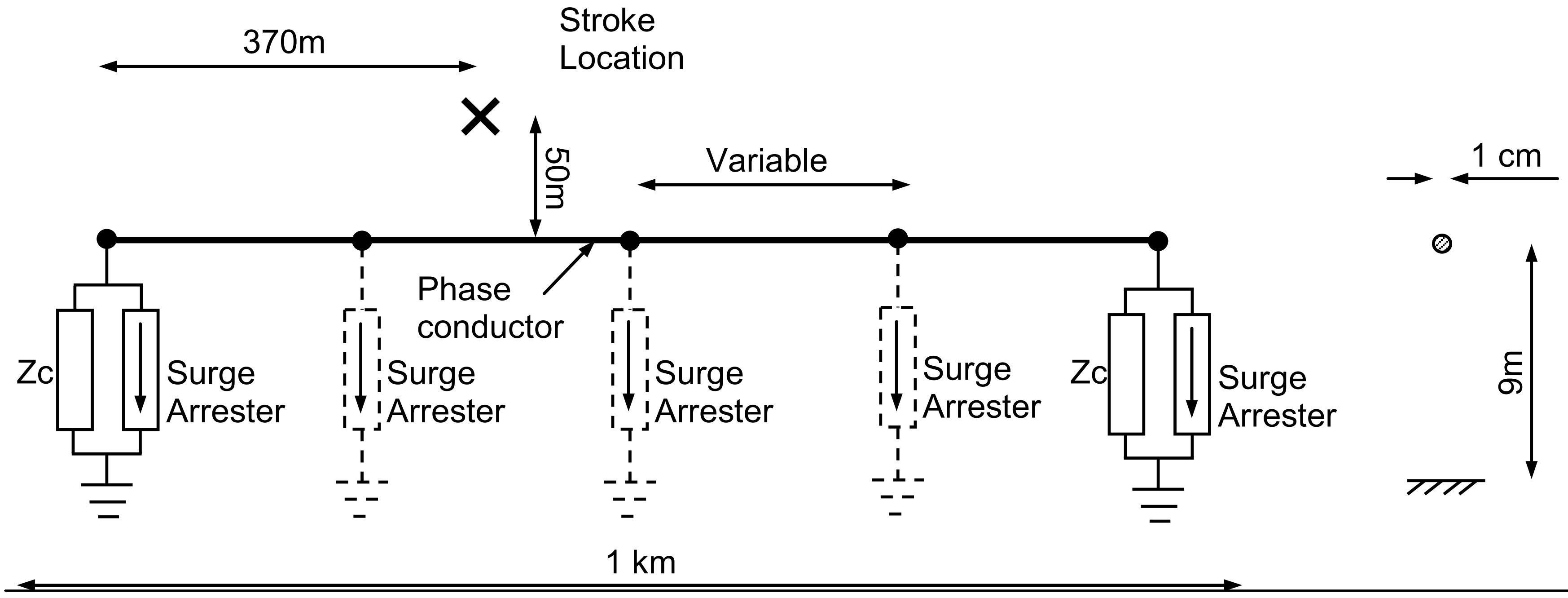
It can also be seen that for some configurations with a **low number of surge arresters** (e.g. **one each 1000 m**), their presence could result in important negative peaks of the induced voltage, which are due to surge reflections occurring in correspondence of surge arresters operation.

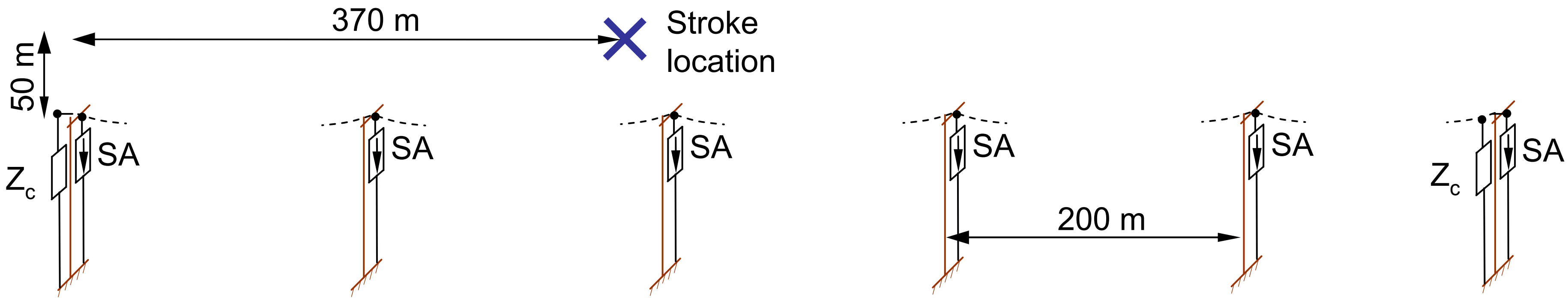
** M. Paolone, C.A. Nucci, E. Petrache, F. Rachidi, "Mitigation of Lightning-Induced Overvoltages in Medium Voltage Distribution Lines by Means of Periodical Grounding of Shielding Wires and of Surge Arresters: Modelling and Experimental Validation", IEEE Trans. on PWDR, Vol. 19, Issue 1, Gennaio 2004, pp. 423-431.*

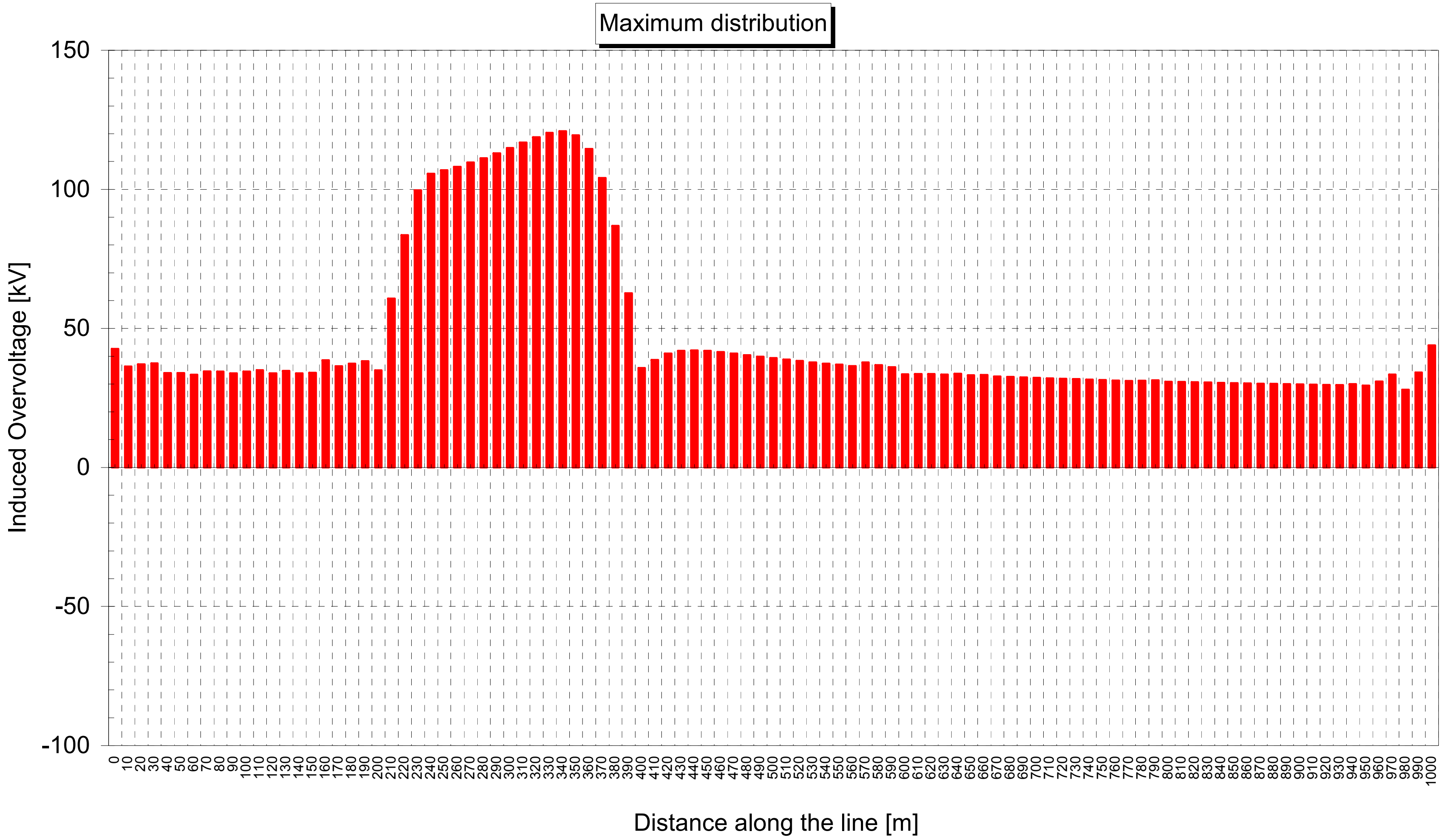
Lightning performance of distribution lines *Cont.*

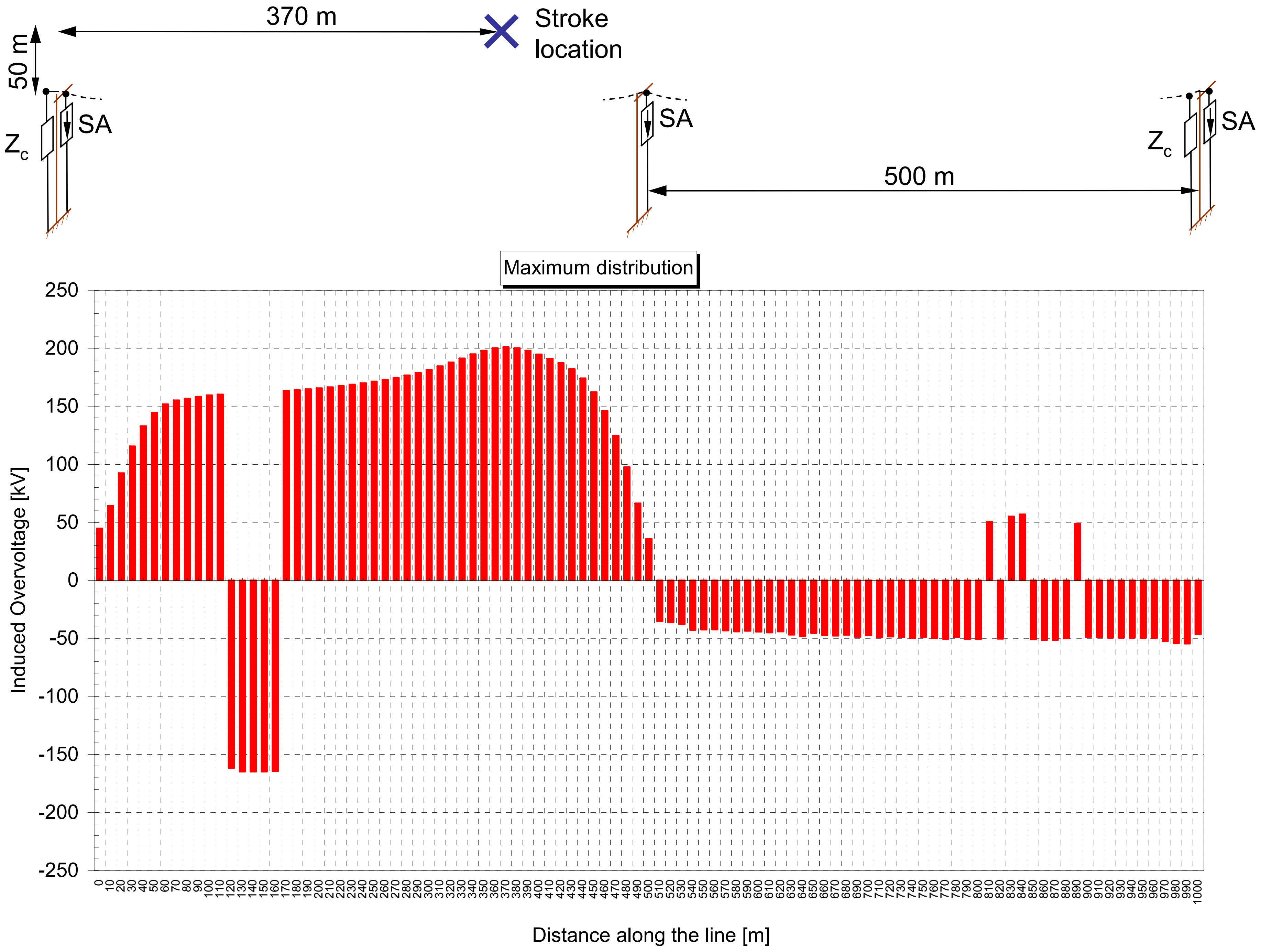
An example for the assessment of the effect of **surge arresters** on the linghtning-induced voltages

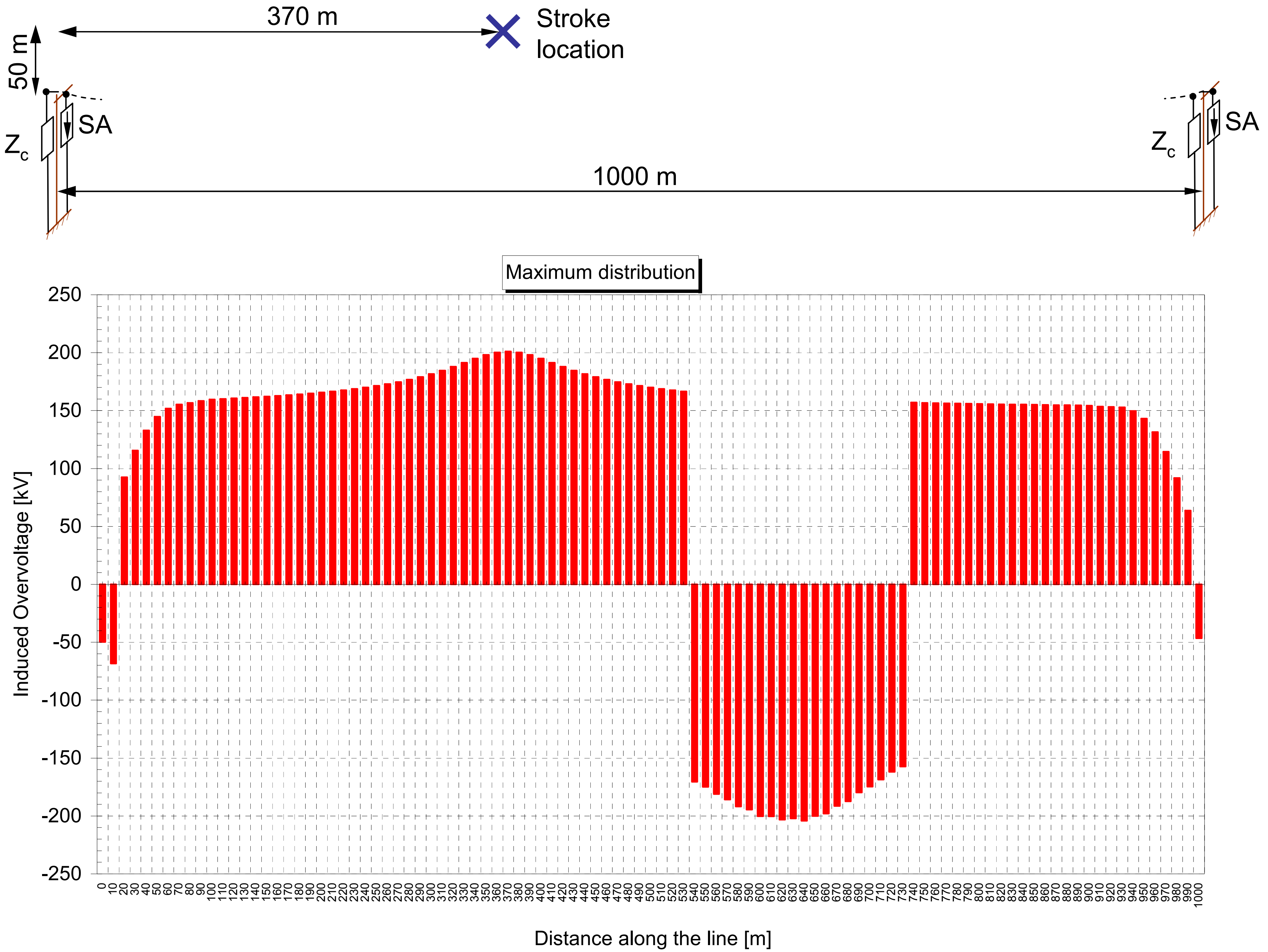
- ❑ single conductor overhead line above an ideal ground:
- ❑ line length 1 km;
- ❑ number of surge arresters: 2, 3, 6 (1000 m, 500m and 200 m);
- ❑ lightning current: 30 kA with max time derivative of 100 kA/μs




370 m
Stroke location
50 m
Z$_c$
SA
SA
SA
SA
SA
200 m
Z$_c$
SA


Maximum distribution
Induced Overvoltage [kV]
150
100
50
0
-50
-100
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260 270 280 290 300 310 320 330 340 350 360 370 380 390 400 410 420 430 440 450 460 470 480 490 500 510 520 530 540 550 560 570 580 590 600 610 620 630 640 650 660 670 680 690 700 710 720 730 740 750 760 770 780 790 800 810 820 830 840 850 860 870 880 890 900 910 920 930 940 950 960 970 980 990 1000
Distance along the line [m]


370 m
Stroke location
50 m
SA
Z_c
SA
500 m
SA
Z_c
Maximum distribution
Induced Overvoltage [kV]
250
200
150
100
50
0
-50
-100
-150
-200
-250
Distance along the line [m]
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260 270 280 290 300 310 320 330 340 350 360 370 380 390 400 410 420 430 440 450 460 470 480 490 500 510 520 530 540 550 560 570 580 590 600 610 620 630 640 650 660 670 680 690 700 710 720 730 740 750 760 770 780 790 800 810 820 830 840 850 860 870 880 890 900 910 920 930 940 950 960 970 980 990 1000

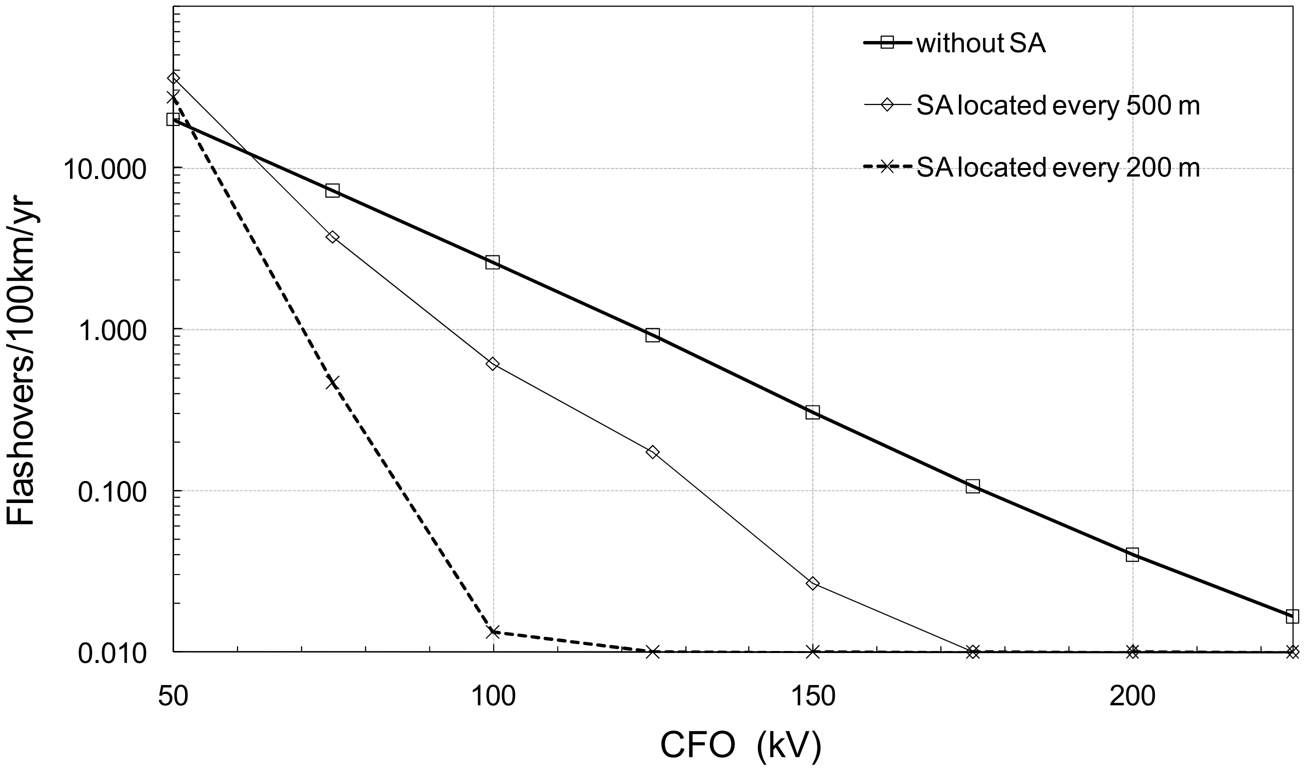

370 m
Stroke location
50 m
SA
Z_c
1000 m
SA
Z_c
Maximum distribution
250
200
150
100
50
0
-50
-100
-150
-200
-250
Induced Overvoltage [kV]
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260 270 280 290 300 310 320 330 340 350 360 370 380 390 400 410 420 430 440 450 460 470 480 490 500 510 520 530 540 550 560 570 580 590 600 610 620 630 640 650 660 670 680 690 700 710 720 730 740 750 760 770 780 790 800 810 820 830 840 850 860 870 880 890 900 910 920 930 940 950 960 970 980 990 1000
Distance along the line [m]

Lightning performance of distribution lines *Cont.*

Depending on the line configuration, stroke location and on the distance between two **consecutive surge arresters**, the negative voltage wave due to the arrester’s non-linear characteristic, make it possible for the **largest amplitude of the induced overvoltage to occur at a point on the line different from that closest to the stroke location**. In addition, this overvoltage **can be more severe** than the maximum voltage amplitude induced in the absence of surge arresters.

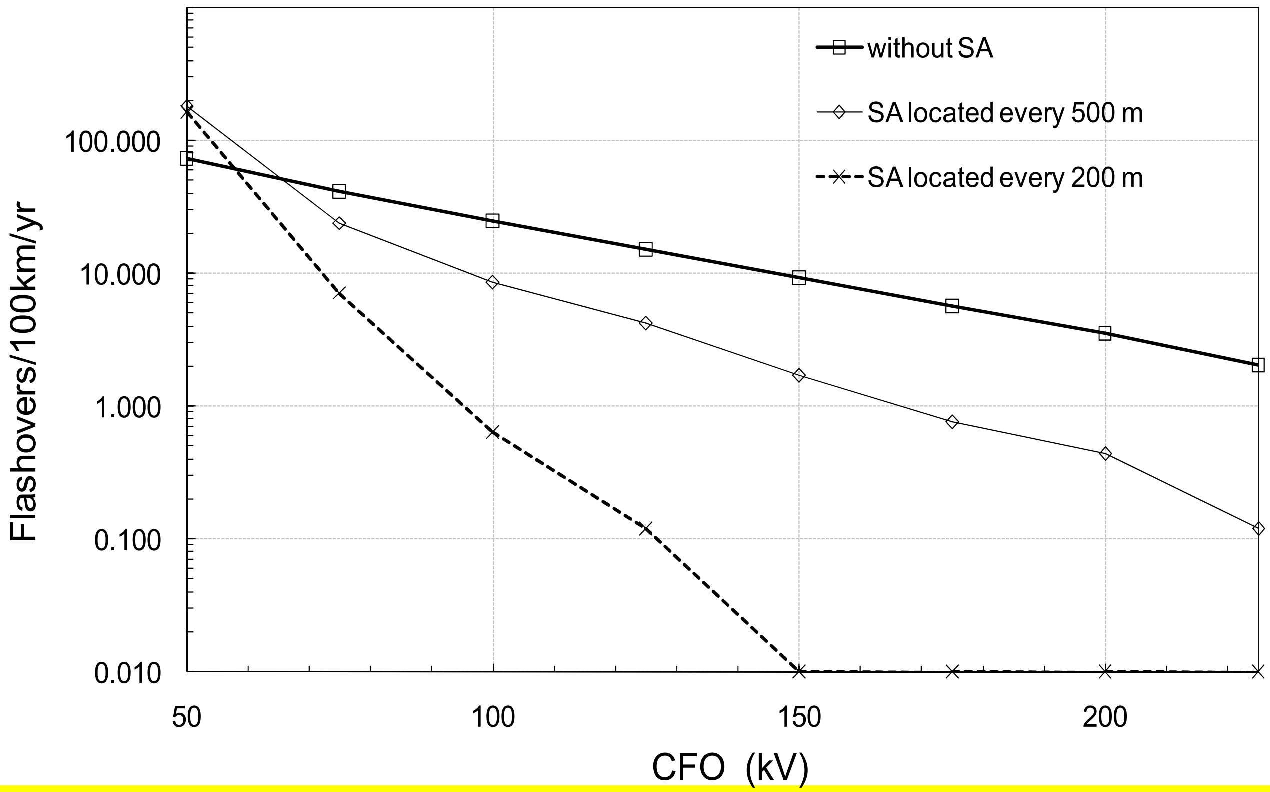
By **increasing the number of surge arresters**, the maximum amplitude of the induced overvoltage tends to be confined within the range defined by the positive and negative values of the threshold voltage of the surge arrester’s non-linear V-I characteristic.

Lightning performance of distribution lines *Cont.*



Line flashover rate curves obtained by using LIOV–MC, for the case of a line with and without surge arresters located every 200 m and 500 m
Ideal ground

Lightning performance of distribution lines *Cont.*



Line flashover rate curves obtained by using LIOV–MC, for the case of a line with and without surge arresters located every 200 m and 500 m
Ideal ground

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