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EM Interaction between LEMP and power distribution systems: modeling and experimental validation

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Presentation outline

1. Illuminated line models

1.a. Lossless single-conductor line

1.b. Lossy single-conductor line

1.c. Multi-conductor line

2. LIOV and LIOV-EMTP codes

2.a. General overview

2.b. Experimental validation

2.c. Applications

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1. Illuminated line models:

1.a. lossless single-conductor line

Main assumptions

EM-Transients are due to various sources such as faults, switching operations and direct lightning strikes to the lines, **but also to the action of external electromagnetic fields** (e.g. nearby lightning strokes).

To solve the problem of interest, use could be made of the **antenna theory**, the general approach based on Maxwell's equations.
However, due to the length of distribution lines, the use of such a theory for practical evaluations implies long computation time, especially when statistical studies are desired (e.g. insulation coordination of power distribution overhead lines, treatment of non-linear phenomena like corona or presence of surge arresters).

Main assumptions

Use of transmission-line theory:

We will denote the relevant trasmission line equations by using the adjective **‘generalized’**, to mean that these equation - describing voltage and current propagation along a transmission line - take into account also the presence of an **external electromagnetic field**.

These equations, which we are going to illustrate, are also called **transmission line coupling equations**: they describe, in general, the electromagnetic coupling between an external electromagnetic pulse and a transmission line.

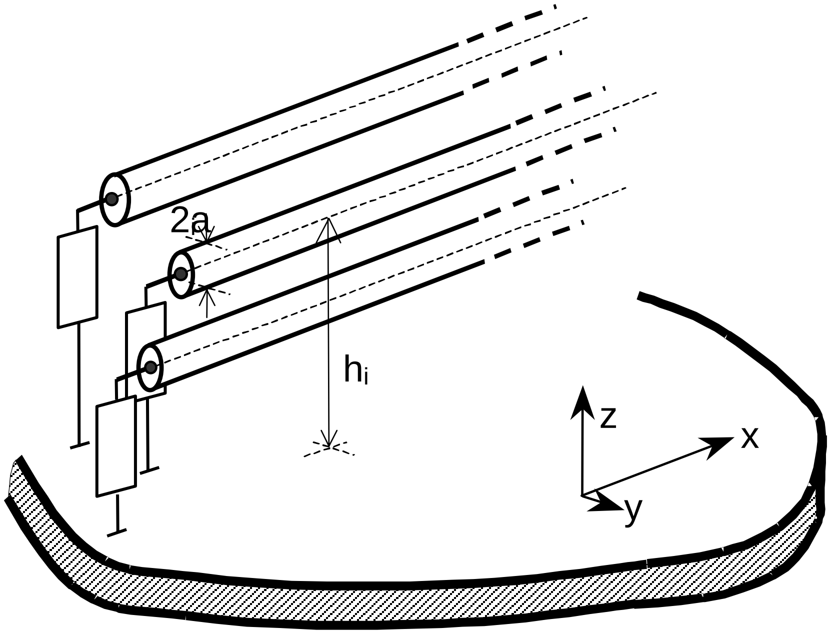
When the external electromagnetic field is equal to zero, they become the **‘classical’** transmission line equations.

1. Illuminated line models:

1.a. lossless single-conductor line

Main assumptions

Let us make reference to the geometry of Figure and make the following assumptions:



- ❑ The line geometry is reasonably uniform;

- ❑ **The transverse dimensions (cross sectional dimensions) of the line are small compared to the minimum wavelength λ_{min} → we can then consider that propagation occurs mainly along *x* axis, and, as we shall see, the line can be represented by a distributed-parameter structure along its axis.**

1. Illuminated line models:

1.a. lossless single-conductor line

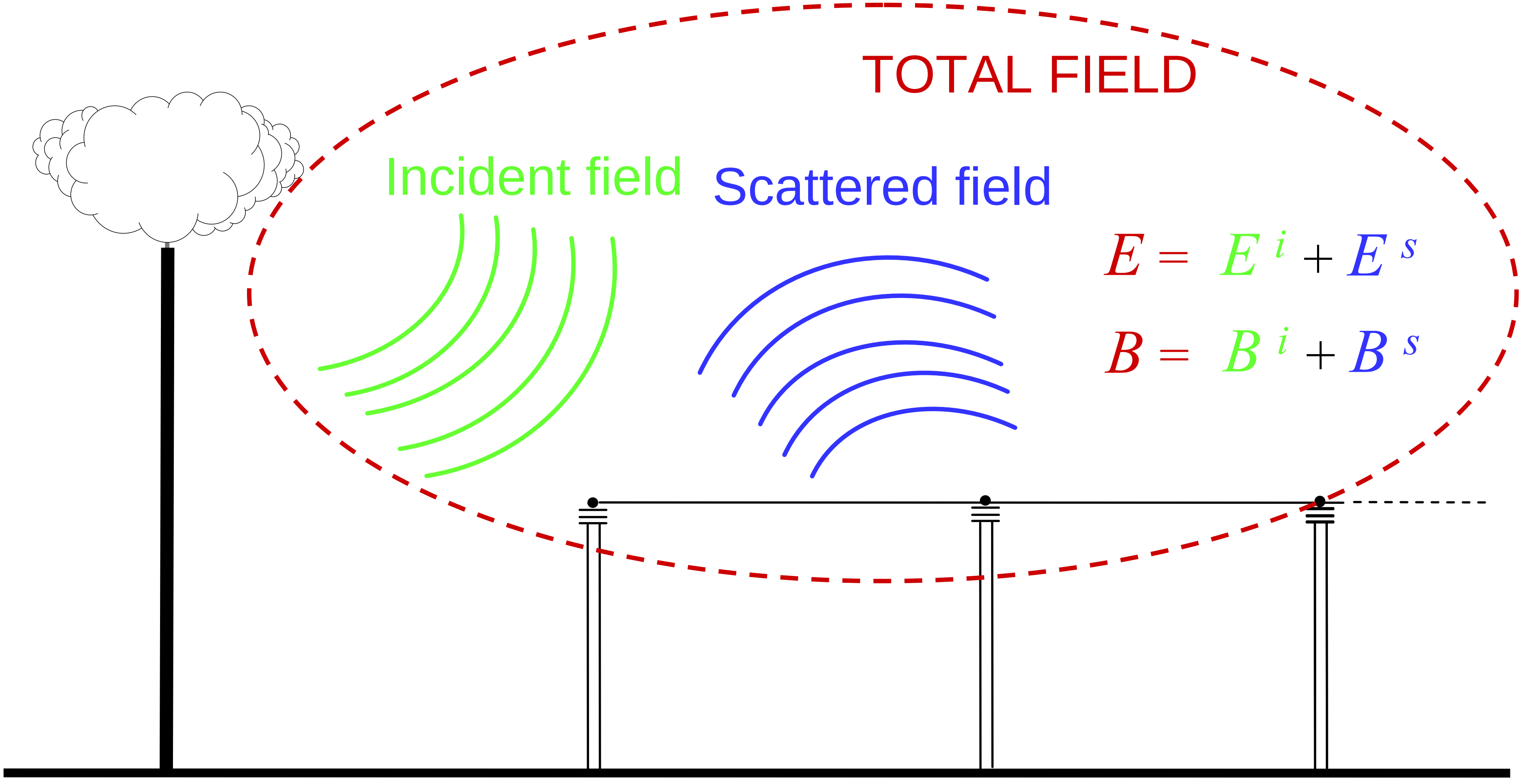
Main assumptions

- **The line response is quasi-TEM (transverse electromagnetic), i.e. the electromagnetic field produced by the electric charges and currents along the line is confined in the transverse plane and perpendicular to the line axis.** (Note that it is in practical impossible that the response of a line be purely TEM. In fact, a pure TEM mode would occur only for the case of a perfectly conducting ground and when the exciting electromagnetic field has no electric field component tangential to the line conductors.)
- **The sum of the line currents at any cross section of the line is zero, i.e. the ground -*the reference conductor*- is the return path for the currents in the *n* overhead conductors.** (→ we are considering only 'transmission line mode' currents and neglecting the so-called 'antenna-mode' currents. If we desire to compute the load responses of the line, this assumption is adequate, because the antenna mode current response is small near the ends of the line. Along the line, however, the presence of antenna-mode currents makes that the sum of the currents at a cross section is not necessarily equal to zero. However, the quasi-symmetry due to the presence of the ground plane results in a very small contribution of antenna mode currents and consequently, the predominant mode on the line will be transmission line.)

1. Illuminated line models:

1.a. lossless single-conductor line

Agrawal, *Price*, and *Gurbaxani* model



To each field component we associate the corresponding voltage.

1. Illuminated line models:

1.a. lossless single-conductor line

Agrawal, *Price*, and *Gurbaxani* model

$$\frac{dU^s(x)}{dx} + j\omega L' I(x) = E_x^i(x,h)$$

$$\frac{dI(x)}{dx} + j\omega C' U^s(x) = 0$$

Total voltage: $u^t(x) = u^s(x) + u^i(x)$

$$u^i(x) = -\int_0^h E_z^i(x)dz$$

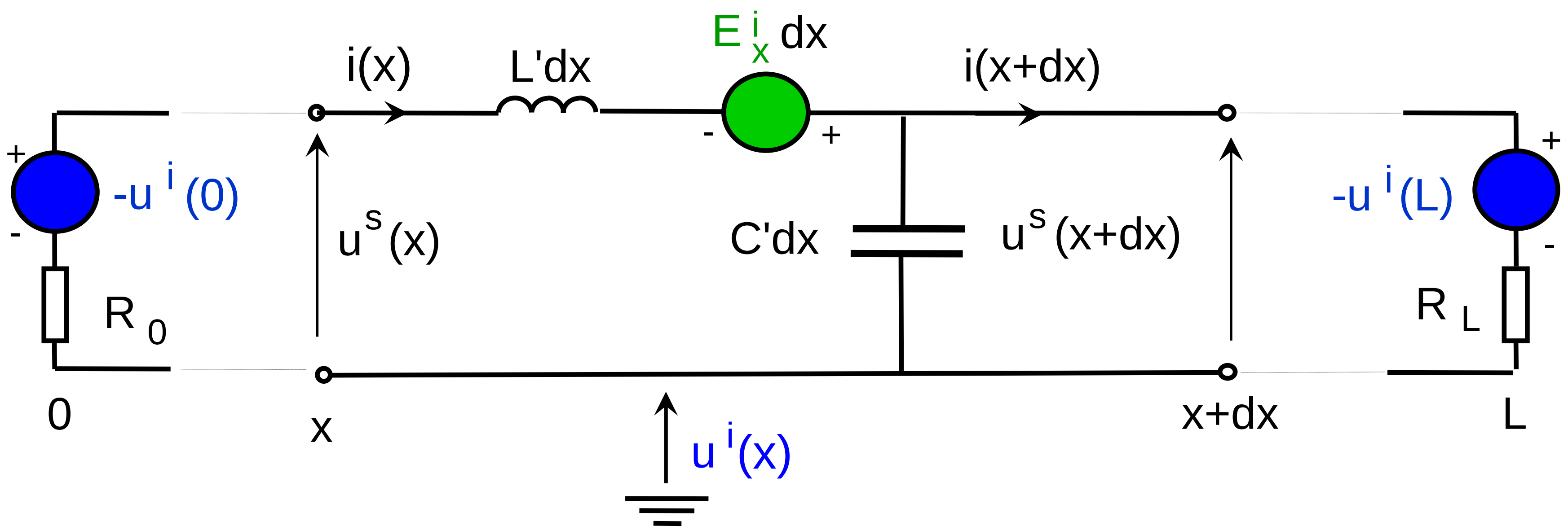
Boundary conditions:

$$\begin{cases} U^s(0) = -Z_A I(0) + \int_0^h E_z^i(0,z)dz \\ U^s(L) = Z_B I(L) + \int_0^h E_z^i(L,z)dz \end{cases}$$

1. Illuminated line models:

1.a. lossless single-conductor line

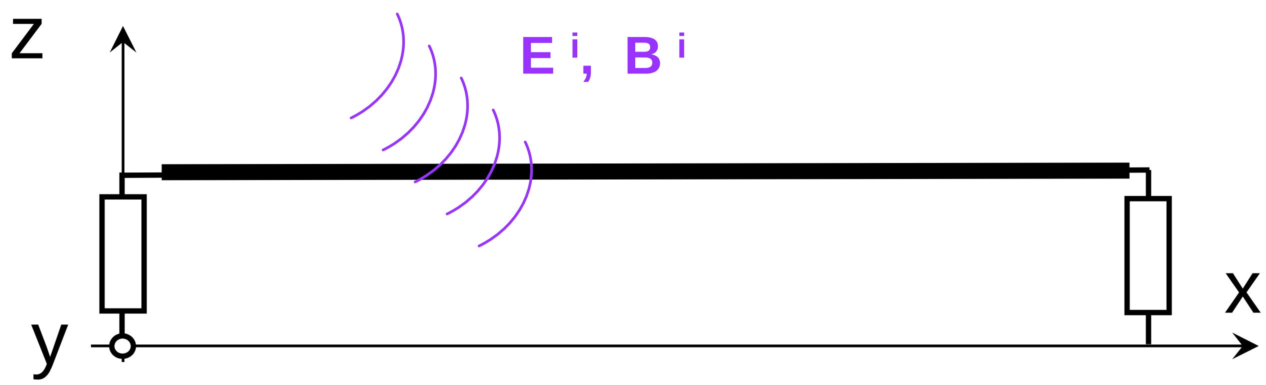
Agrawal, *Price*, and *Gurbaxani* model



1. Illuminated line models:

1.a. lossless single-conductor line

Various equivalent model representations are possible

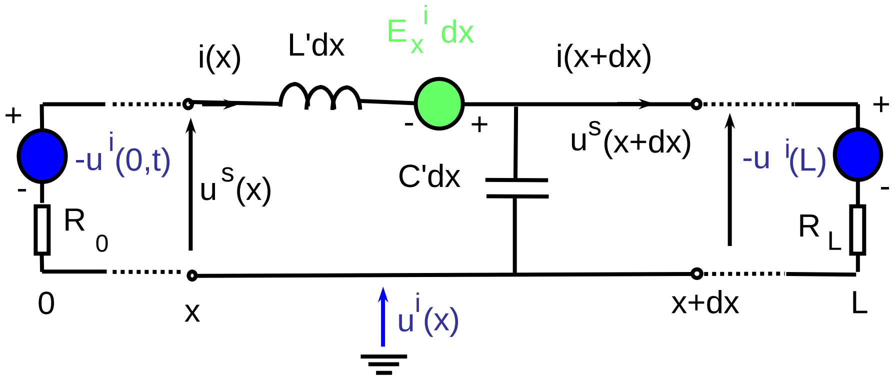


$$\frac{\partial}{\partial t}\int_0^h B_y^i(x,z,t)dz = -E_x^i(x,h,t) + \frac{\partial}{\partial x}\int_0^h E_z^i(x,z,t)dz$$

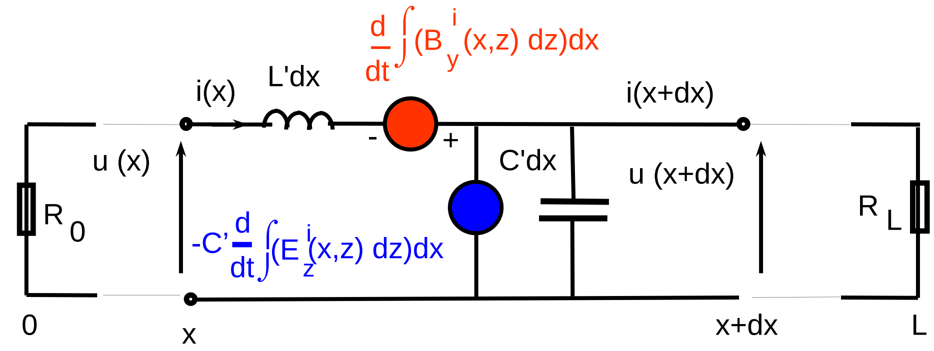
1. Illuminated line models:

1.a. lossless single-conductor line

Taylor, *Satterwhite*, and *Harrison* model



Agrawal et al.



Taylor et al.

$$\frac{dU^s(x)}{dx} + j\omega L' I(x) = E_x^i(x,h)$$

$$\frac{dI(x)}{dx} + j\omega C' U^s(x) = 0$$

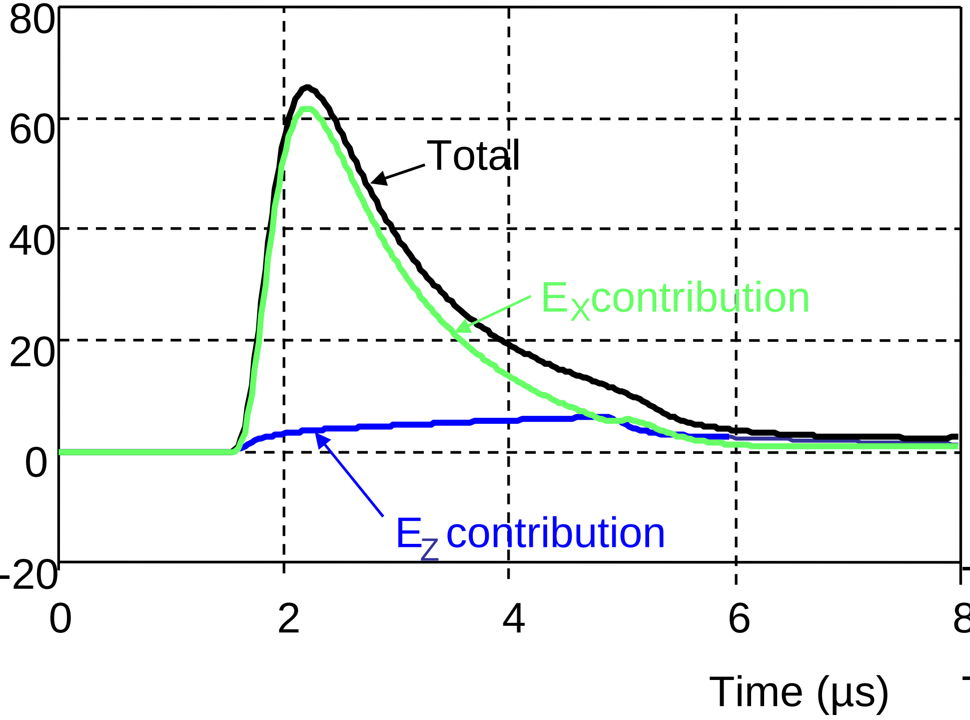
$$U(x) = U^s(x) + U^i(x) = U^s(x) - \int_0^h E_z^i(x,z)dz$$

$$\frac{dU(x)}{dx} + j\omega L' I(x) = -j\omega \int_0^h B_y^i(x,z)dz$$

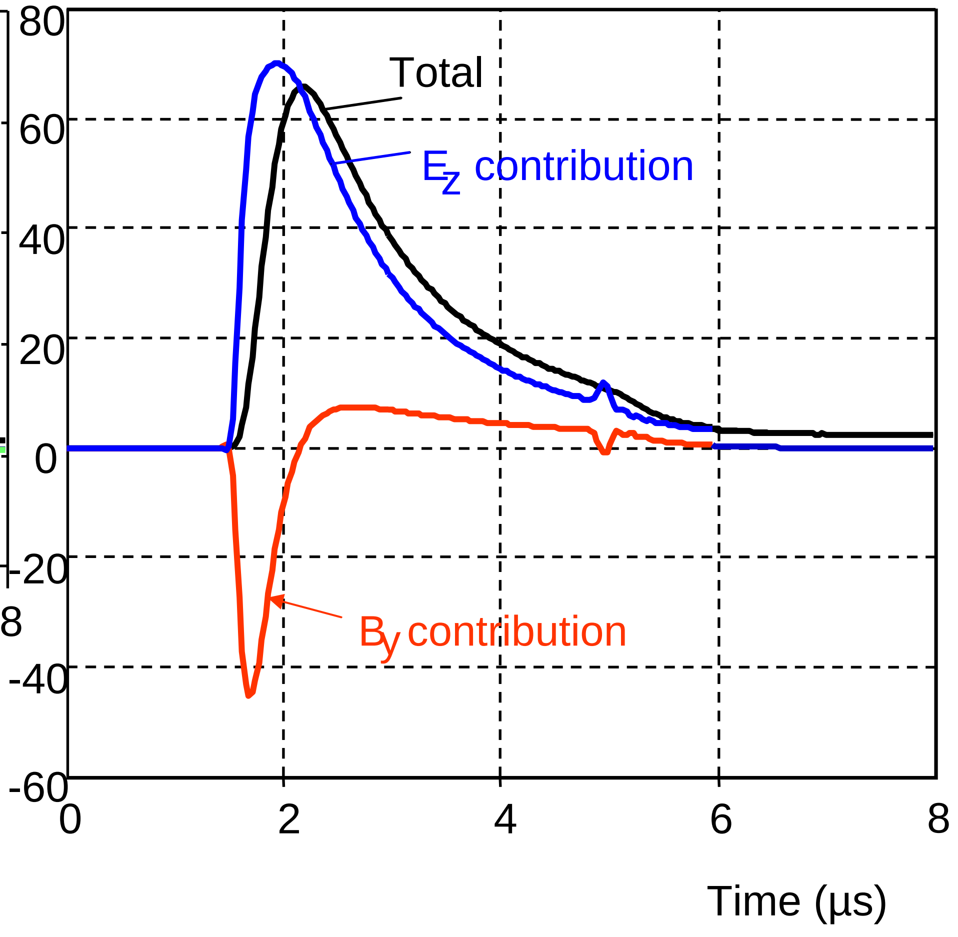
$$\frac{dI(x)}{dx} + j\omega C' U(x) = -j\omega C' \int_0^h E_z^i(x,z)dz$$

1. Illuminated line models:

1.a. lossless single-conductor line



Agrawal et al.

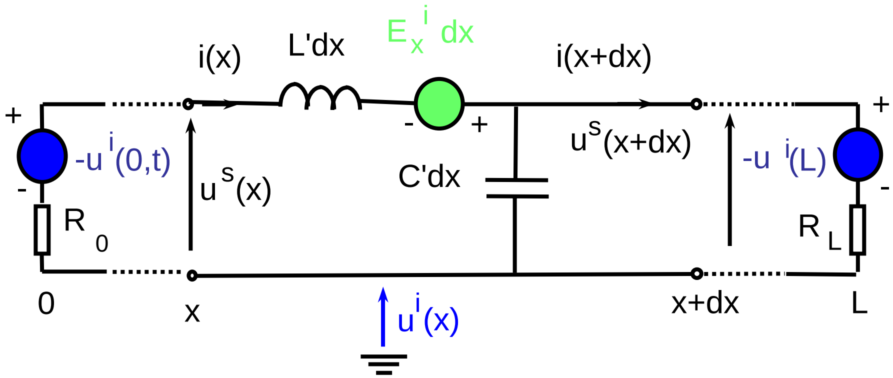


Taylor et al.

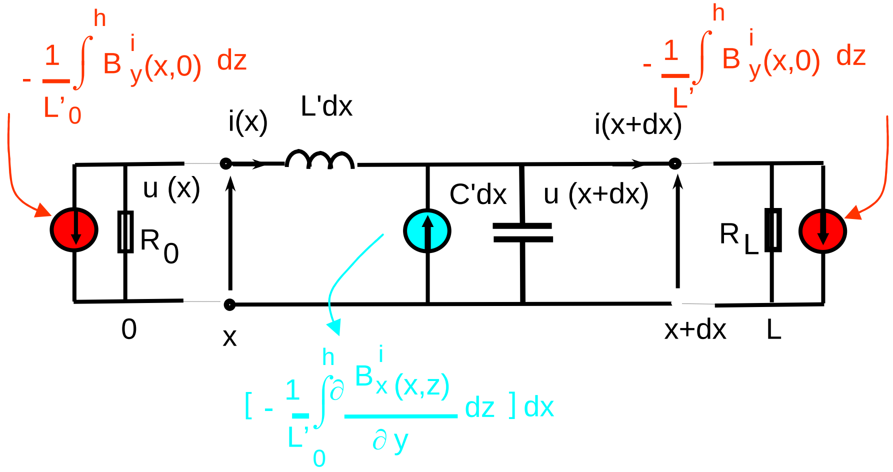
1. Illuminated line models:

1.a. lossless single-conductor line

Rachidi model



Agrawal et al.



Rachidi

$$\frac{dU(x)}{dx} + j\omega L' I(x) = E_x^i(x,h)$$

$$\frac{dI(x)}{dx} + j\omega C' U^s(x) = 0$$

$$U(x) = U^s(x) + U^e(x) = U^s(x) - \int_0^h E_z^e(x,z)dz$$

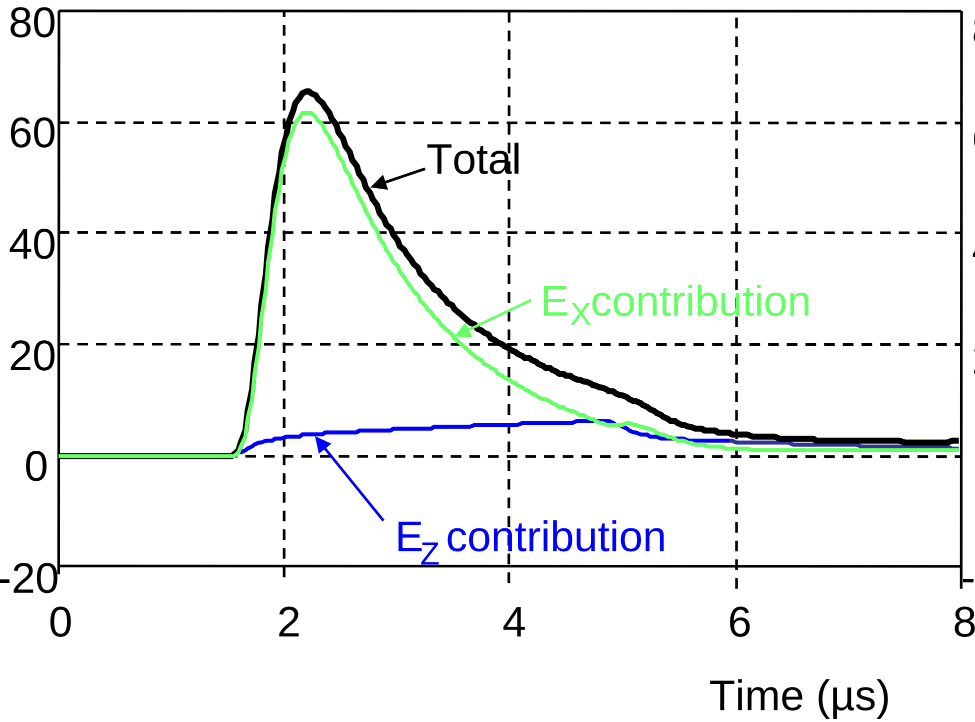
$$\frac{dU(x)}{dx} + j\omega L' I^s(x) = 0$$

$$\frac{dI^s(x)}{dx} + j\omega C' U(x) = \frac{1}{L'}\int_0^h \frac{\partial B_x^i(x,z)}{\partial y} dz$$

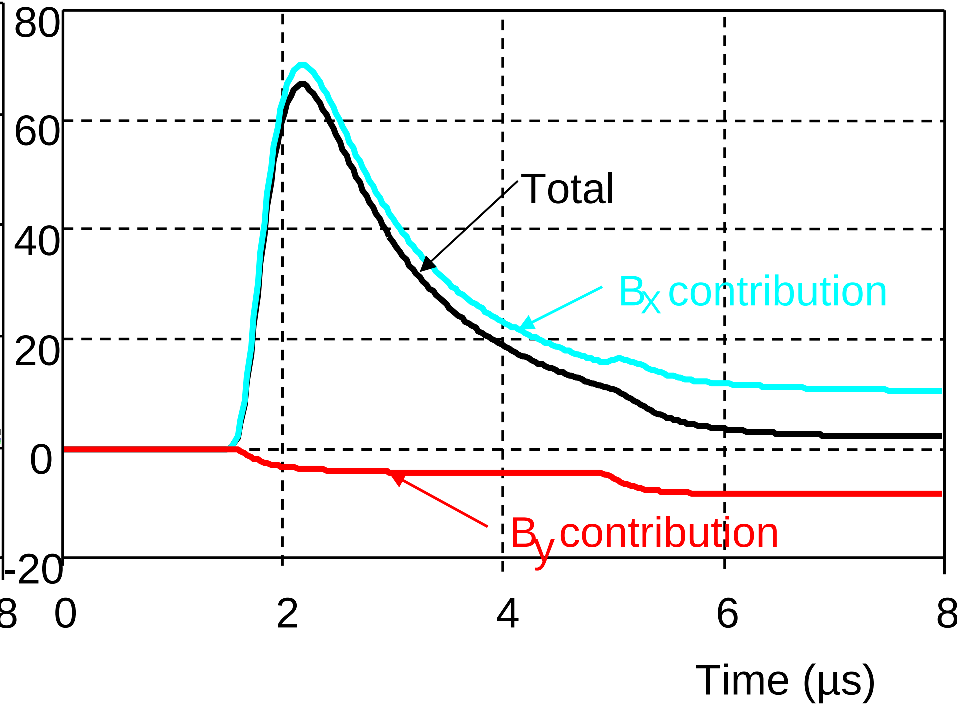
$$I(x) = I^s(x) - \frac{1}{L'}\int_0^h B_y^e(x,z)dz$$

1. Illuminated line models:

1.a. lossless single-conductor line



Agrawal et al.



Rachidi

1. Illuminated line models:

1.a. lossless single-conductor line

The contribution of a given electromagnetic field component in the coupling mechanism depends strongly on the used model.

Thus, when speaking about the contribution of a given electromagnetic field component to the induced voltages, <u>one has to specify the coupling model he is using</u>.

[Nucci and Rachidi, 1995]

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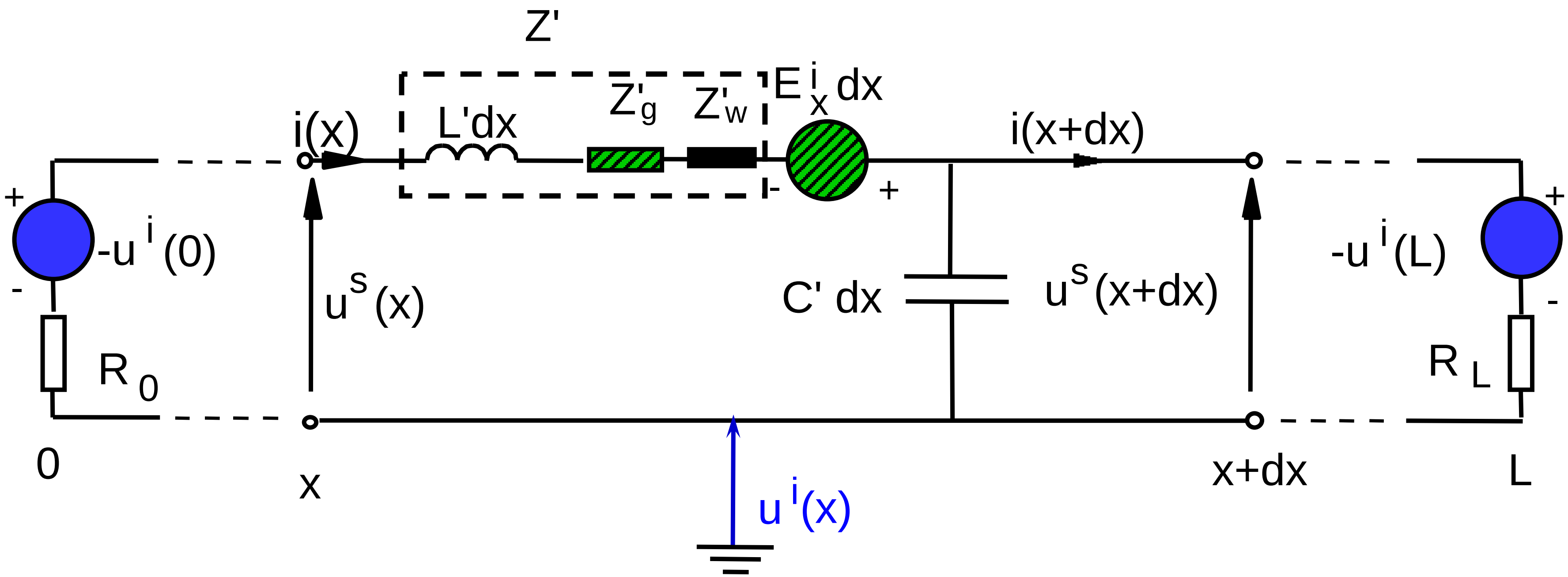
1. Illuminated line models:

2.b. lossy single-conductor line



Equivalent circuit of an overhead line above a lossy ground illuminated by an external electromagnetic field
(frequency domain)

1. Illuminated line models:

2.b. lossy single-conductor line

Time-domain representation of Agrawal Model (lossy)

We here assume negligible Z'_w

$$\frac{\partial}{\partial x}u^s(x,t)+L'\frac{\partial}{\partial t}i(x,t)+\int_0^t \xi_g'(t-\tau)\frac{\partial i(x,\tau)}{\partial \tau}d\tau = E_x^i(x,t,h)$$

$$\frac{\partial}{\partial x}i(x,t)+C'\frac{\partial}{\partial t}u^s(x,t)=0$$

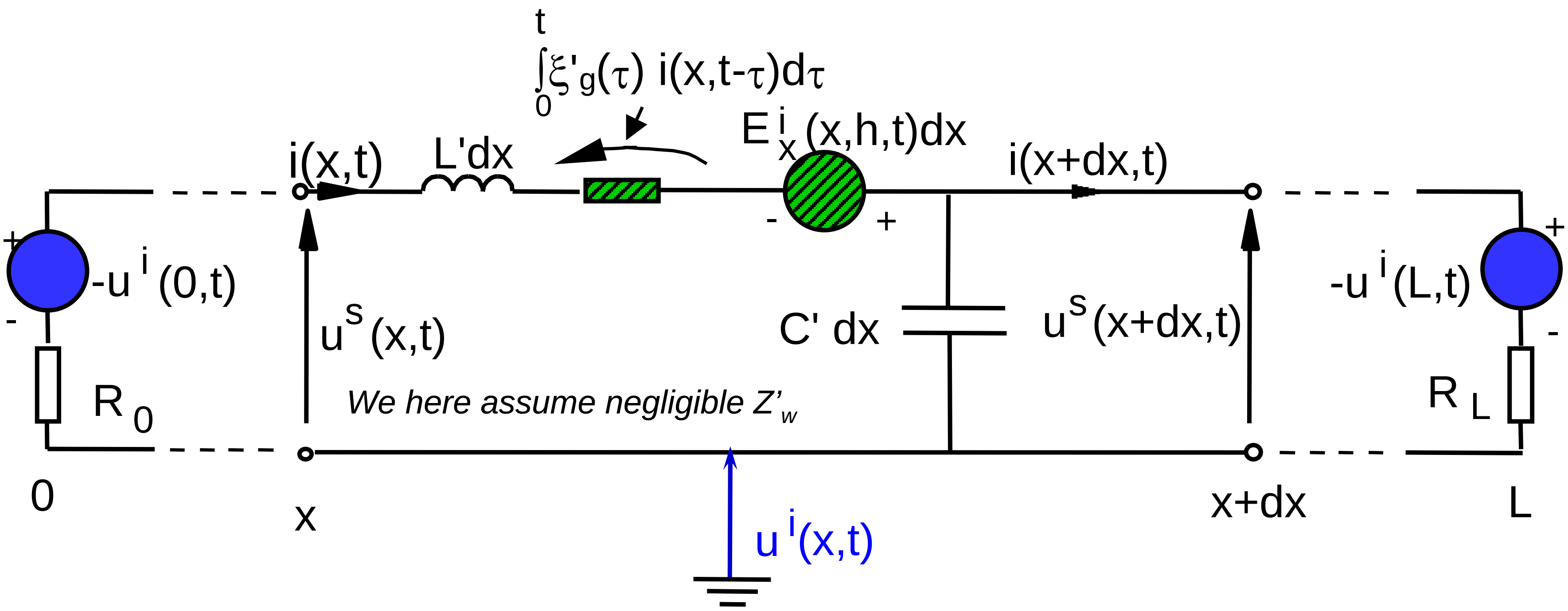
Note: ground resistivity plays a role in

1) the calculation of the line parameters

2) the calculation of the electromagnetic field

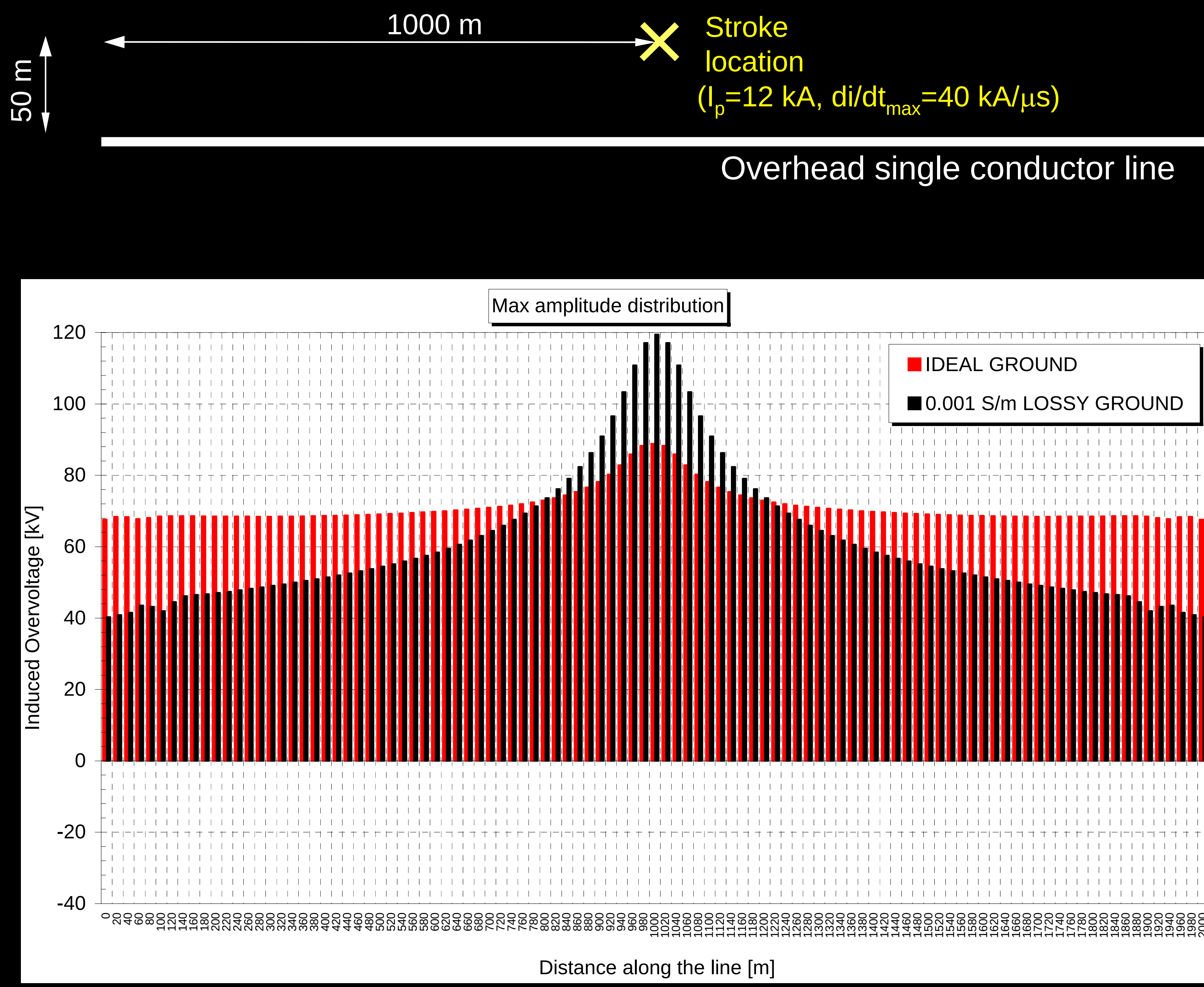
1. Illuminated line models:

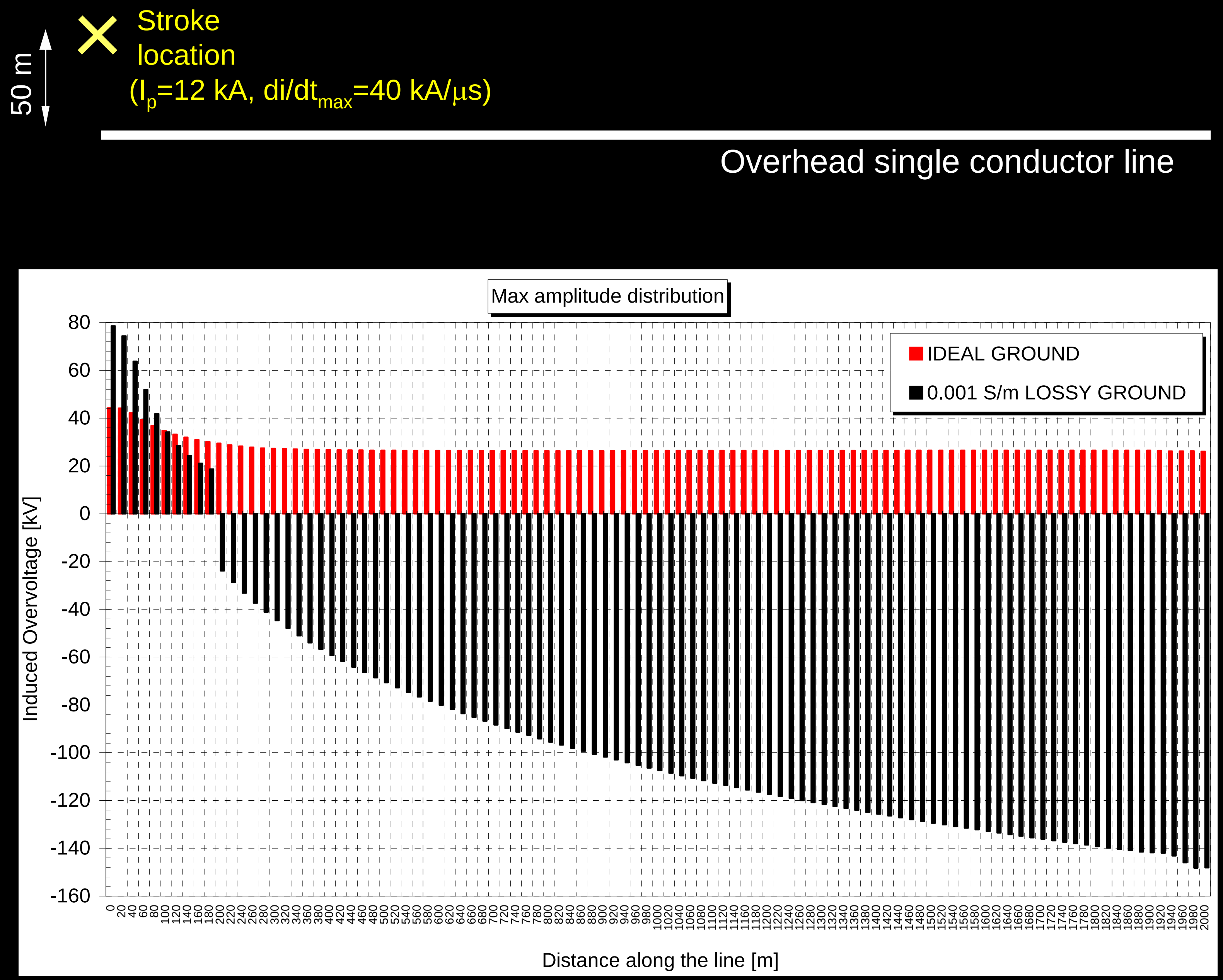
2.b. lossy single-conductor line



Equivament circuit of an overhead line above a lossy ground illuminated by an external electromagnetic field

(time domain)


1000 m
50 m
Stroke
location
(I_p=12 kA, di/dt_{max}=40 kA/μs)
Overhead single conductor line
Max amplitude distribution
IDEAL GROUND
0.001 S/m LOSSY GROUND
Induced Overvoltage [kV]
120
100
80
60
40
20
0
-20
-40
Distance along the line [m]
0 200 400 600 800 1000 1200 1400 1600 1800 2000



50 m
Stroke location
(I_p=12 kA, di/dt_{max}=40 kA/μs)
Overhead single conductor line
Max amplitude distribution
IDEAL GROUND
0.001 S/m LOSSY GROUND
Induced Overvoltage [kV]
80 60 40 20 0 -20 -40 -60 -80 -100 -120 -140 -160
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400 420 440 460 480 500 520 540 560 580 600 620 640 660 680 700 720 740 760 780 800 820 840 860 880 900 920 940 960 980 1000 1020 1040 1060 1080 1100 1120 1140 1160 1180 1200 1220 1240 1260 1280 1300 1320 1340 1360 1380 1400 1420 1440 1460 1480 1500 1520 1540 1560 1580 1600 1620 1640 1660 1680 1700 1720 1740 1760 1780 1800 1820 1840 1860 1880 1900 1920 1940 1960 1980 2000
Distance along the line [m]

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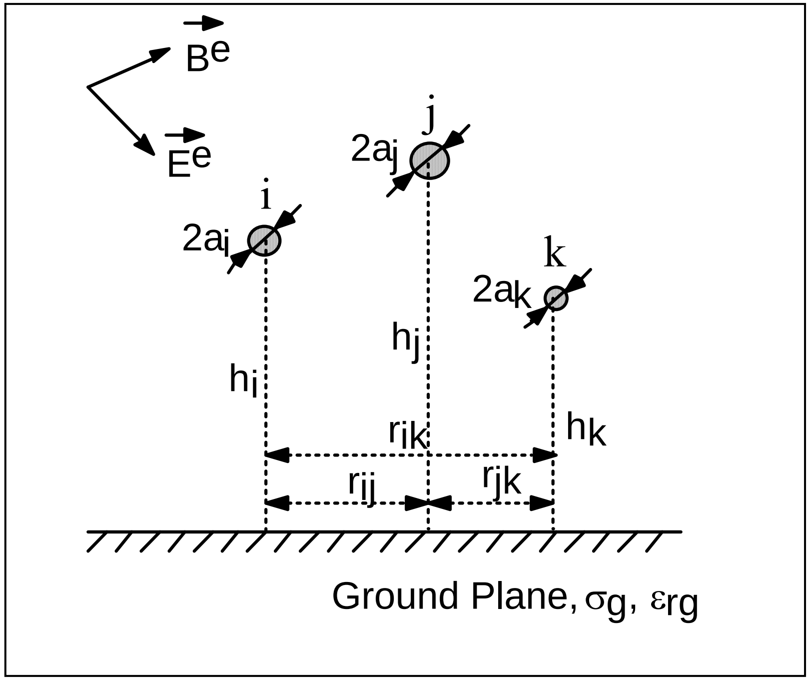
1. Illuminated line models:

1.c. multi-conductor line

Frequency domain

$$\frac{d}{dx}[U_i^s(x)] + j\omega[L'_{ij}][I_i(x)] + [Z'_{g_{ij}}][I_i(x)] = [E_x^e(x, h_i)]$$

$$\frac{d}{dx}[I_i(x)] + [G'_{ij}][U_i^s(x)] + j\omega[C'_{ij}][U_i^s(x)] = [0]$$



Boundary Conditions

$$[U_i^s(0)] = -[Z_A][I_i(0)] + [\int_0^{h_i} E_z^e(0,z)dz]$$

$$[U_i^s(L)] = [Z_B][I_i(L)] + [\int_0^{h_i} E_z^e(L,z)dz]$$

1. Illuminated line models:

1.c. multi-conductor line

Time domain

Note that in equations below symbol *u* is replaced with symbol *v*

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

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

where $\otimes$ denotes convolution integral

and $[\xi'_{g_{ij}}]\cong \mathrm{F}^{-1}\left\{\frac{Z'_{g_{ij}}}{j\omega}\right\}$ is the transient ground resistance matrix

Boundary Conditions:

$$\begin{cases}\left[v_i^s(0,t)\right]=-\left[R_A\right]\left[i_i(0,t)\right]+\left[\int_0^{h_i}E_z^e(0,z,t)dz\right]\\ \left[v_i^s(L)\right]=\left[R_B\right]\left[i_i(0)\right]+\left[\int_0^{h_i}E_z^e(L,z,t)dz\right]\end{cases}$$

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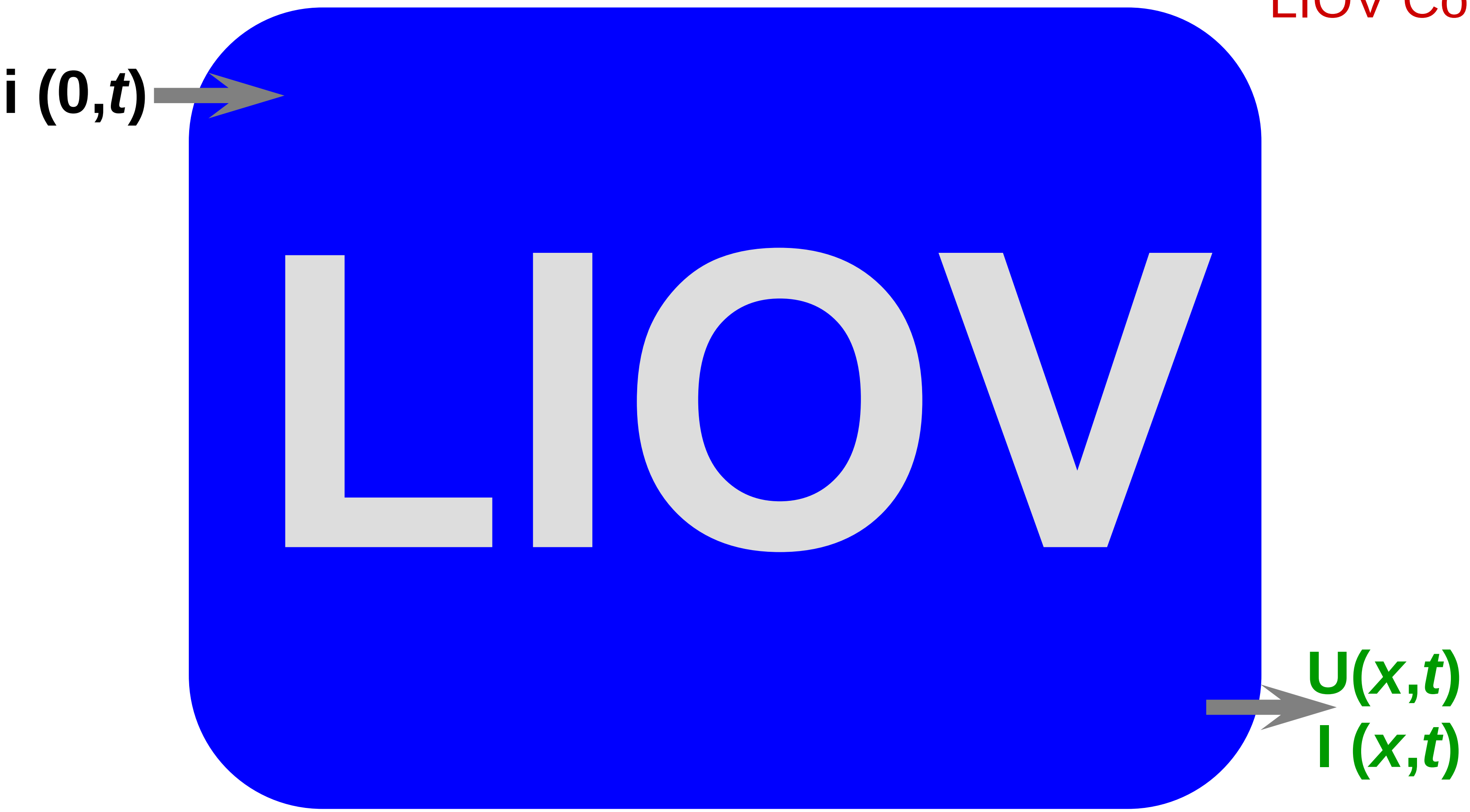
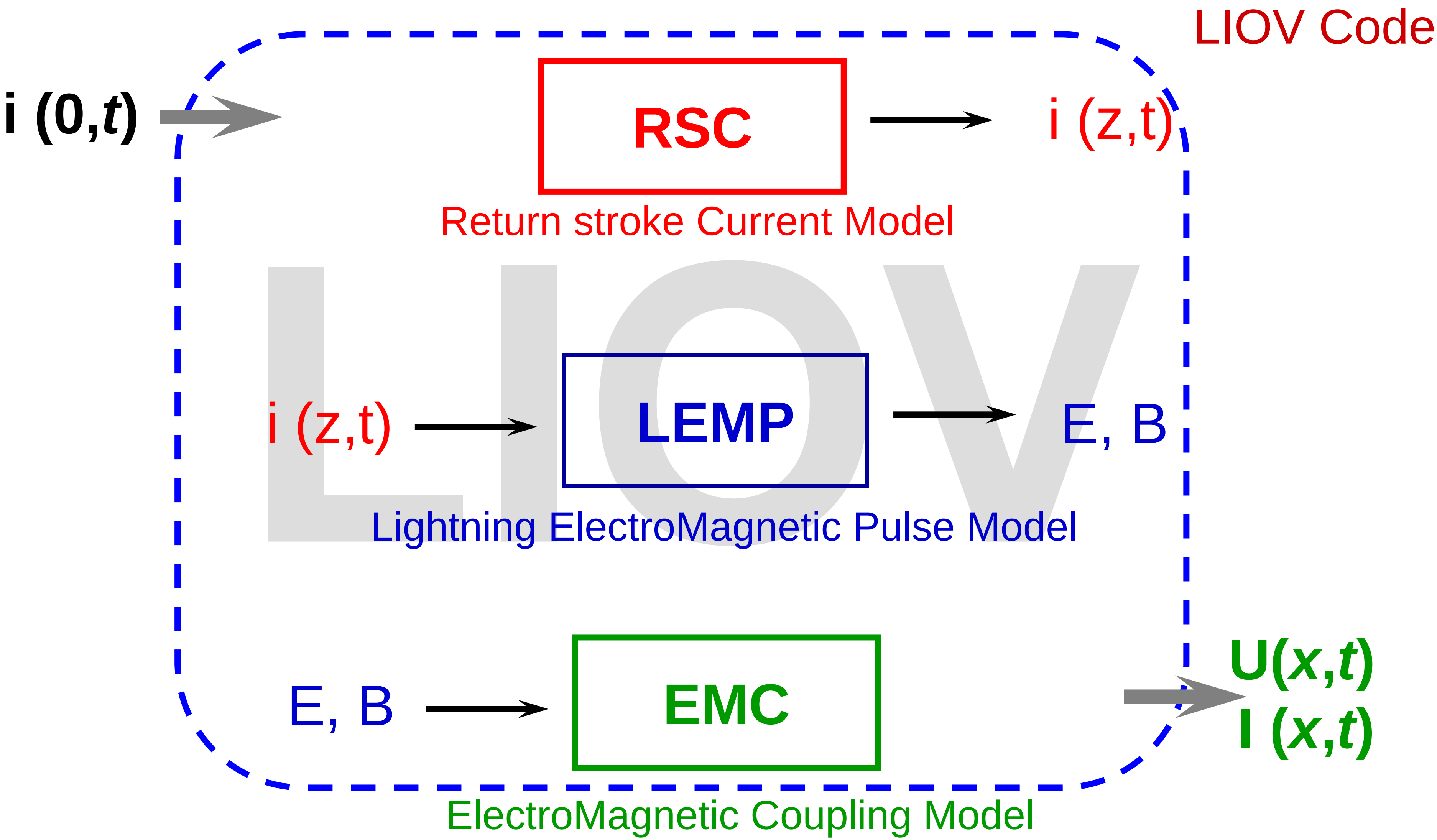
LIOV Code



2. LIOV and LIOV-EMTP codes

2.a. General overview



LIOV Code

Return stroke model: **Modified Transmission Line Exp decay (MTLE) and any other**

LEMP: **Uman, Krider and McLain; Cooray-Rubinstein (Wait correction)**

Coupling model: **Agrawal (multi-conductor lines) extended to the case of lossy ground**

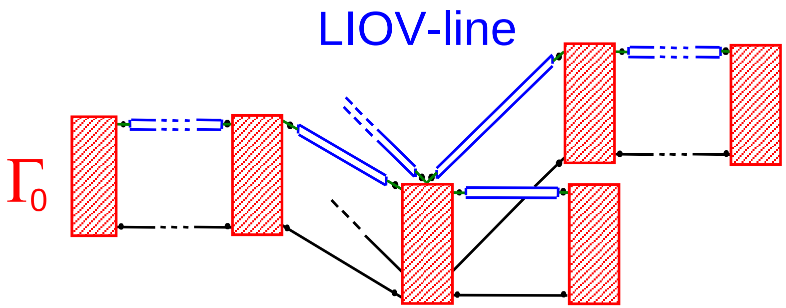
In the LIOV code [Nucci and Rachidi, 2003] the Agrawal et al. model has been implemented for dealing with the case of multi-conductor lines closed on resistive terminations. In principle, the LIOV code could be suitably modified, case by case, in order to take into account the presence of the specific type of termination, line-discontinuities (e.g. surge arresters across the line, see next slide) and of complex system topologies.

This procedure requires that the boundary conditions for the transmission-line coupling equations be properly re-written case by case, as discussed in [Nucci et al., 1994].

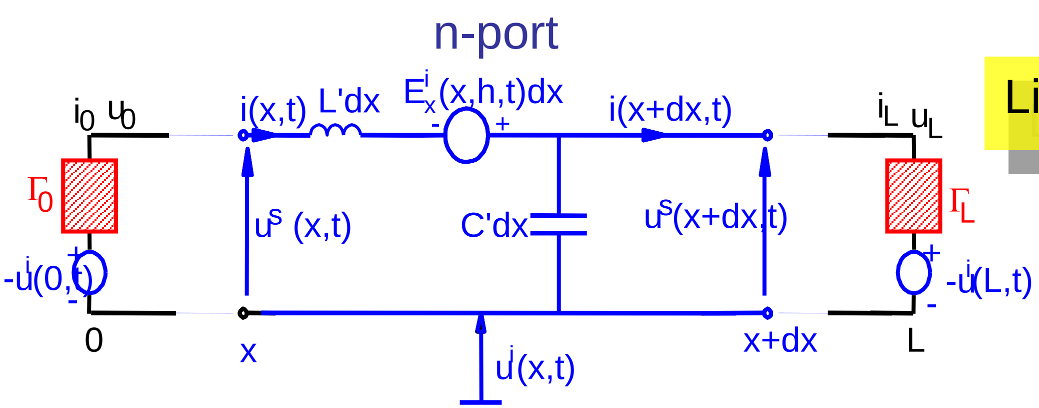
2. LIOV and LIOV-EMTP codes

2.a. General overview

LIOV-EMTP Code



Structure of a typical distribution system



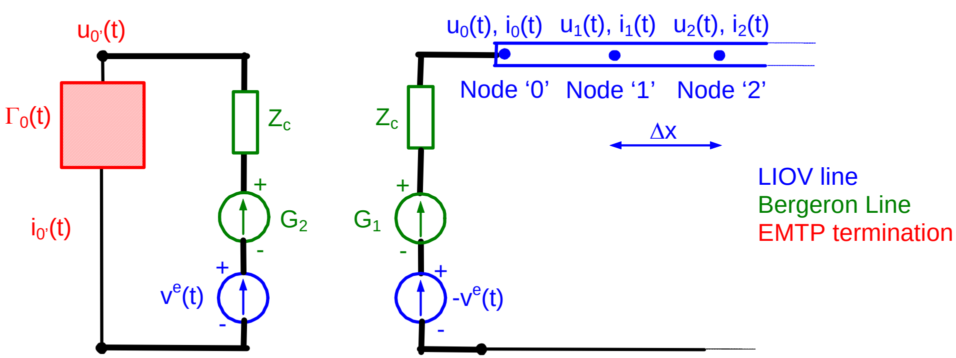
Link between LIOV and EMTP

The **LIOV** code calculates:

- LEMP
- Coupling

The **EMTP** :

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



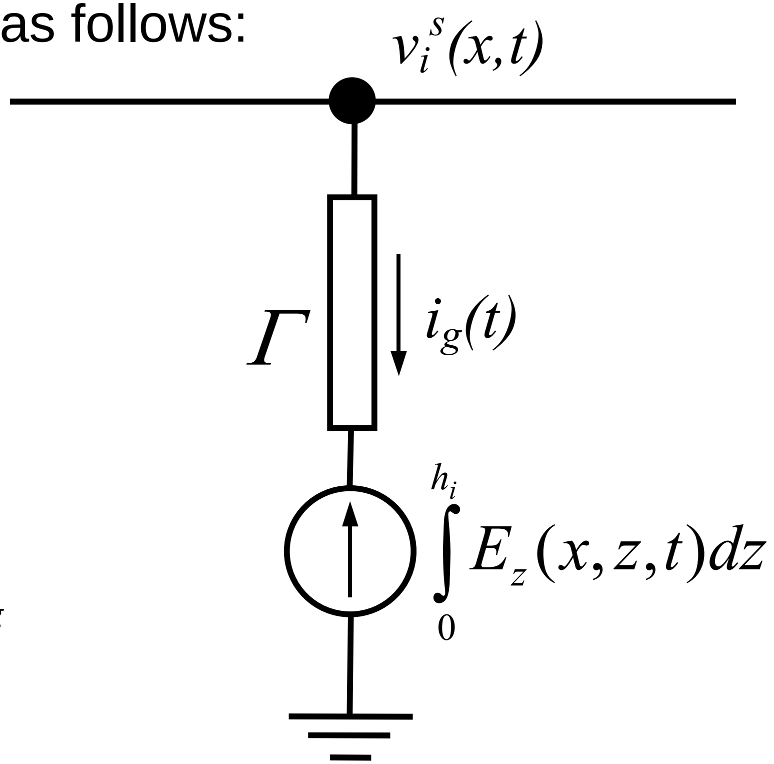
Boundary conditions, data exchange between the LIOV code and the EMTP

[Nucci et al., 1994; Paolone 2001; Borghetti et al, 2004]

LIOV Code

Treatment of line transverse discontinuities in LIOV code

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



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

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).

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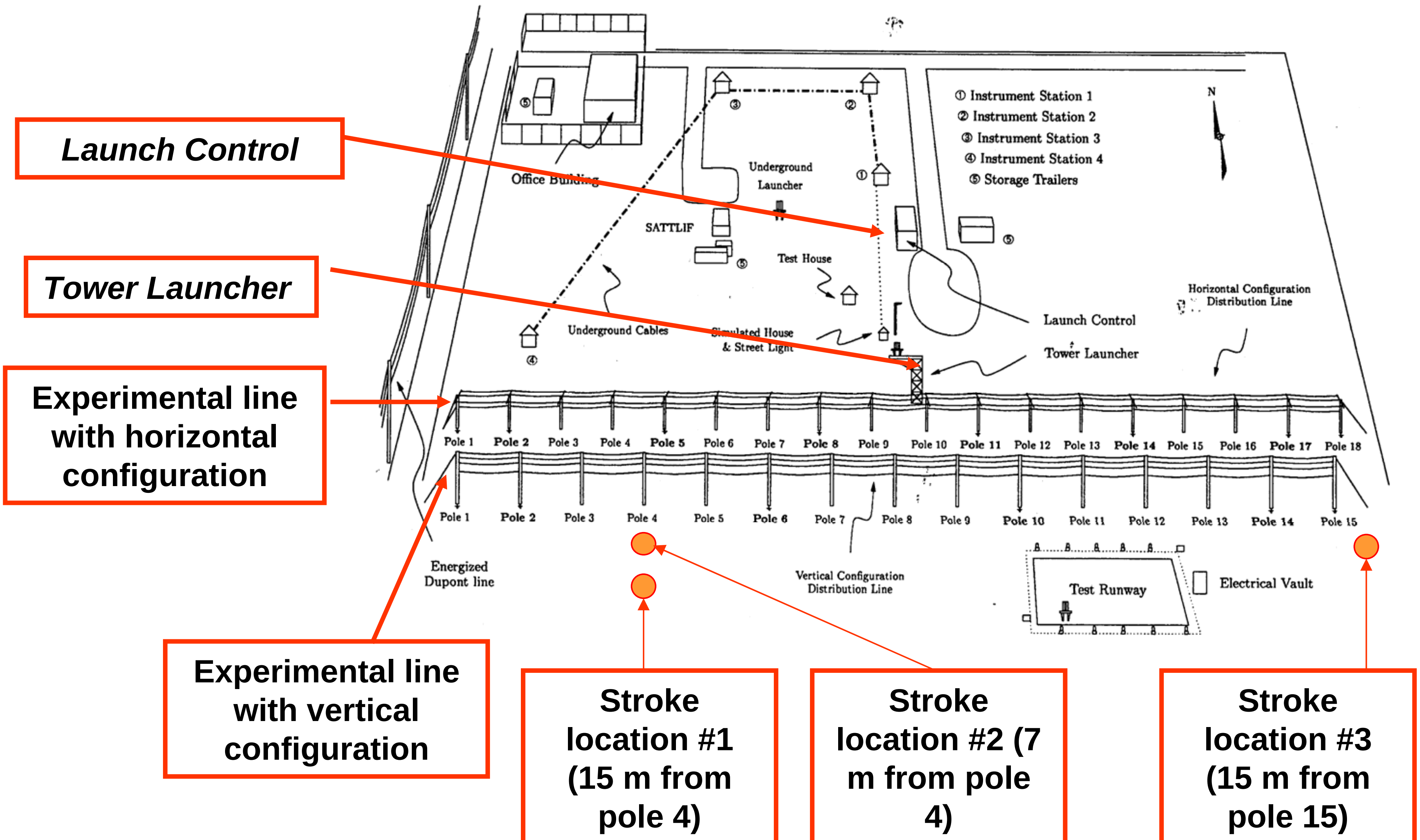
2. LIOV and LIOV-EMTP codes

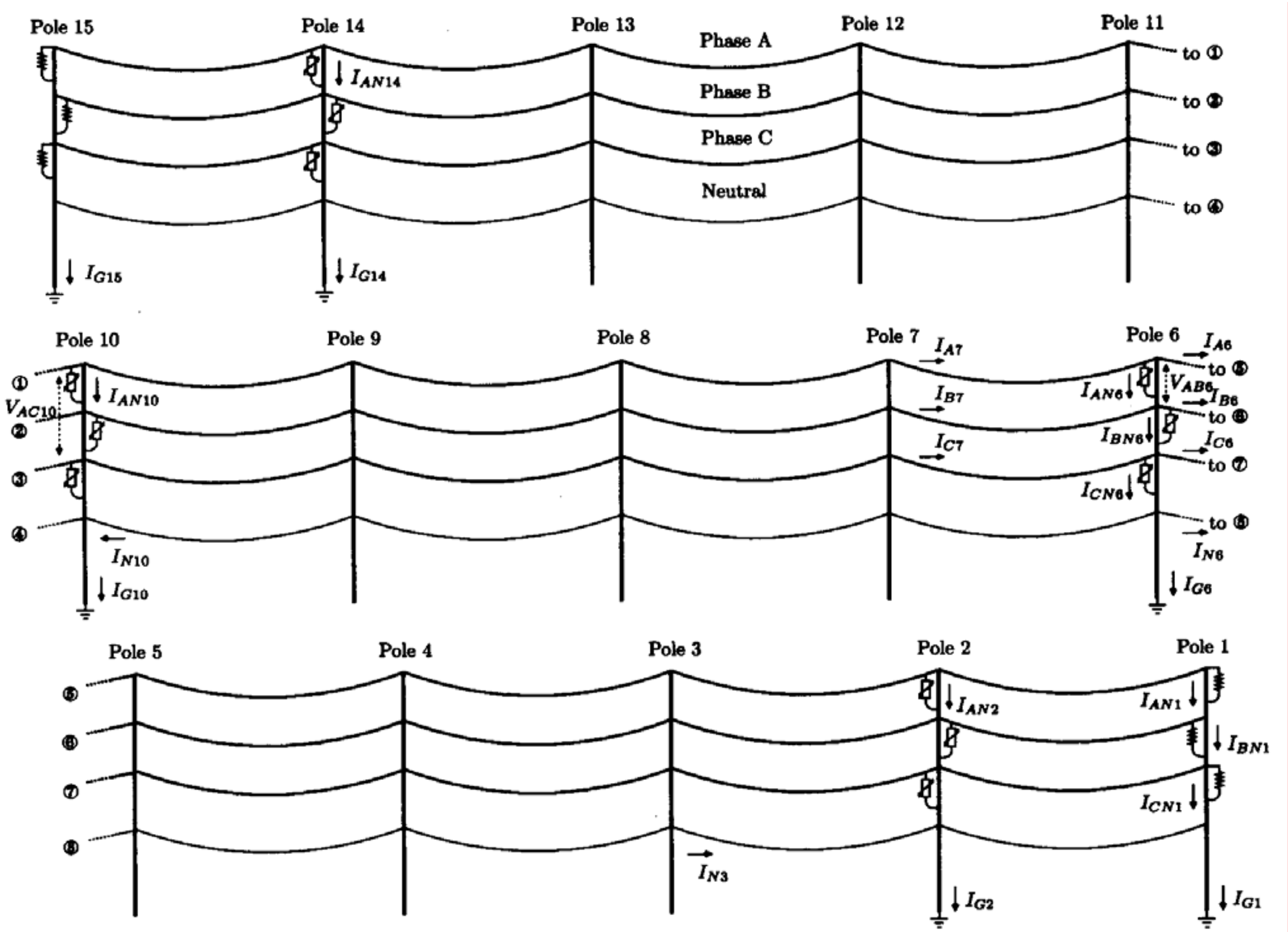
2.b. Experimental validation

ICLRT, Camp Blanding, University of Florida, 2002-2003



2. LIOV and LIOV-EMTP codes

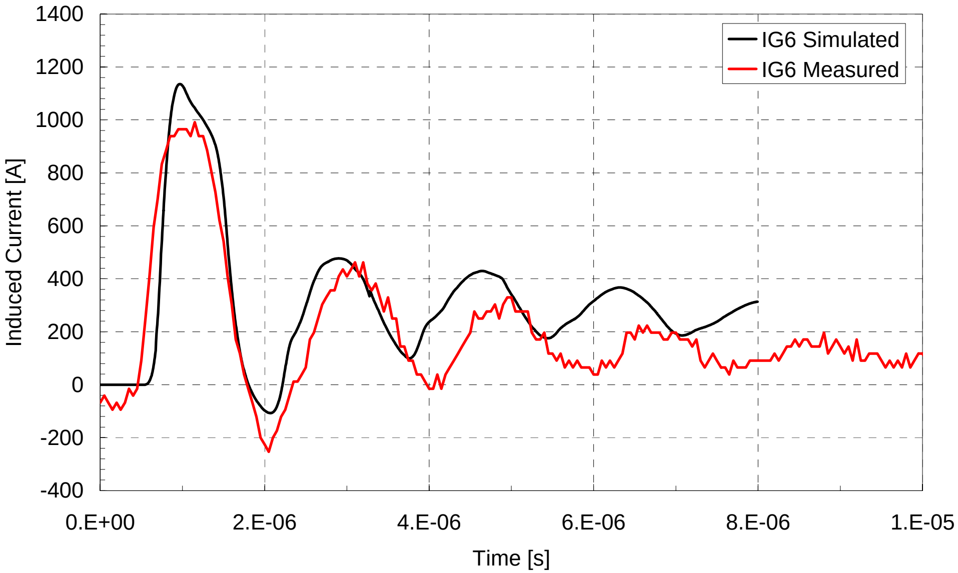
2.b. Experimental validation

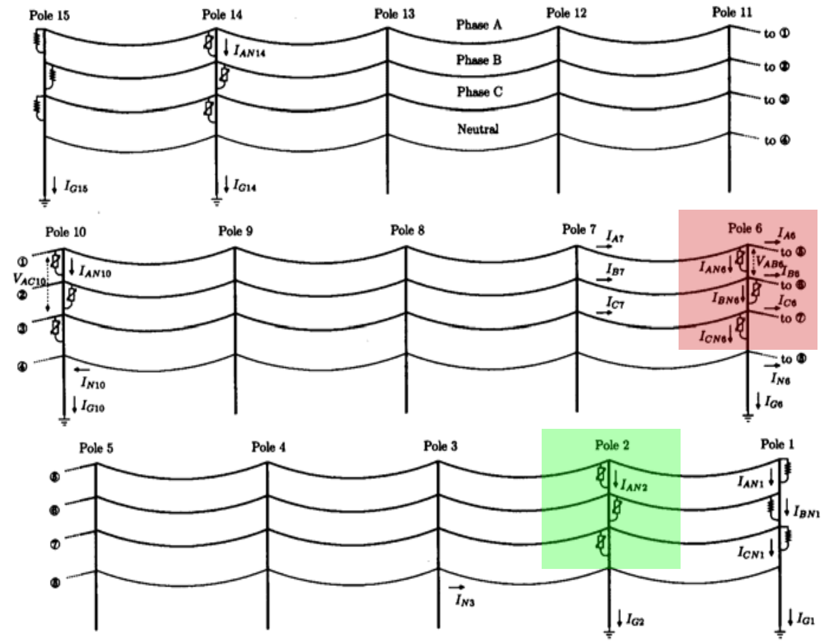


- ❑ vertically configured experimental line with 3 phase conductors plus neutral periodically grounded, 764 m length, 15 poles;
- ❑ 4 surge arrester stations;
- ❑ line terminations matched (500 Ω).

2. LIOV and LIOV-EMTP codes

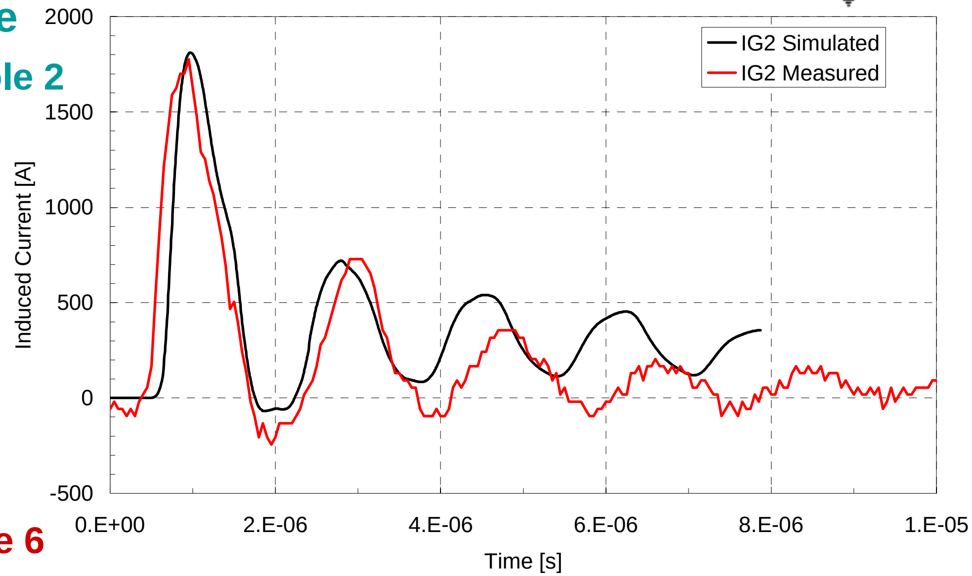
2.b. Experimental validation





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

Current flowing through the grounding of pole 2

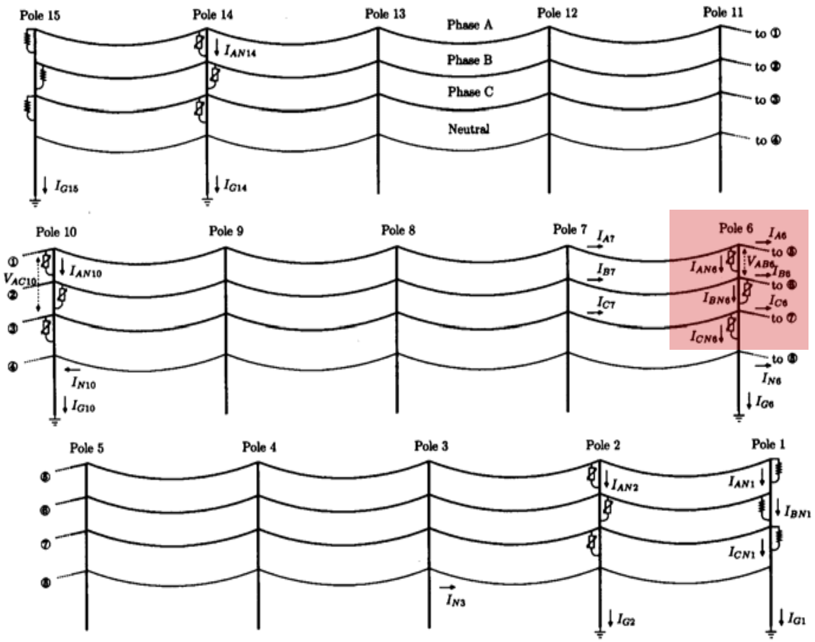


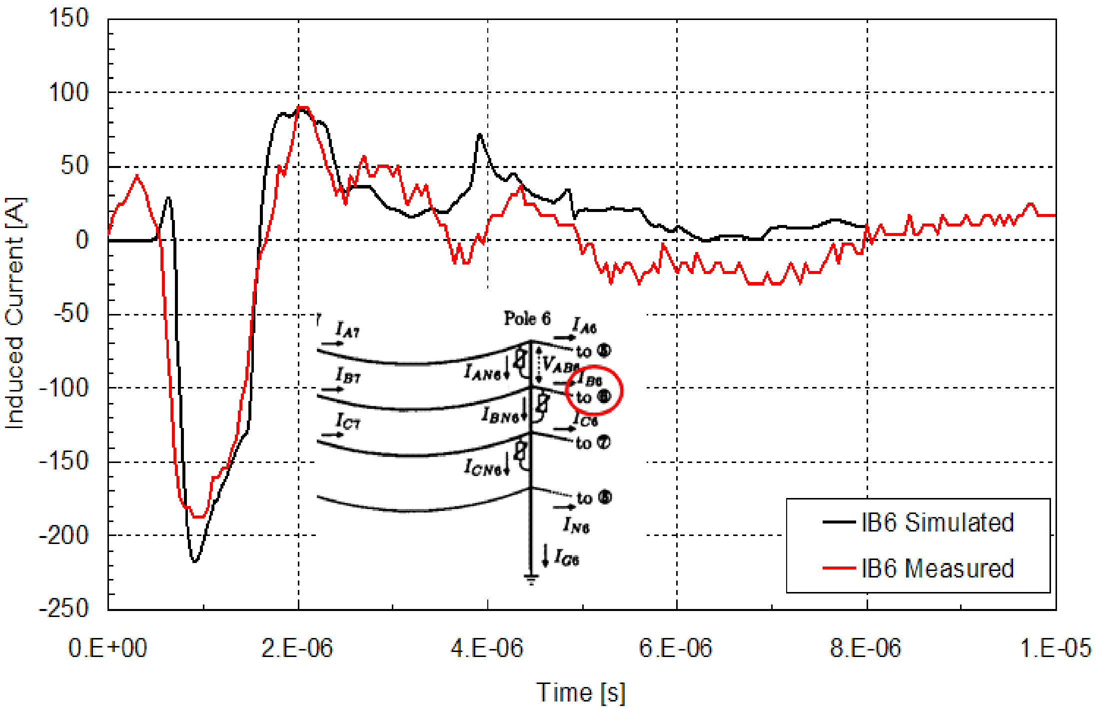
First event of 02-08-03 6th return stroke

Current flowing through the grounding of pole 6

2. LIOV and LIOV-EMTP codes

2.b. Experimental validation





First event of 02-08-03 6th r.s.
Current flowing through
the phase B conductor of pole 6

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Use of surge arresters for the mitigation of indirect lightning-induced voltages

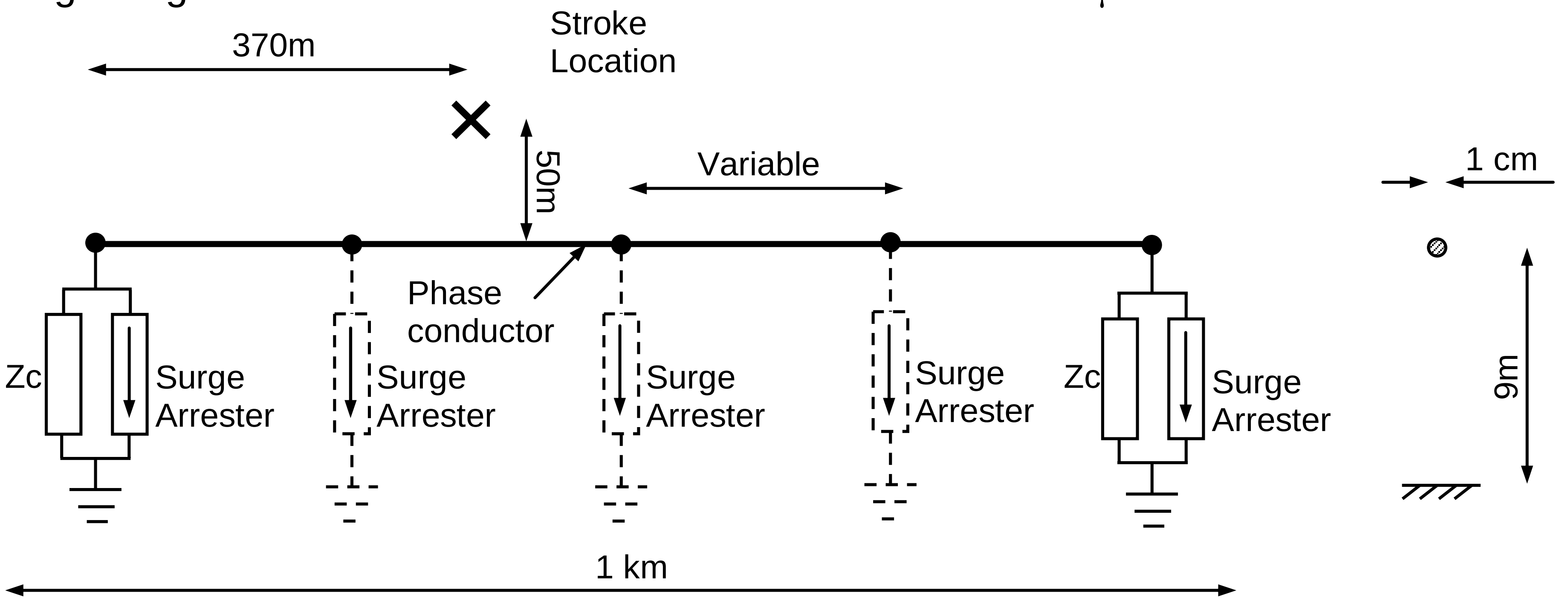
According with preliminary studies*, simulations performed with LIOV-EMTP96 code shows that *an important reduction of the induced overvoltages on typical distribution overhead lines can be achieved only with a large number of surge arresters namely 1 surge arrester every 200 m*.

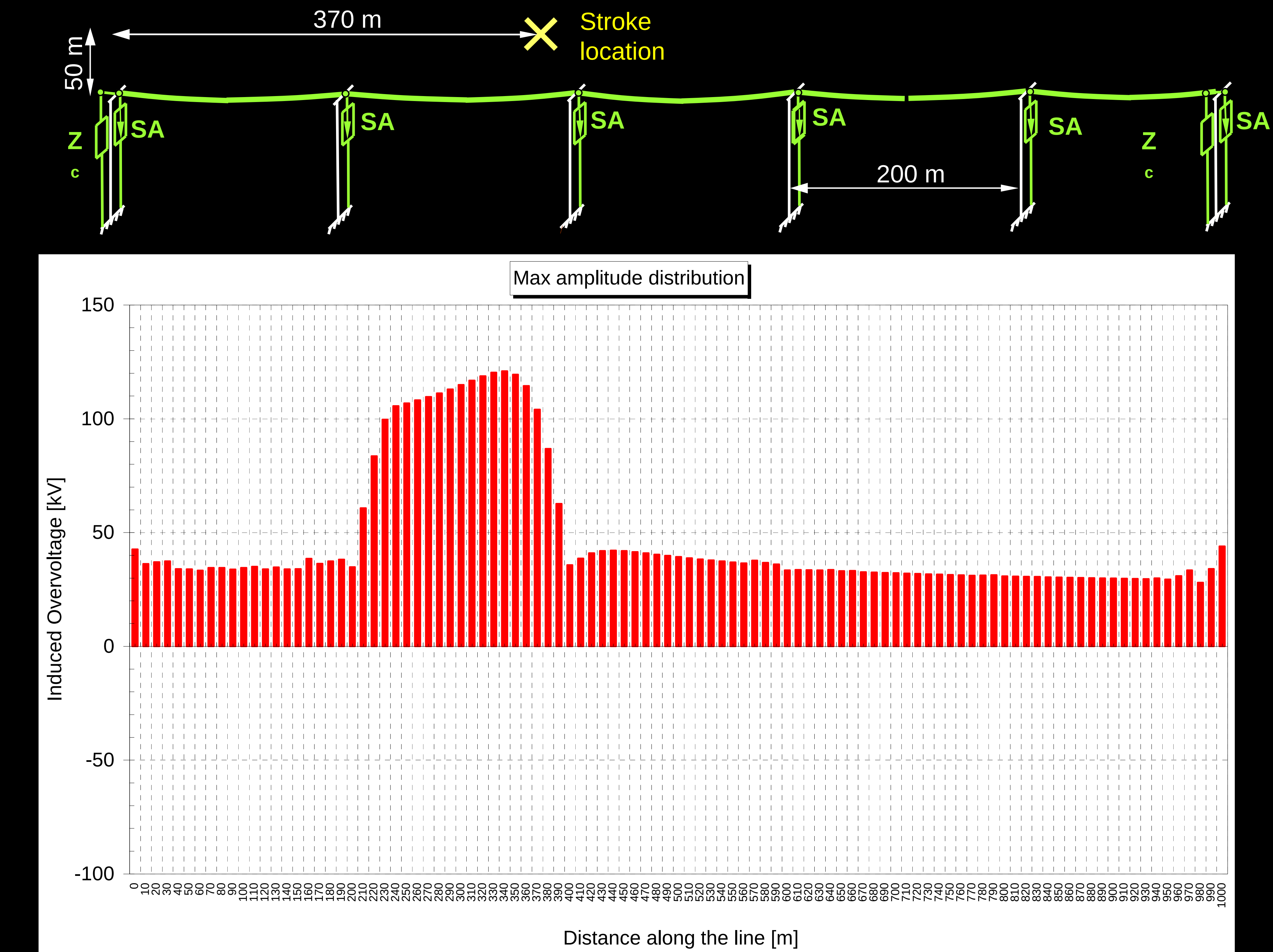
It can also be seen that for some configurations with a *low number of surge arresters* (e.g. *one each 1000 m*), their presence could result in important negative peaks of the induced voltage, which are due to surge reflections occurring in correspondence of surge arresters operation.

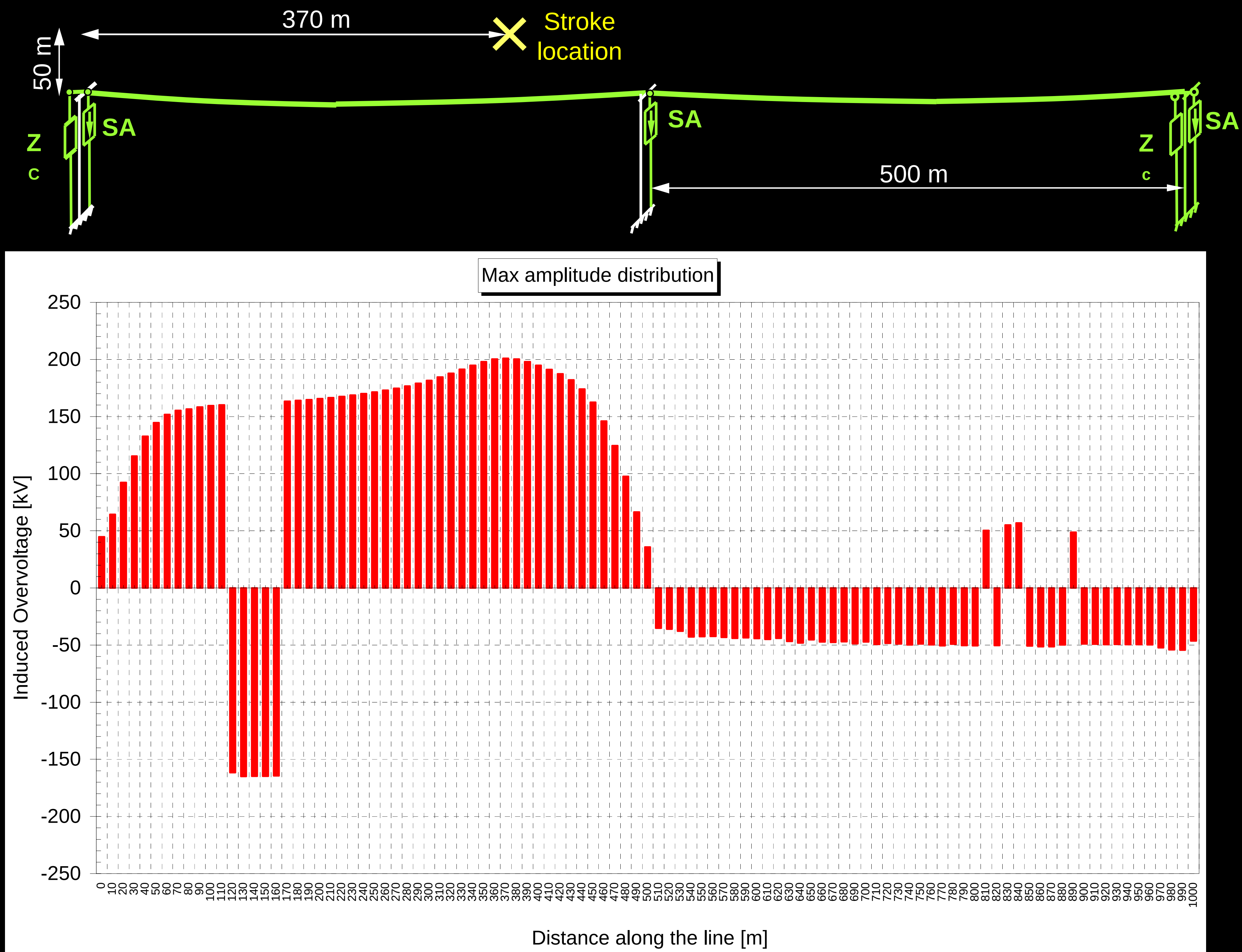
***** *M. Paolone, C.A. Nucci, E. Petrache, F. Rachidi, "Mitigation of Lightning-Induced Overvoltages in Medium Voltage Distribution Lines by Means of Periodical Grounding of Shielding Wires and of Surge Arresters: Modelling and Experimental Validation", IEEE Trans. on PWDR, Vol. 19, Issue 1, Gennaio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

Use of surge arresters for the mitigation of indirect lightning-induced voltages

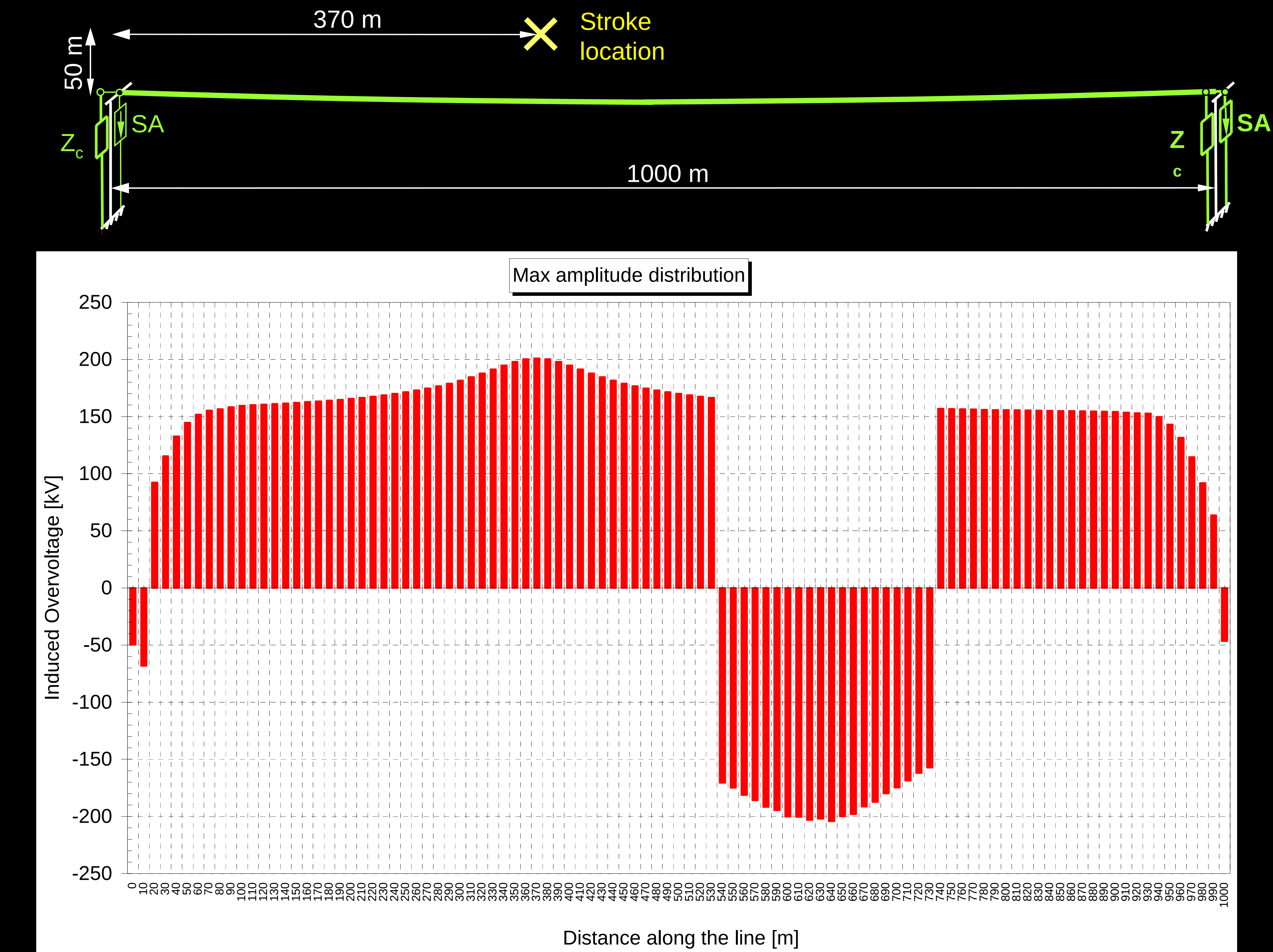
- single conductor overhead line above an ideal ground:
- line length 1 km;
- number of surge arresters: 2, 3, 6 (1000 m, 500m and 200 m);
- lightning current: 30 kA with max time derivative of 100 kA/μs




370 m
Stroke location
50 m
SA
Z c
200 m
Max amplitude distribution
Induced Overvoltage [kV]
Distance along the line [m]



370 m
Stroke location
50 m
SA
Zc
SA
SA
Zc
500 m
Max amplitude distribution
Induced Overvoltage [kV]
Distance along the line [m]


370 m
Stroke location
50 m
SA
Z
c
SA
Z
c
1000 m
Max amplitude distribution
Induced Overvoltage [kV]
Distance along the line [m]

Use of surge arresters for the mitigation of indirect lightning-induced voltages

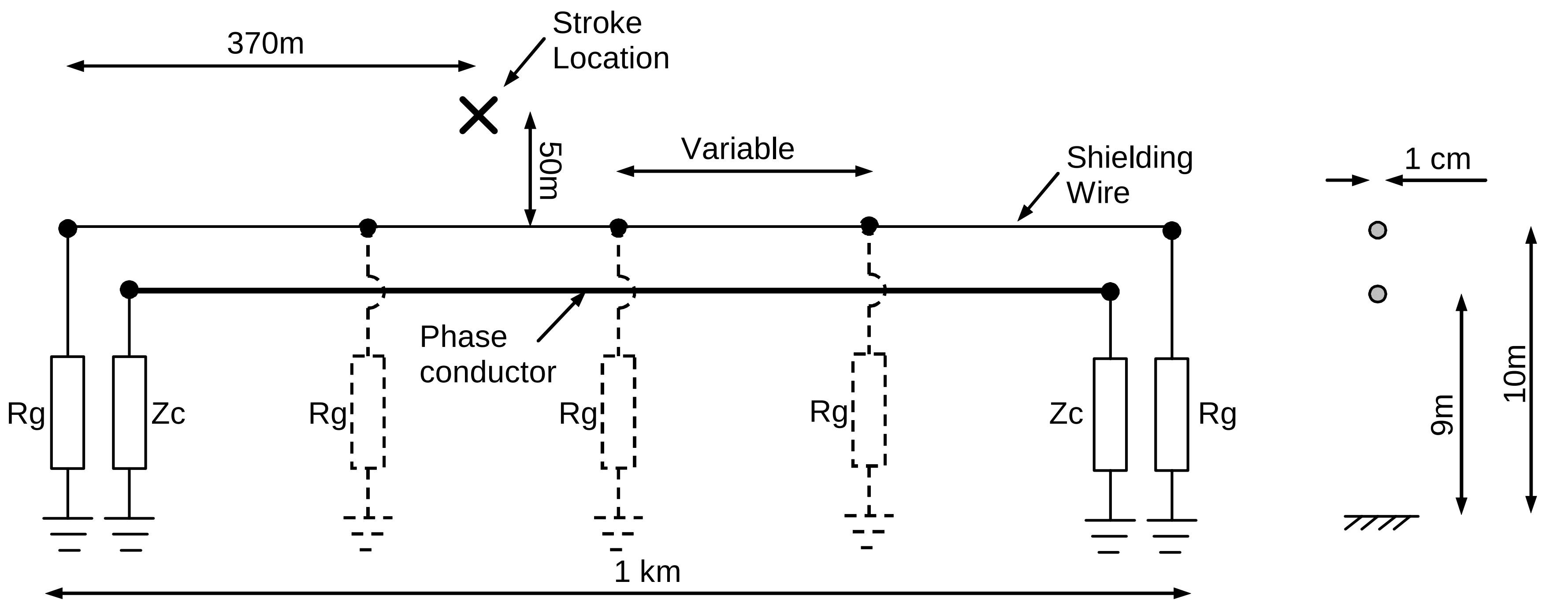
Depending on the line configuration, stroke location and on the distance between two consecutive surge arresters, the negative voltage wave due to the arrester's non-linear characteristic, make it possible for the *largest amplitude of the induced overvoltage to occur at a point on the line different 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.

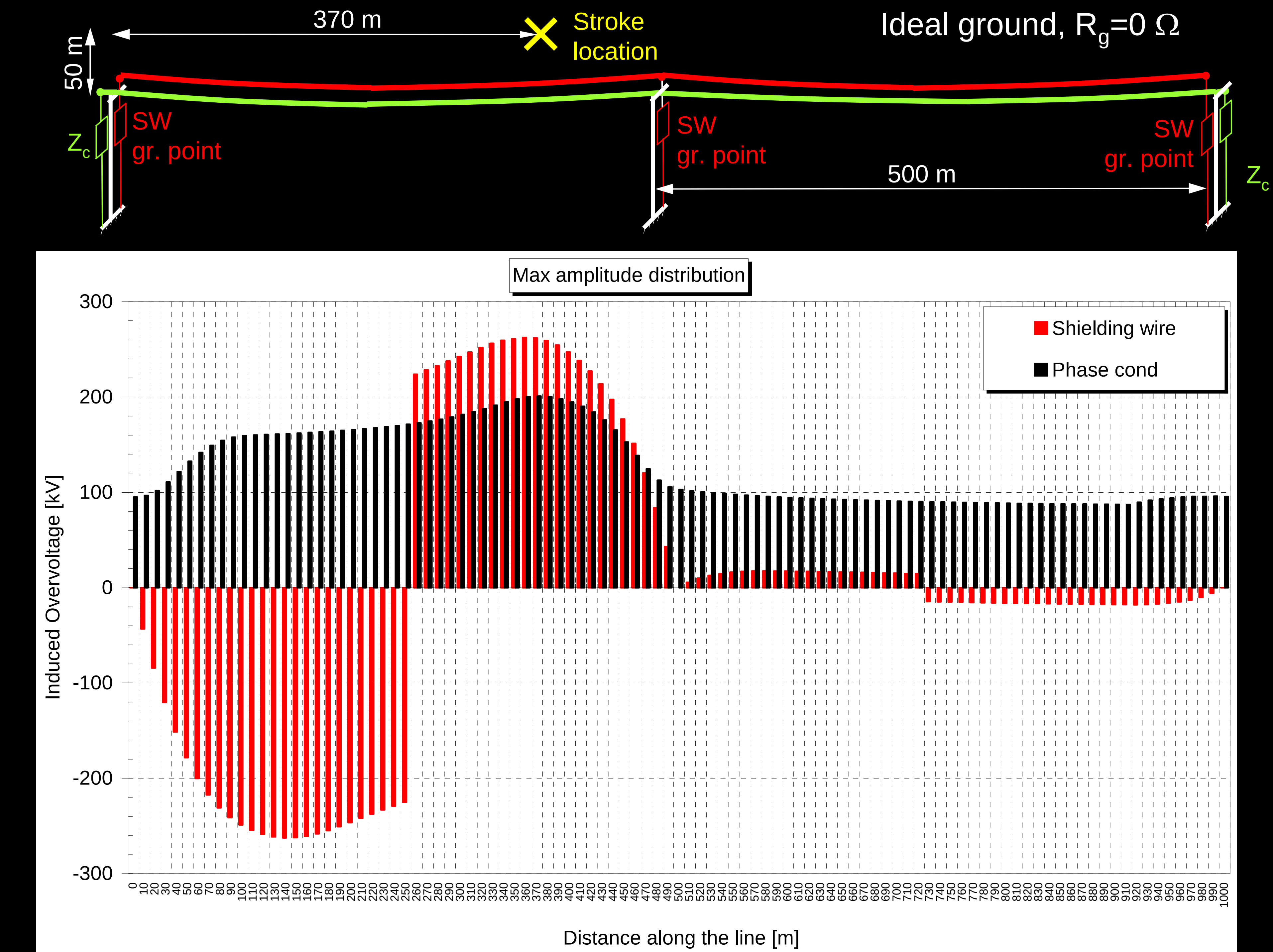
By *increasing the number of surge arresters*, the maximum amplitude of the induced overvoltage tends to be confined within the range defined by the positive and negative values of the threshold voltage of the surge arrester's non-linear V-I characteristic.

Use of grounding of shielding wires/neutral conductor for the mitigation of indirect lightning-induced voltages

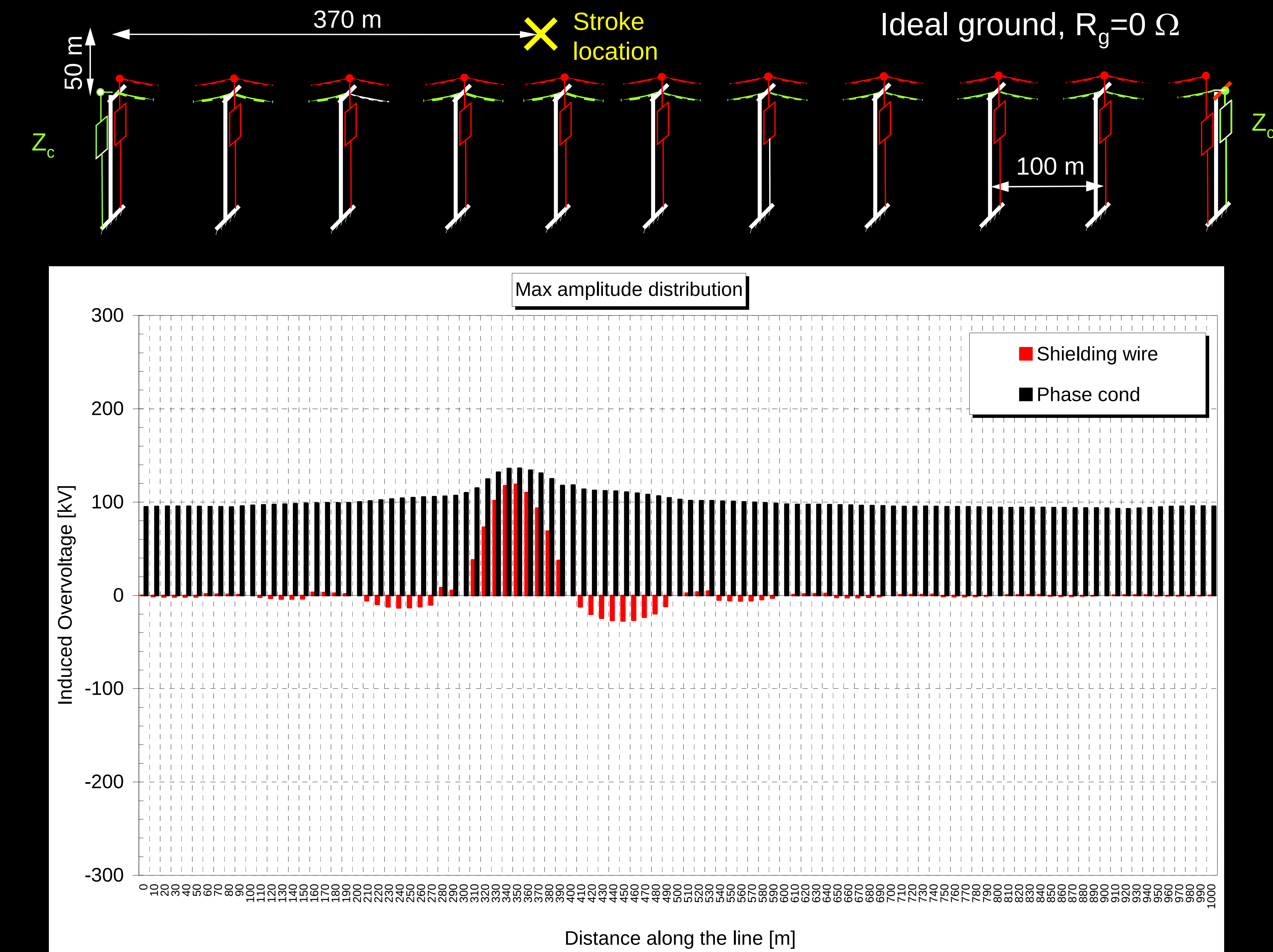
Let assume a stroke location which does not “face” any of the grounding resistances.
Lightning current with:

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





370 m
Stroke location
Ideal ground, R_g=0 Ω
50 m
Z_c
SW gr. point
SW gr. point
500 m
SW gr. point
Z_c
Max amplitude distribution
Shielding wire
Phase cond
Induced Overvoltage [kV]
300
200
100
0
-100
-200
-300
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
Ideal ground, R_g=0 Ω
50 m
Z_c
Z_c
100 m
Max amplitude distribution
Shielding wire
Phase cond
Induced Overvoltage [kV]
300
200
100
0
-100
-200
-300
Distance along the line [m]

Use of grounding of shielding wires/neutral conductor for the mitigation of indirect lightning-induced voltages

We can see that, for the considered case, an overall effective protection of the line can be achieved only if the spacing between two consecutive groundings is less than about **200 m**.

This value approximately corresponds to the risetime of the lightning electromagnetic field illuminating the line, for the assumed lightning current waveshape. For larger values of spacing (namely 500 m and 1000 m), only the portion of the line in the immediate vicinity of the grounding points appears to be protected.

2. LIOV and LIOV-EMTP codes

2.c. Applications

To better comprehend the last conclusion →

Fig. a and **Fig. b** show the induced voltages along the shielding wire (lossy ground case with σ_g = 0.001 S/m – field calculation – grounding resistance $\boldsymbol{R_g}$ **= 10 Ω**, for two different grounding spacing (**500 m**, Fig. a, and **100 m**, Fig. b, respectively.

Fig. a → the voltage along the shielding wire varies significantly as a function of time and position along the wire → the assumption of considering the shielding wire as a zero-potential conductor is not realistic.

Fig. b → variation of the shielding wire voltage for a 100 m spacing is less important → simplified formula approaches (e.g. the Rusck one) gives adequate results for this case.