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Lightning Interaction with Transmission and Distribution Power Systems

Alexandre Piantini

University of São Paulo, Brazil

piantini@iee.usp.br

OUTLINE

- **Introduction**
- **Lightning Phenomenon** (main processes)
- **Transmission Lines**
- **Distribution Networks (MV, LV)**
- **Conclusions**

INTRODUCTION

Lightning:

- equipment damages and failures
- damages to customer electronic devices
- voltage sags
- supply interruptions

Widespread use + growing dependence on the continuous operation of sensitive electronic equipment

→ **increasing awareness of the importance of improving the reliability and PQ levels of electrical systems**

INTRODUCTION

Evaluate the characteristics and the effects of lightning transients and the effectivenesses of protective measures

- → characterization of the lightning phenomenon (parameters + stat. distributions)
- → interaction with T&D (MV + LV) systems
- → models for representing the behaviors of the soil and of the most important power equipment under lightning surges
- → validation through simulations / measurements (field / laboratory)

INTRODUCTION

To improve the LP of a TL or distrib. network:

1) main types of overvoltages to which the system is subjected
2) evaluate and compare the effectivenesses of different protection measures
3) select the best one according to a cost/benefit analysis

Scope of the lecture:

To present the major mechanisms by which lightning can lead to outages in T&D power systems.

But what is lightning?

A transient, high-current (typically tens of kA) electric discharge in air whose length is measured in km.

About 75% of lightning flashes include intracloud, intercloud, and cloud-to-air discharges.

Lightning flashes between cloud and Earth constitute about 25% of global lightning activity, but…

- people and animals' deaths
- material damages
- losses (esp. to the electrical and telecommunications sectors)

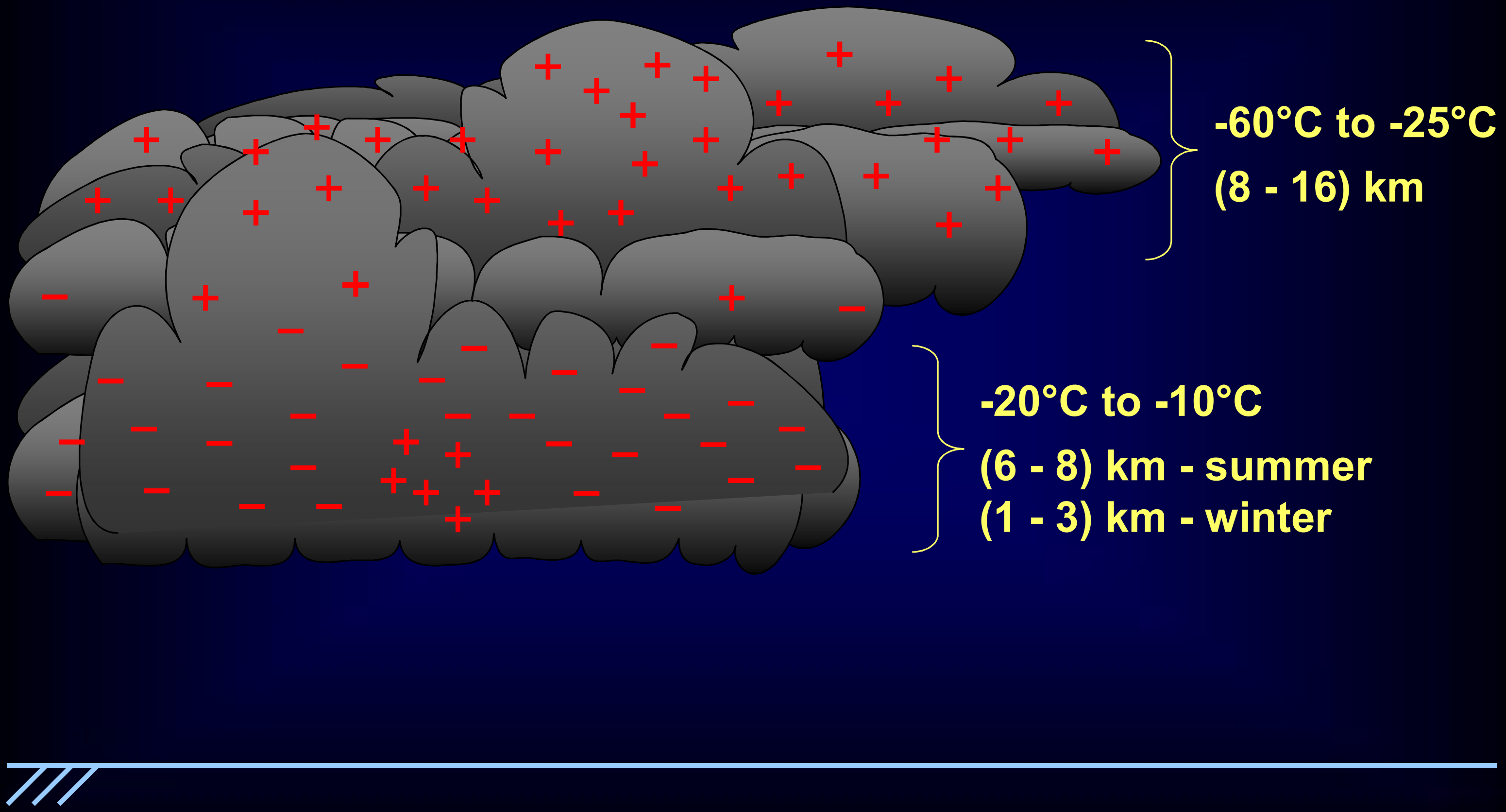
Rakov V. A., 'Lightning phenomenon and parameters for engineering application'. In Piantini A., *Lightning interaction with power systems - Fundamentals,* Vol. 2, Chap. 2, pp. 47-99 (IET, London, Jan. 2020, 1st ed.).

CUMULUS – NIMBUS CLOUD

Clouds that produce lightning (CB) are characterized by great vertical extent.

Typical charge distribution in a thundercloud

Electric field measurements in stations at the ground and also inside CB clouds.



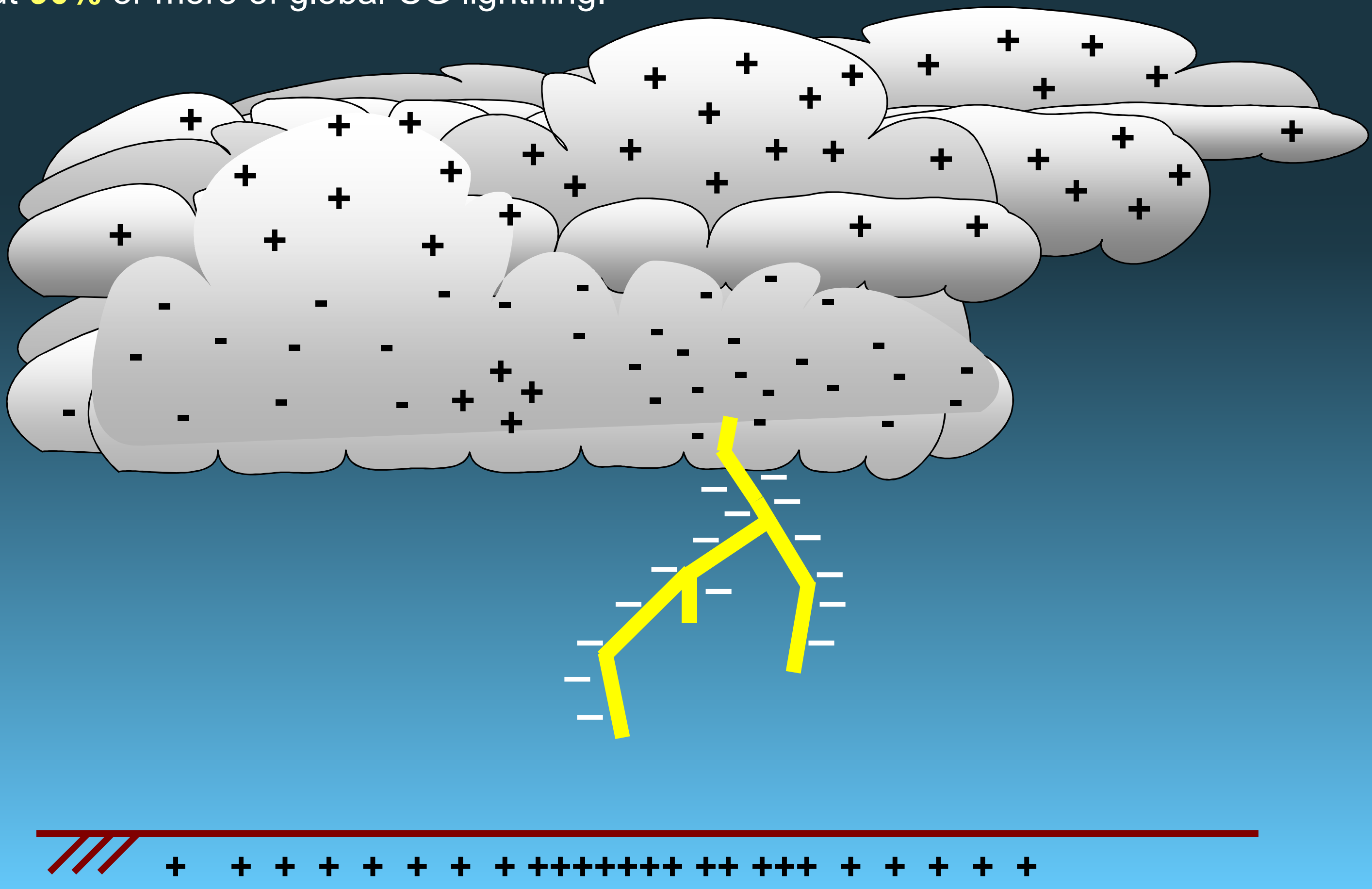
TYPES OF CG LIGHTNING

CG flashes can be classified into 4 types, according to the:

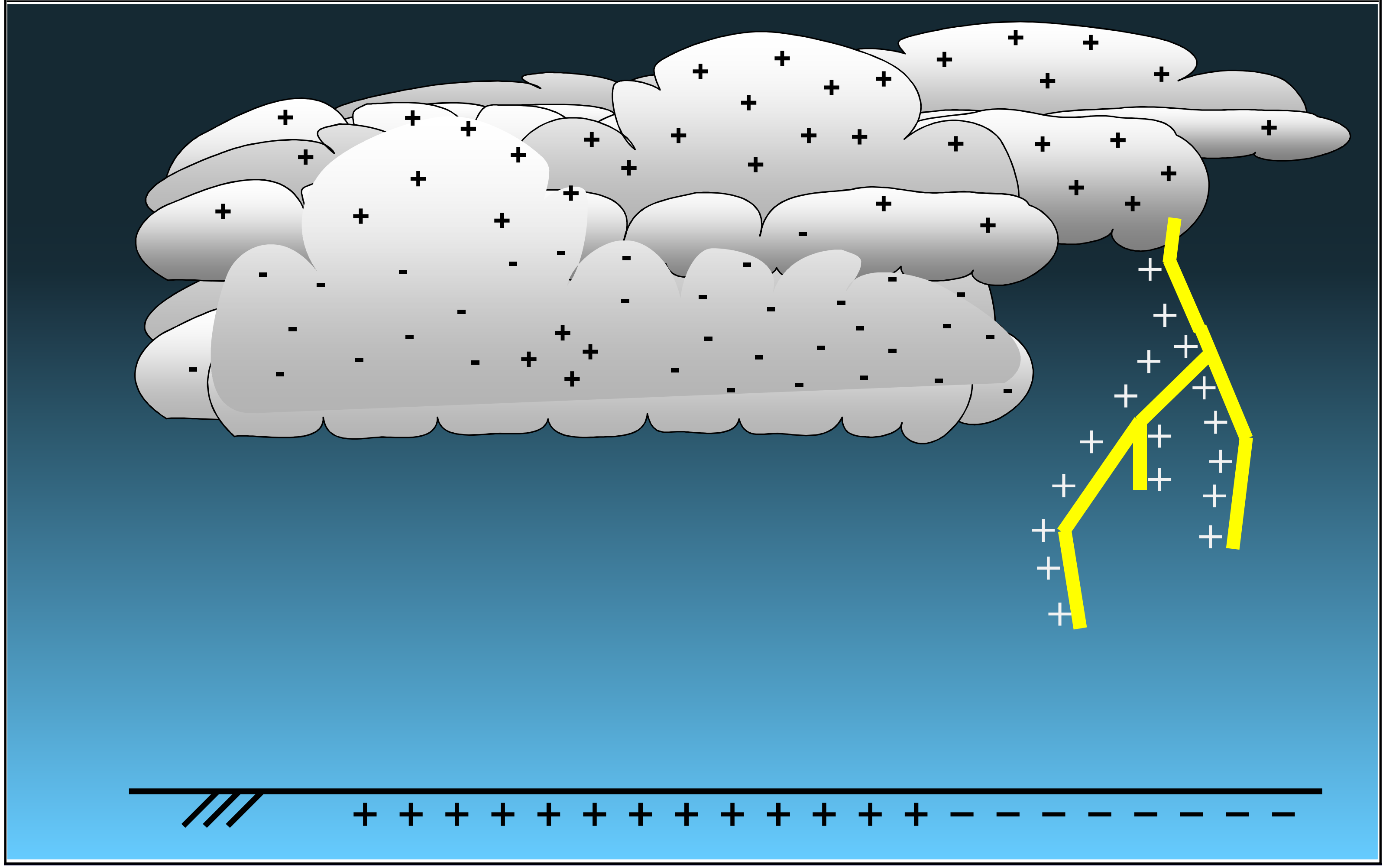
- direction of propagation of the initial leader;
- polarity of the cloud charge effectively lowered to ground.

DOWNWARD (-) LIGHTNING

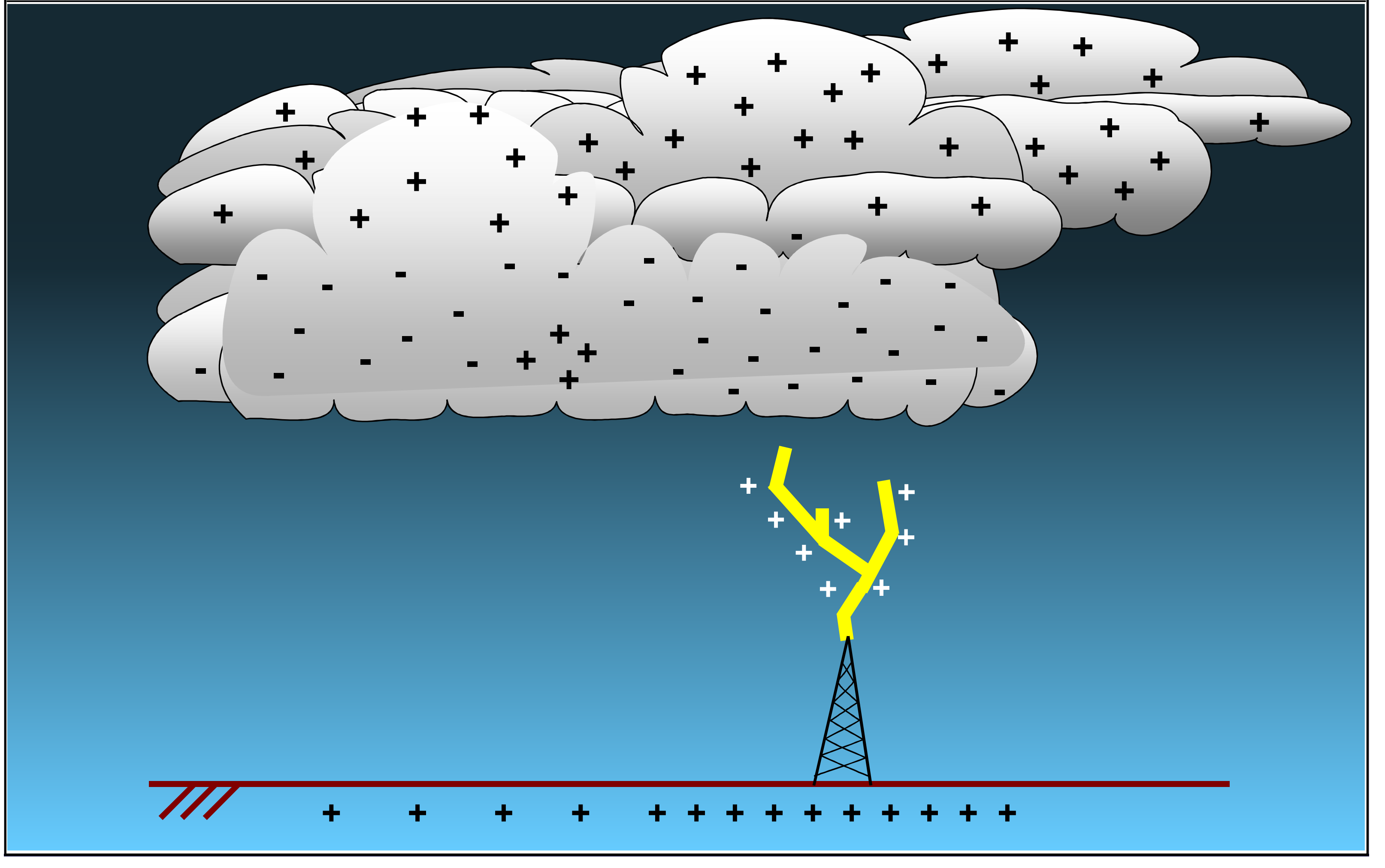
About **90%** or more of global CG lightning.



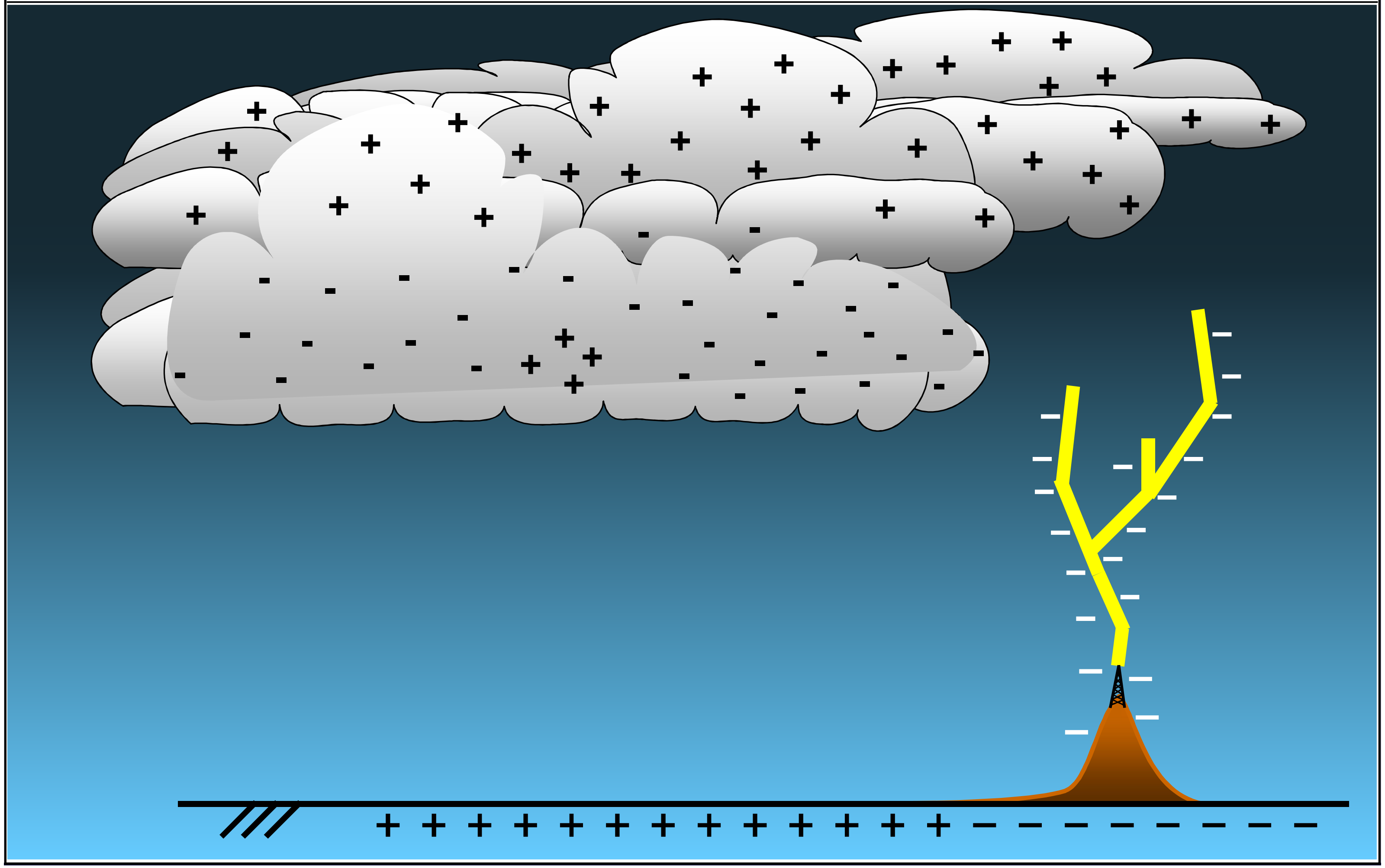
DOWNWARD (+) LIGHTNING

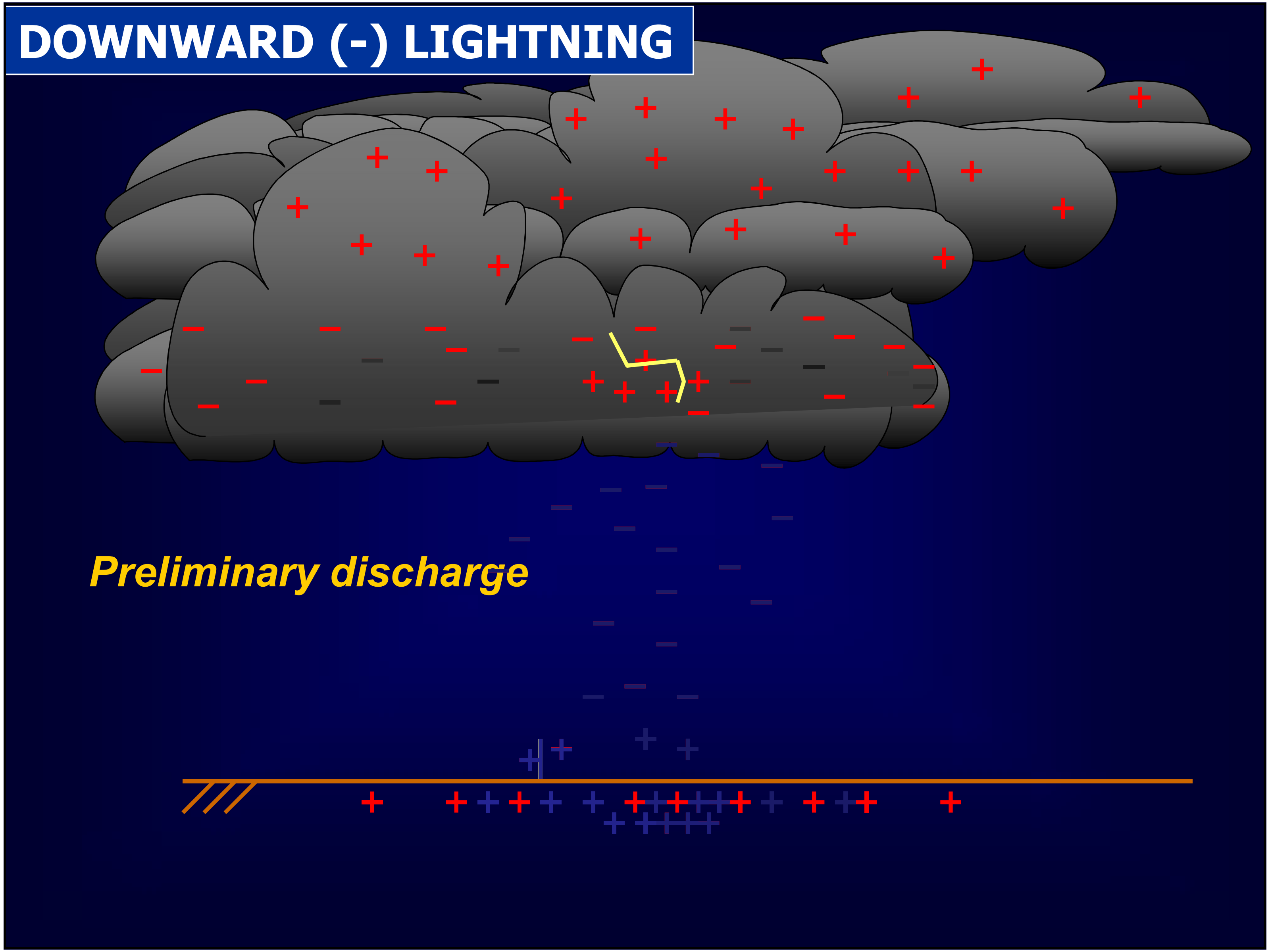


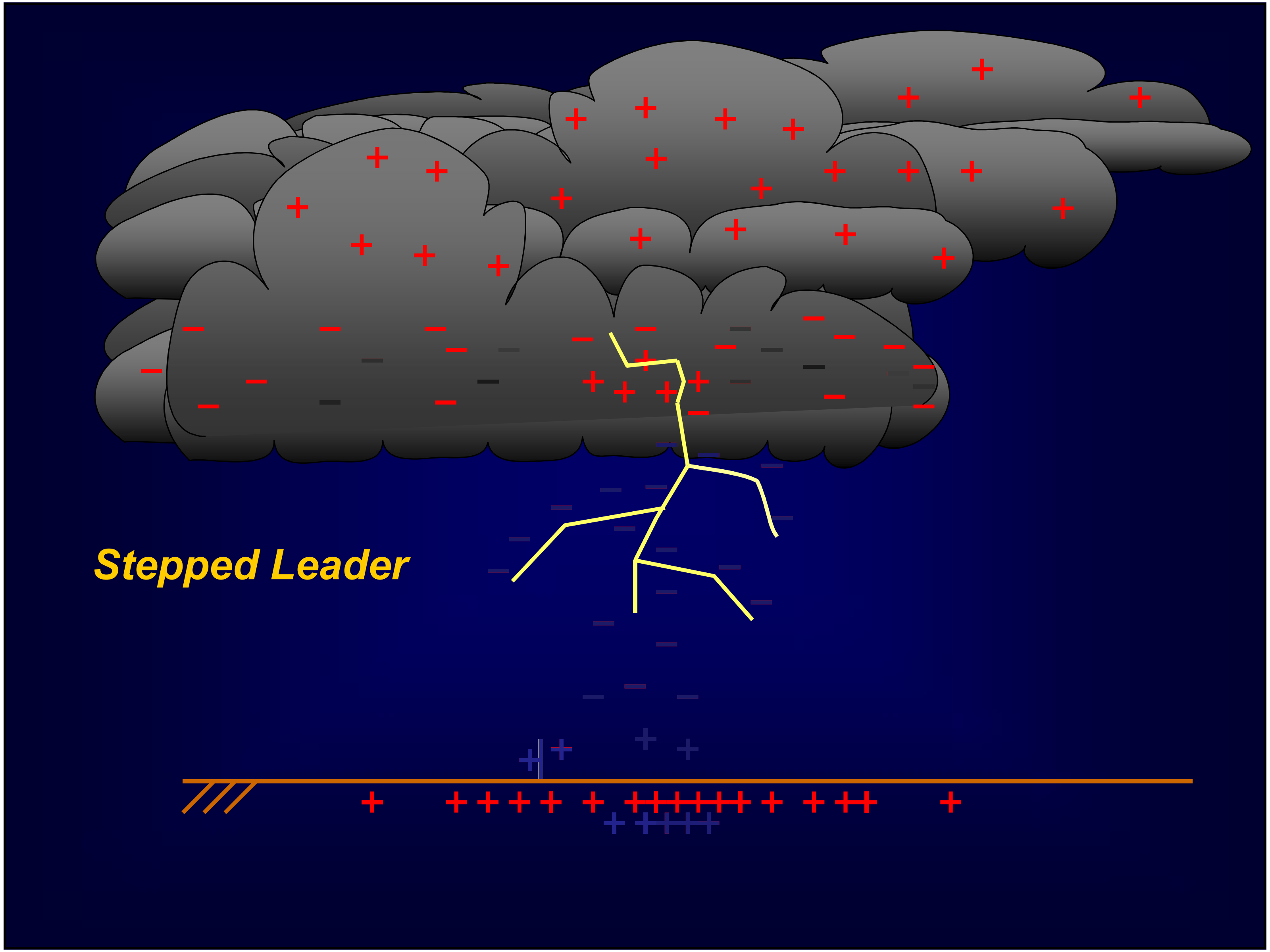
UPWARD (-) LIGHTNING

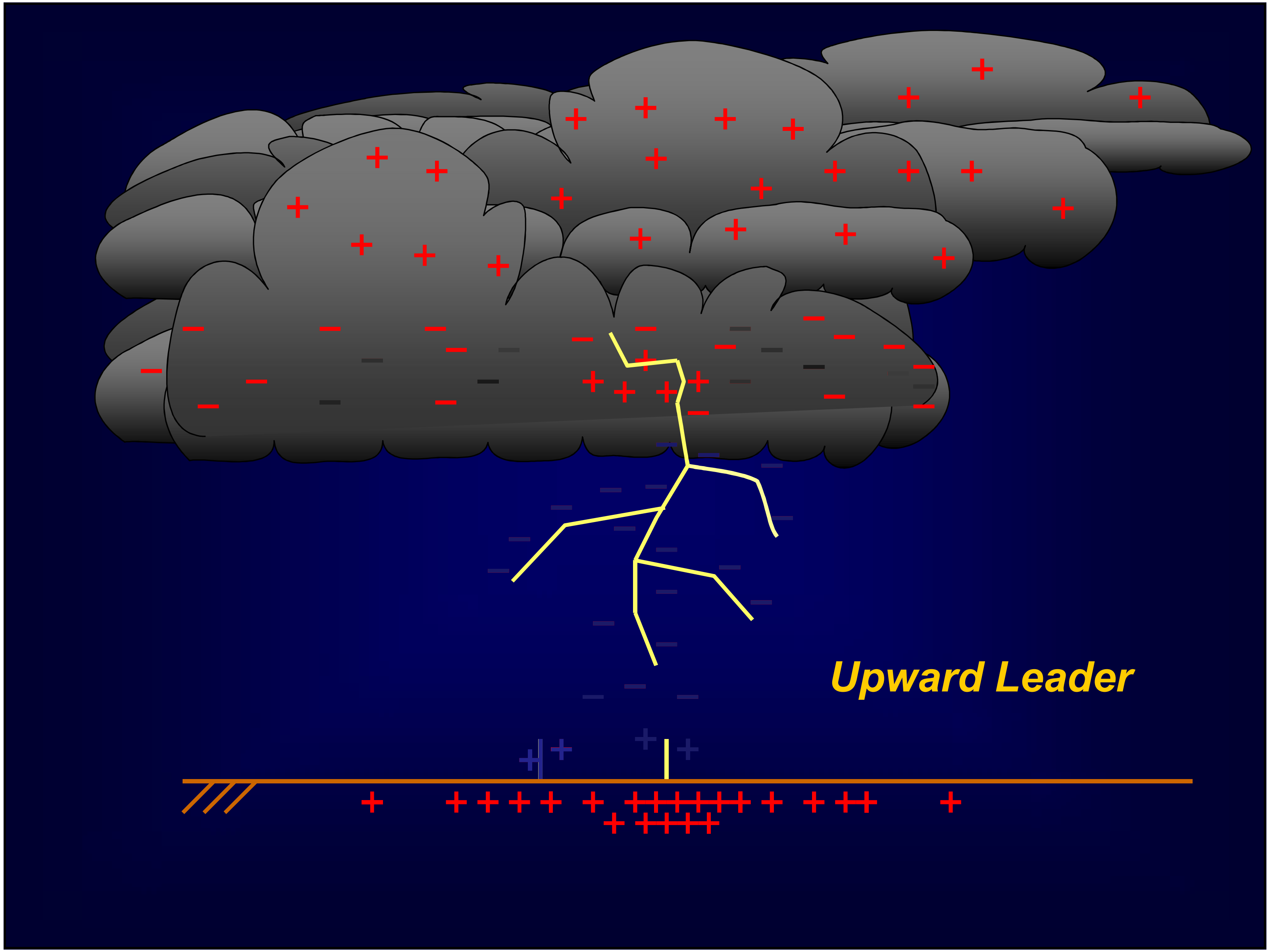


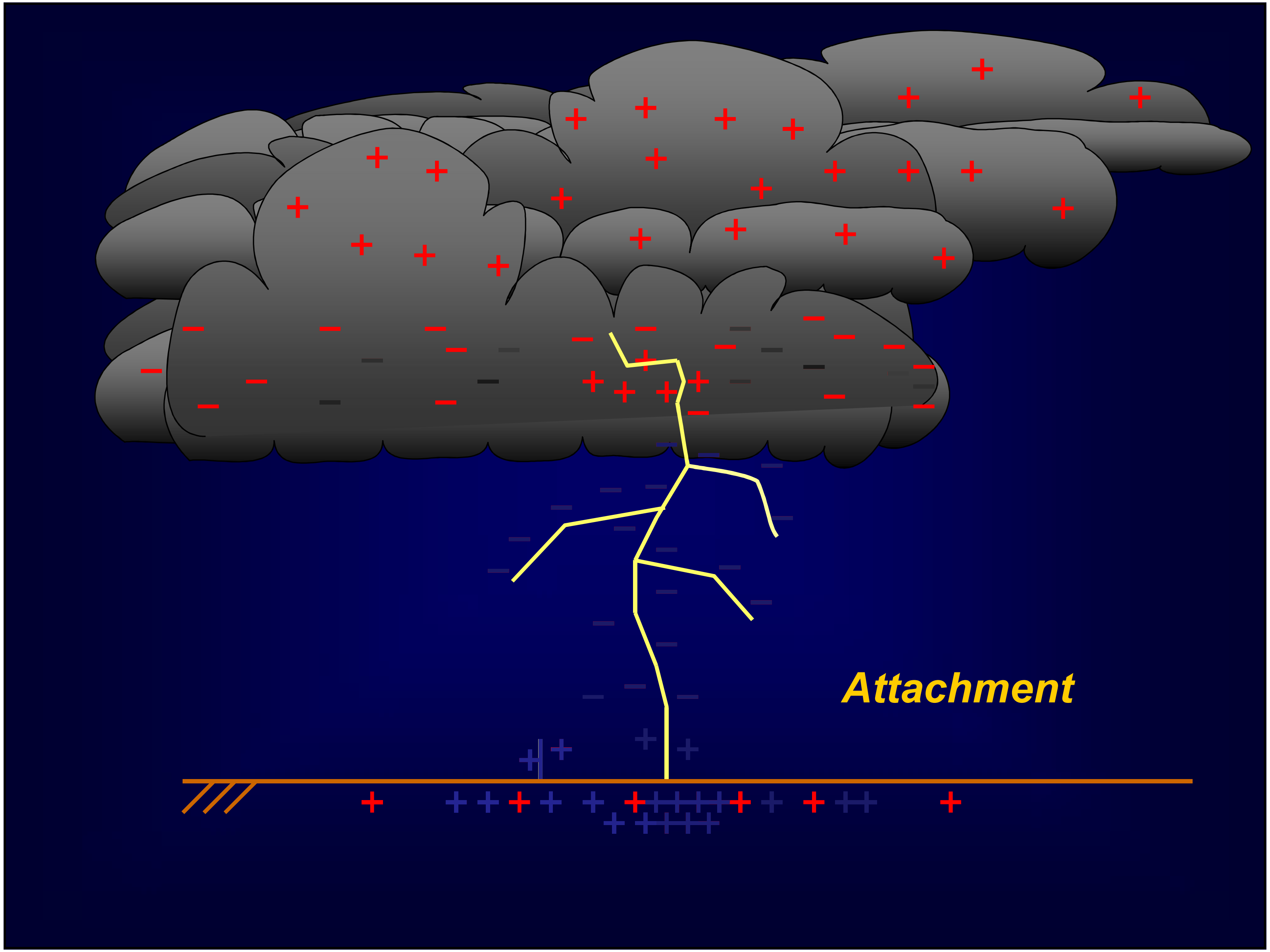
UPWARD (+) LIGHTNING

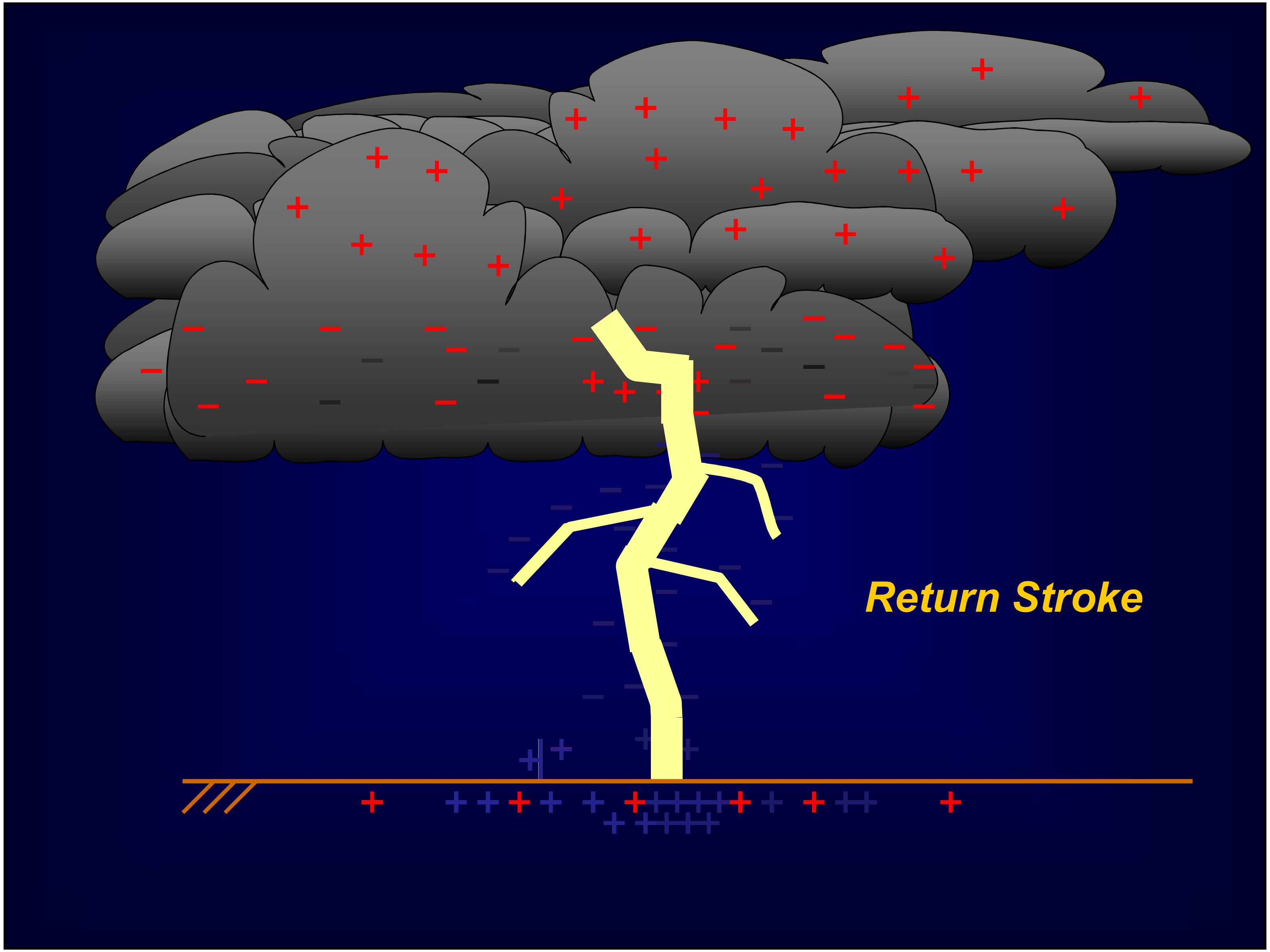


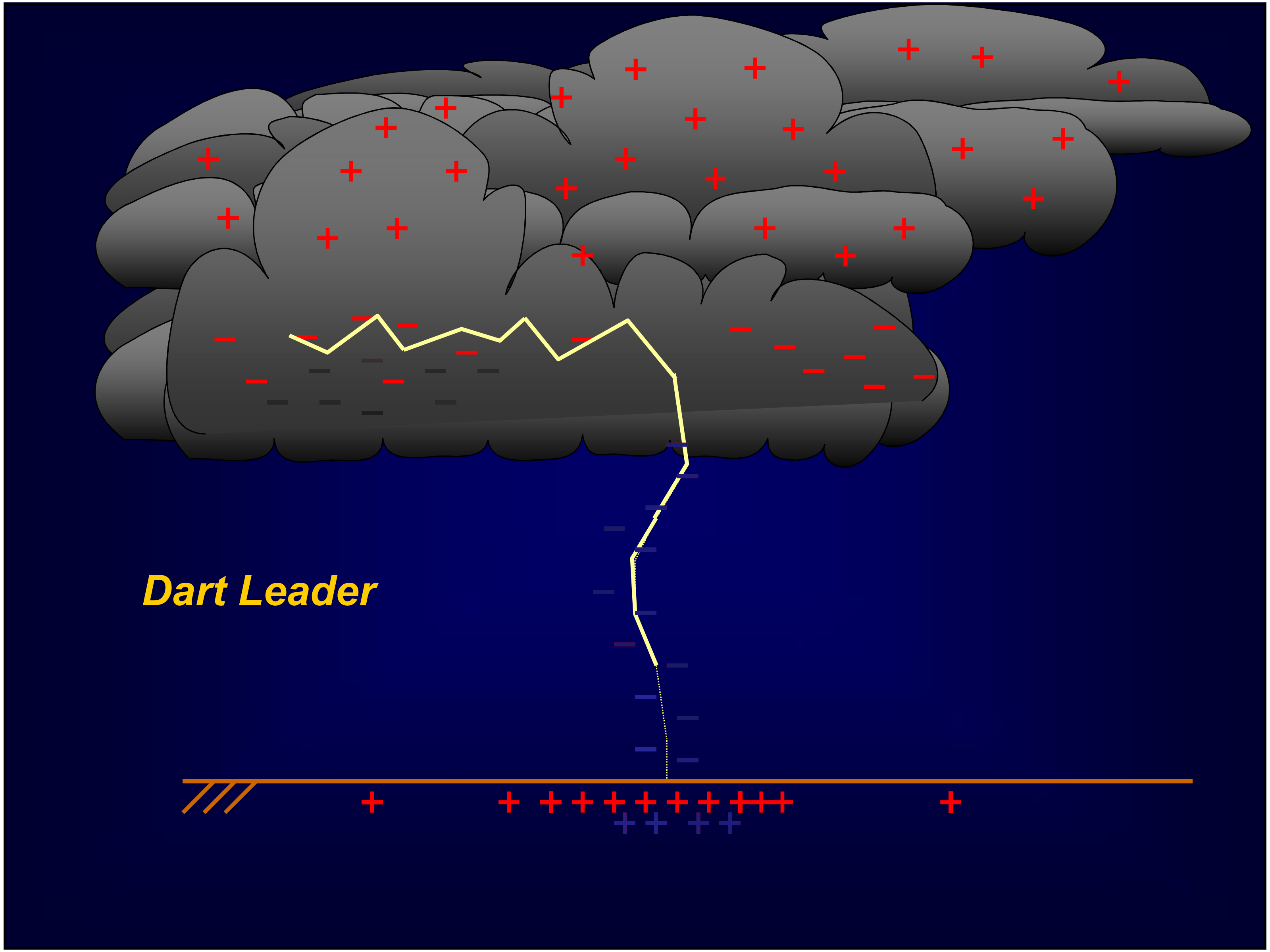

DOWNWARD (-) LIGHTNING
Preliminary discharge

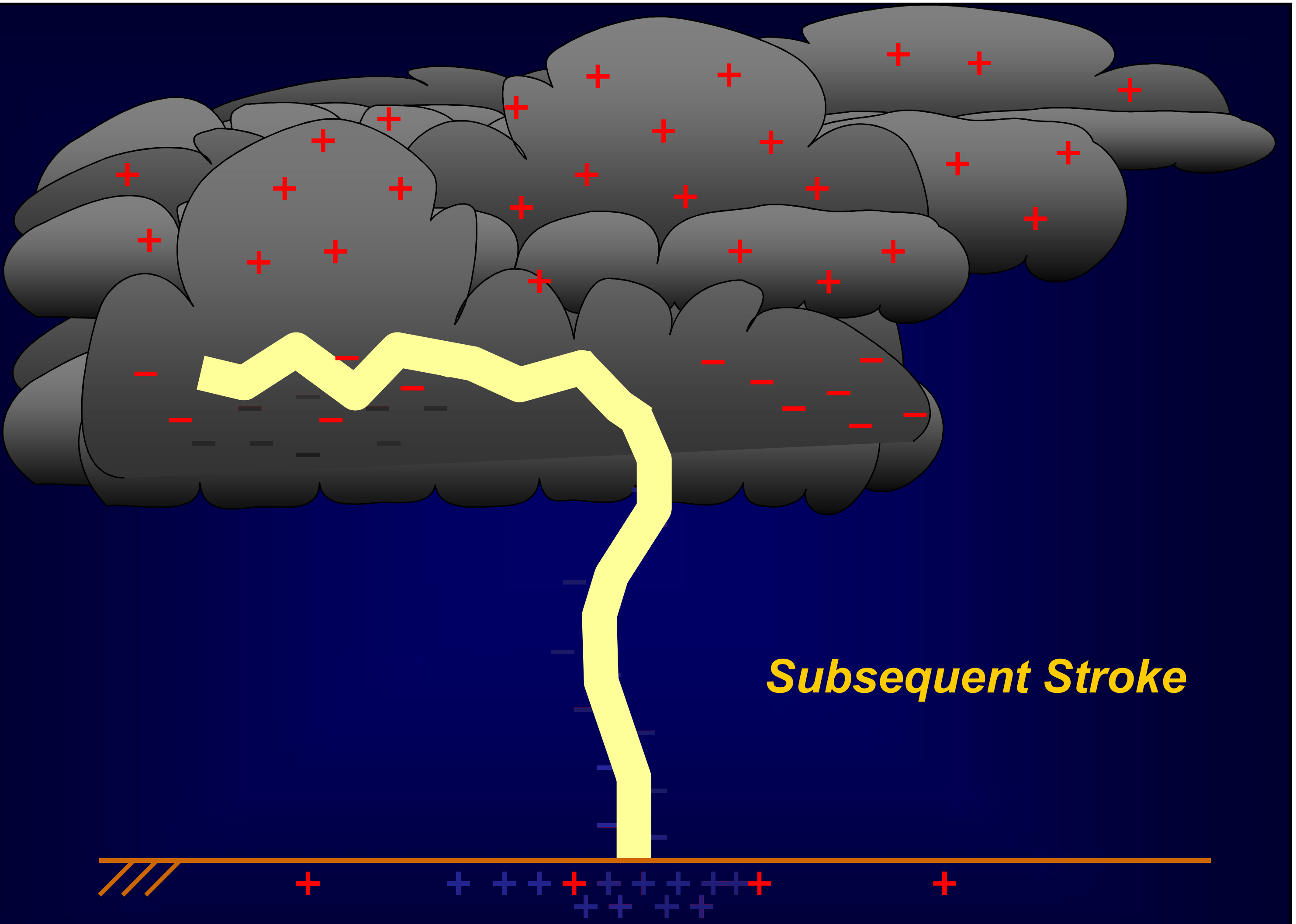

Stepped Leader


Upward Leader


Attachment

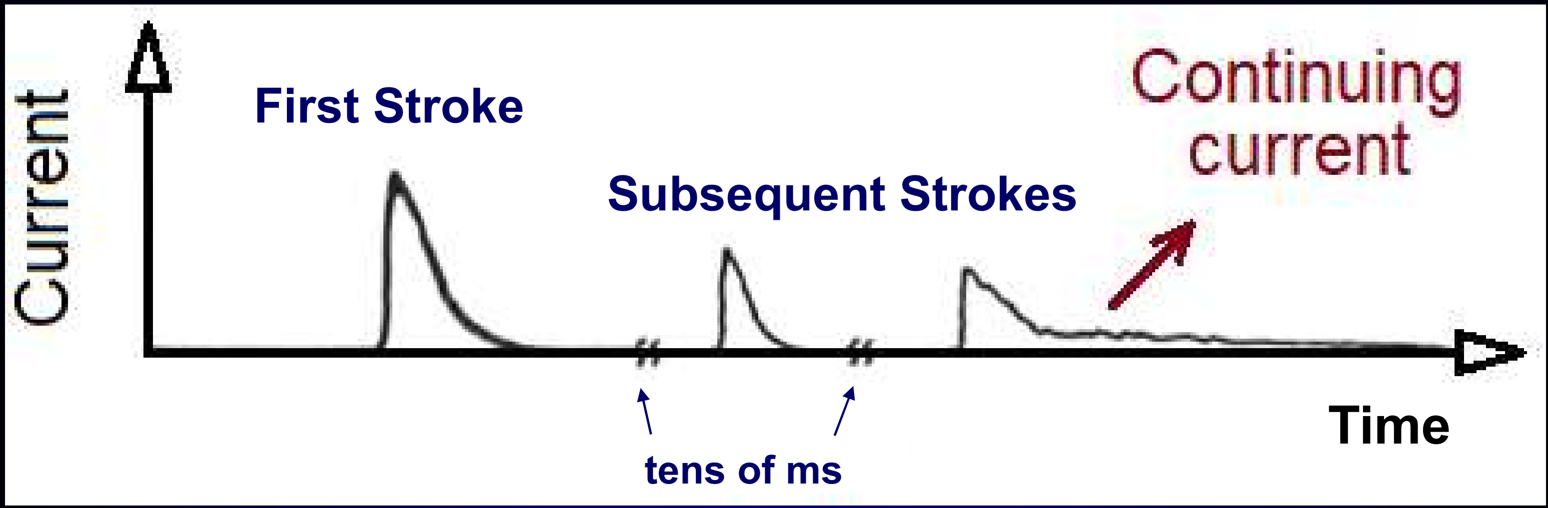

Return Stroke


Dart Leader



A typical (-) CG flash is composed of **3 to 5** strokes, with typical interstroke intervals of some tens of ms, but a flash with 26 strokes was observed in New Mexico.

Channel-base current

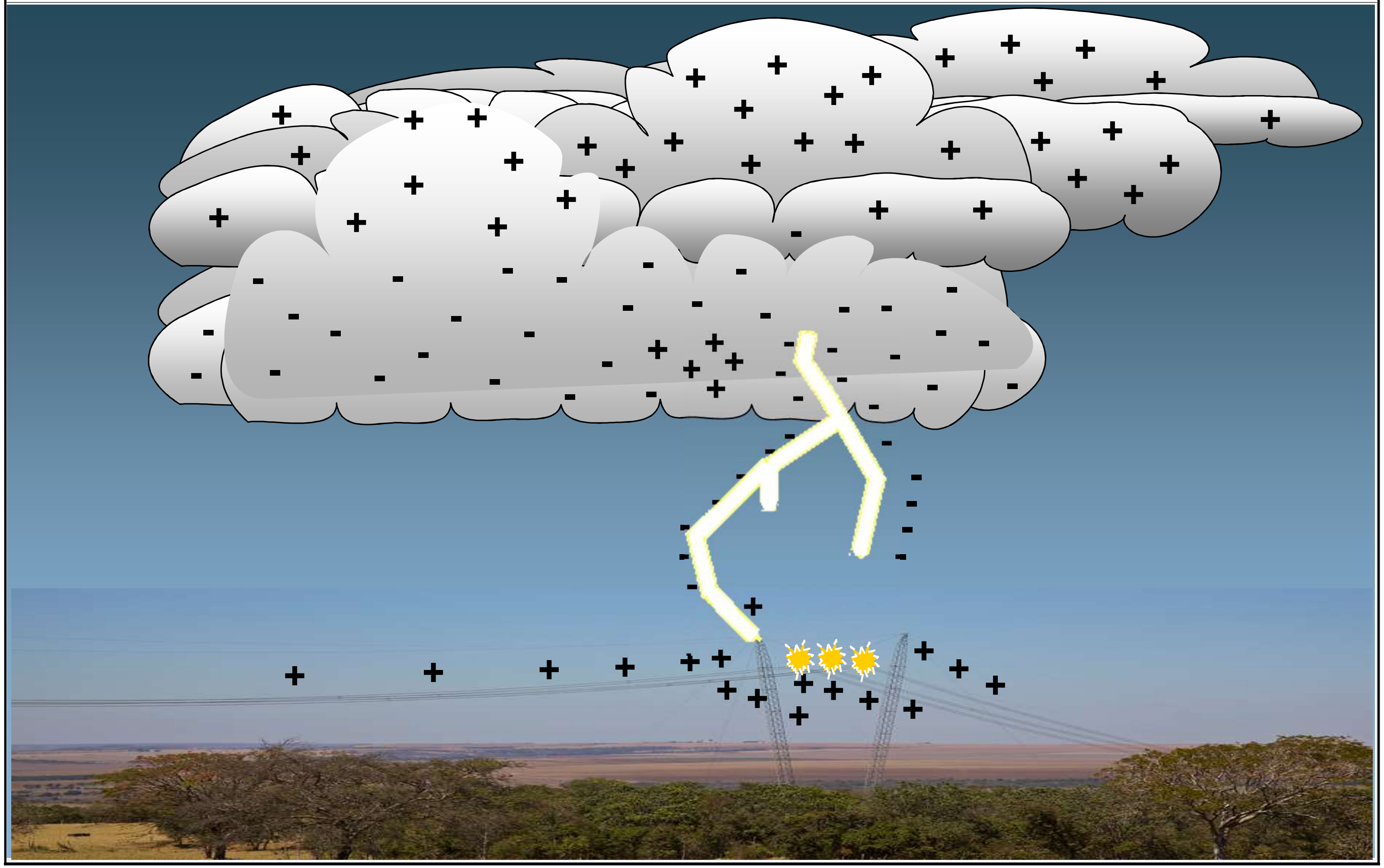


The strokes are often followed by a continuing current (tens to hundreds of amperes and up to hundreds of ms).

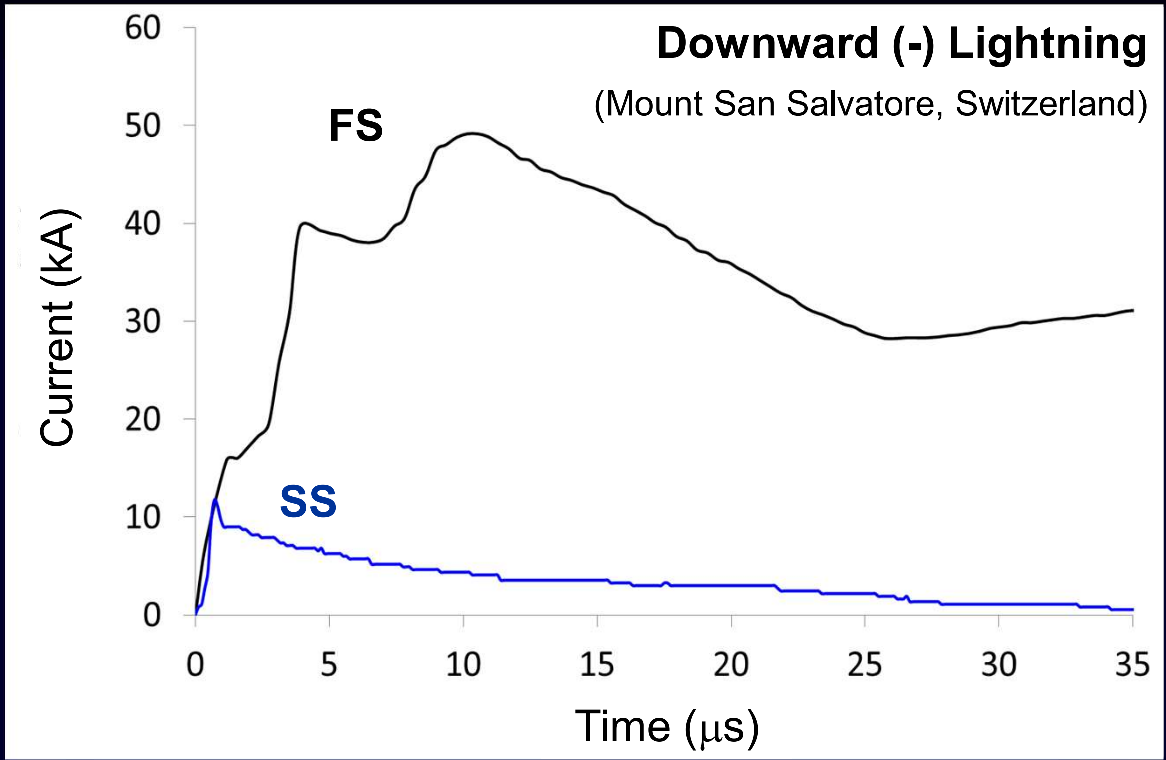
Between 30% and 50% of all (-) CG flashes contain long continuing currents (duration > 40 ms).

Rakov V. A., 'Lightning phenomenon and parameters for engineering application'. In Piantini A., *Lightning interaction with power systems - Fundamentals,* Vol. 2, Chap. 2, pp. 47-99 (IET, London, Jan. 2020, 1st ed.).

Lightning Parameters for Eng. Applications



Main Lightning Parameters



Magnitude (- and +): 2 kA – 300 kA ($I_{50\%FS-} \approx 31$ kA; $I_{50\%SS} \approx 12$ kA)

Front time: a few μs ($T_{f30(50\%)FS-} \approx 3{,}8$ μs; $T_{f30(50\%)SS} \approx 0{,}7$ μs)

Time to half-value: tens of μs

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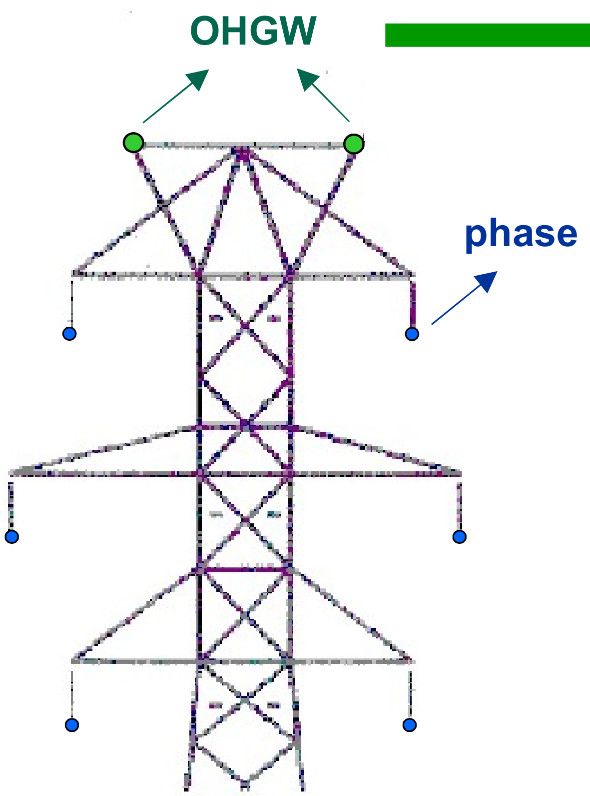
- **Transmission Lines**
- Medium-Voltage Lines
- Low-Voltage Networks
- Conclusions

TRANSMISSION LINES { Shielding Failure / Backflashover

Double-circuit TL

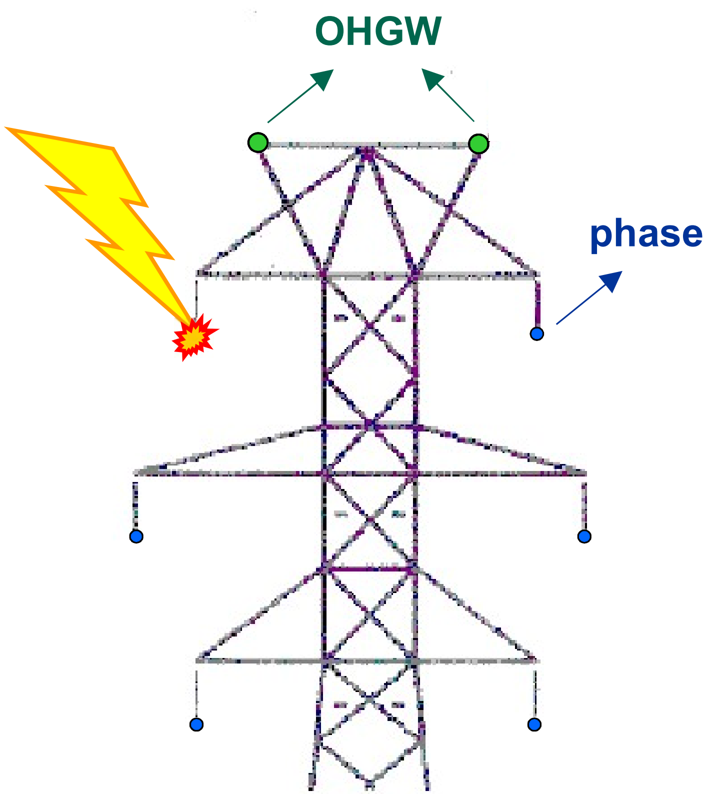


Grounded wire or wires placed above the phase conductors for the purpose of intercepting direct strokes that could cause insulator flashovers

500 kV TL
(Feb. 26, 1995)
(Hokuriku Electric Power Co.)

TRANSMISSION LINES - Shielding Failure

Double-circuit TL

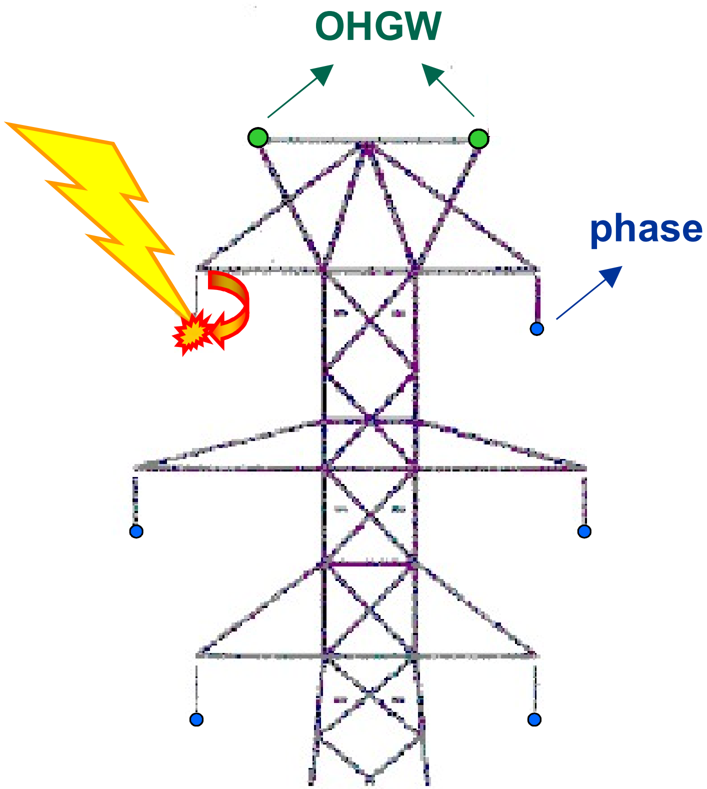


Direct lightning stroke to the upper phase conductor (no flashover)

J. Takami and S. Okabe, "Characteristics of Direct Lightning Strokes to Phase Conductors of UHV Transmission Lines," IEEE Trans. Power Delivery, vol. 22, pp. 537-546, 2007.

TRANSMISSION LINES - Shielding Failure

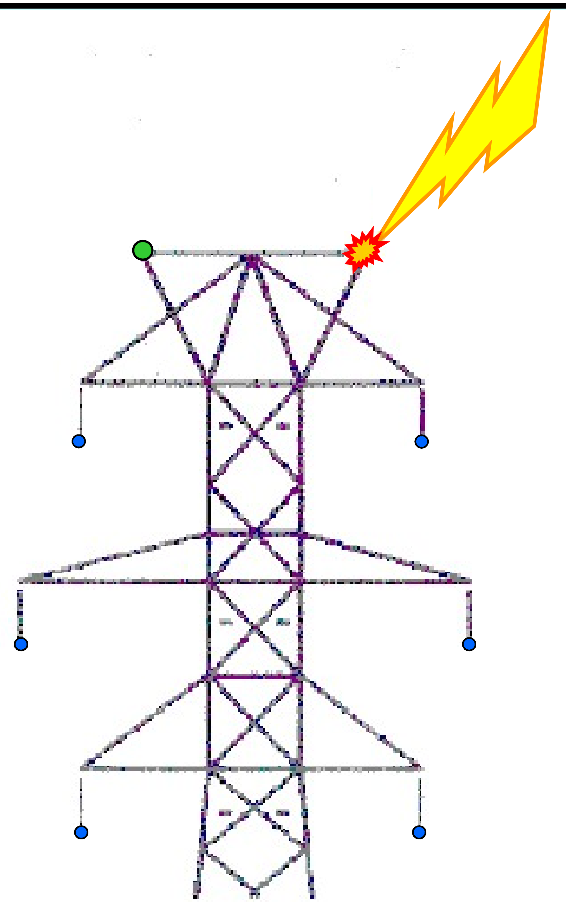
Double-circuit TL

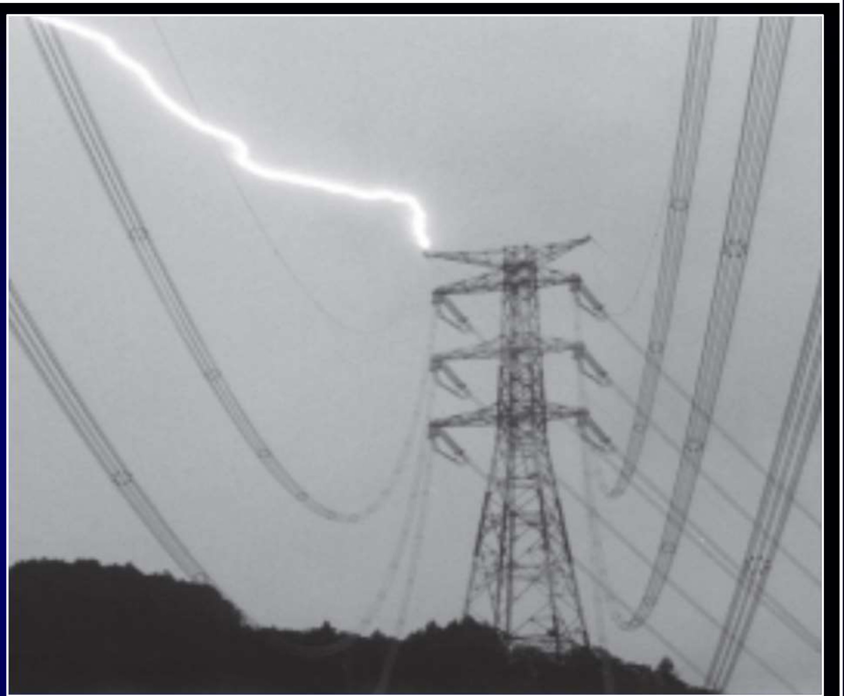


Flashover (direct lightning stroke to the middle phase conductor)

J. Takami and S. Okabe, "Characteristics of Direct Lightning Strokes to Phase Conductors of UHV Transmission Lines," IEEE Trans. Power Delivery, vol. 22, pp. 537-546, 2007.

TRANSMISSION LINES - Backflashover

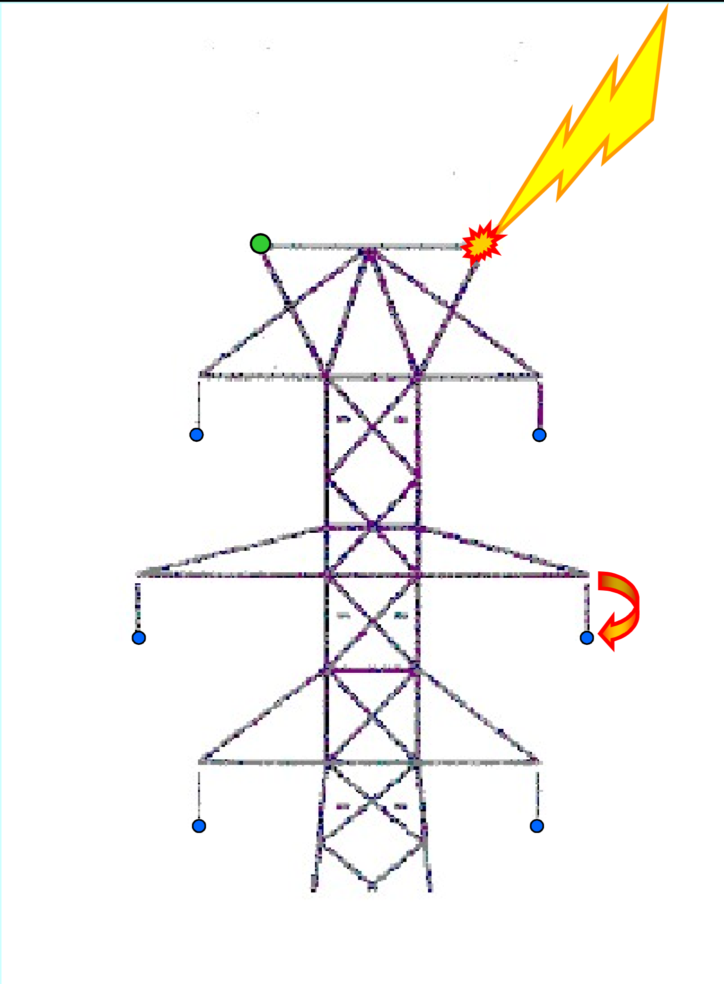


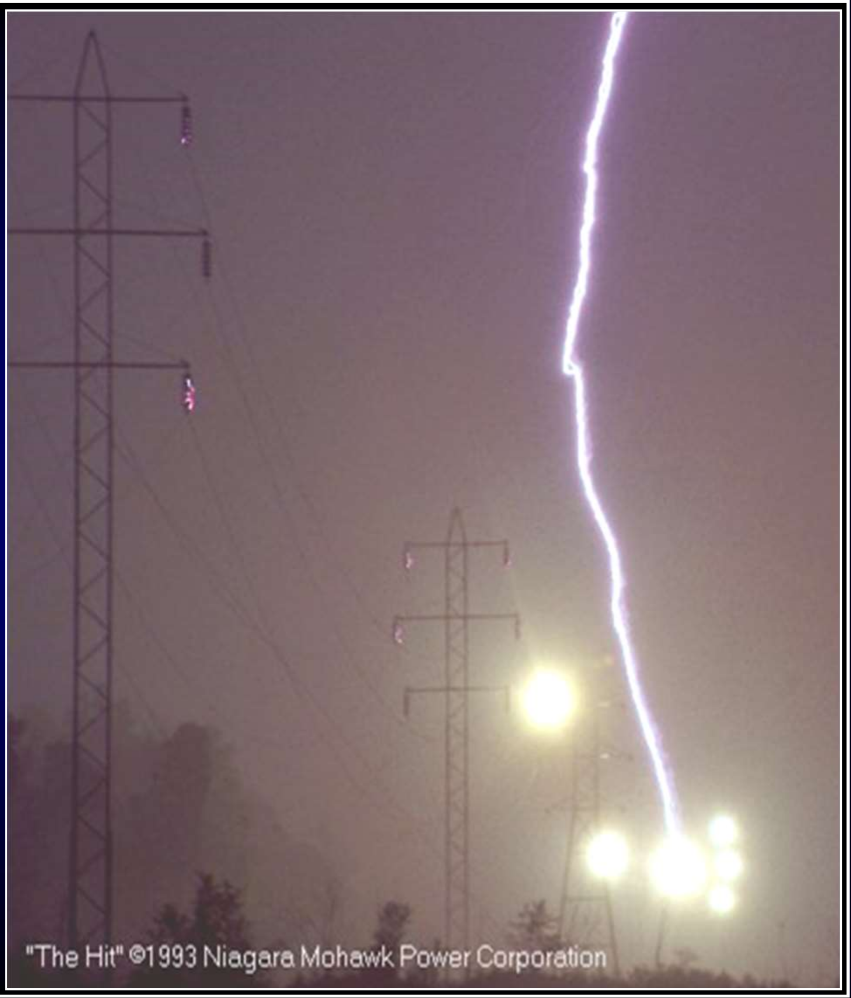


Lightning stroke to the top of the tower

J. Takami and S. Okabe, "Characteristics of Direct Lightning Strokes to Phase Conductors of UHV Transmission Lines," IEEE Trans. Power Delivery, vol. 22, pp. 537-546, 2007.

TRANSMISSION LINES - Backflashover

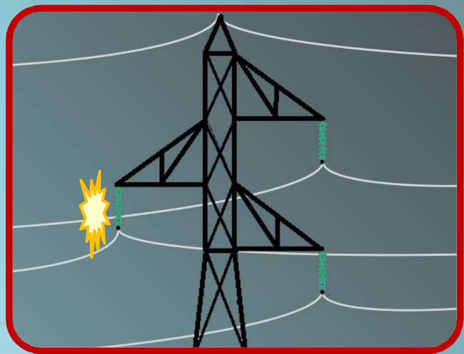


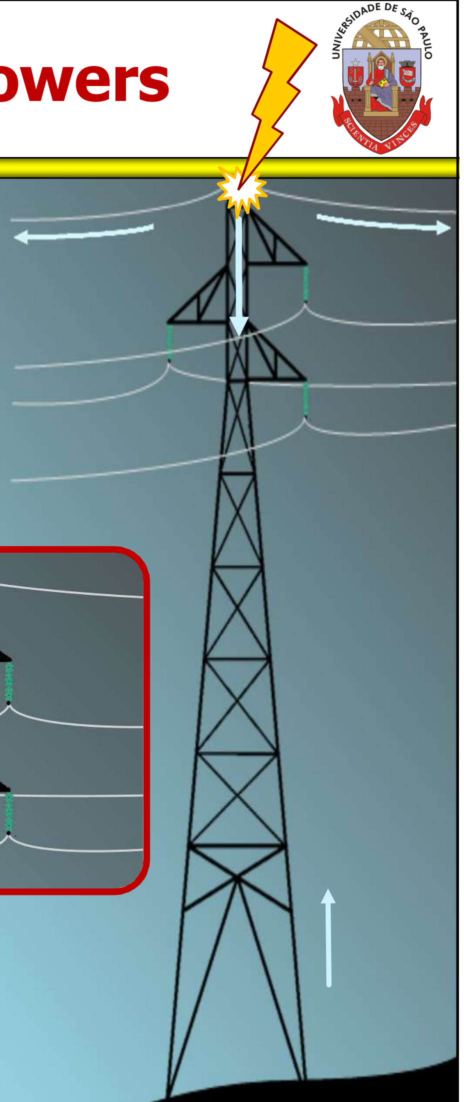


Lightning Strikes to Transmission Towers

Insulator voltages depend on the:

- strike point
- stroke current (magnitude + waveshape)
- conductors’ heights
- no. and positions of shield wire(s)
- surge impedances (tower, conductors)
- ground impedance
- reflections from adjacent towers
- power frequency voltage





TRANSMISSION LINES - Backflashover

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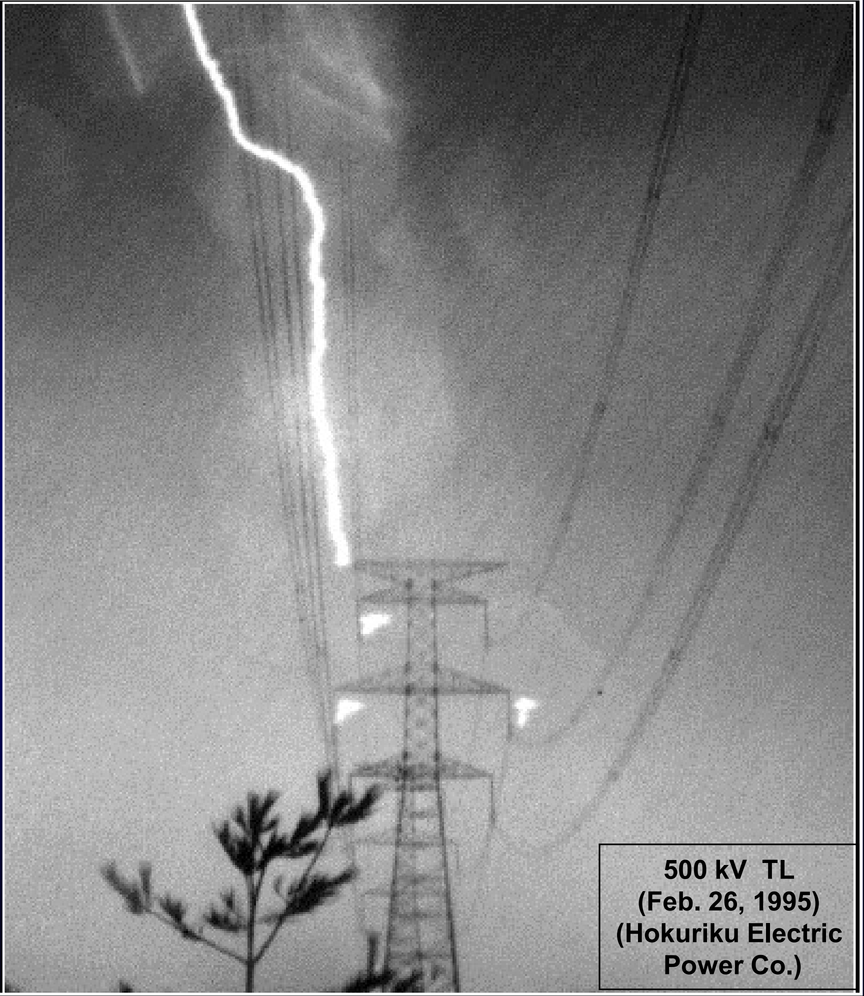

500 kV TL (Feb. 26, 1995) (Hokuriku Electric Power Co.)

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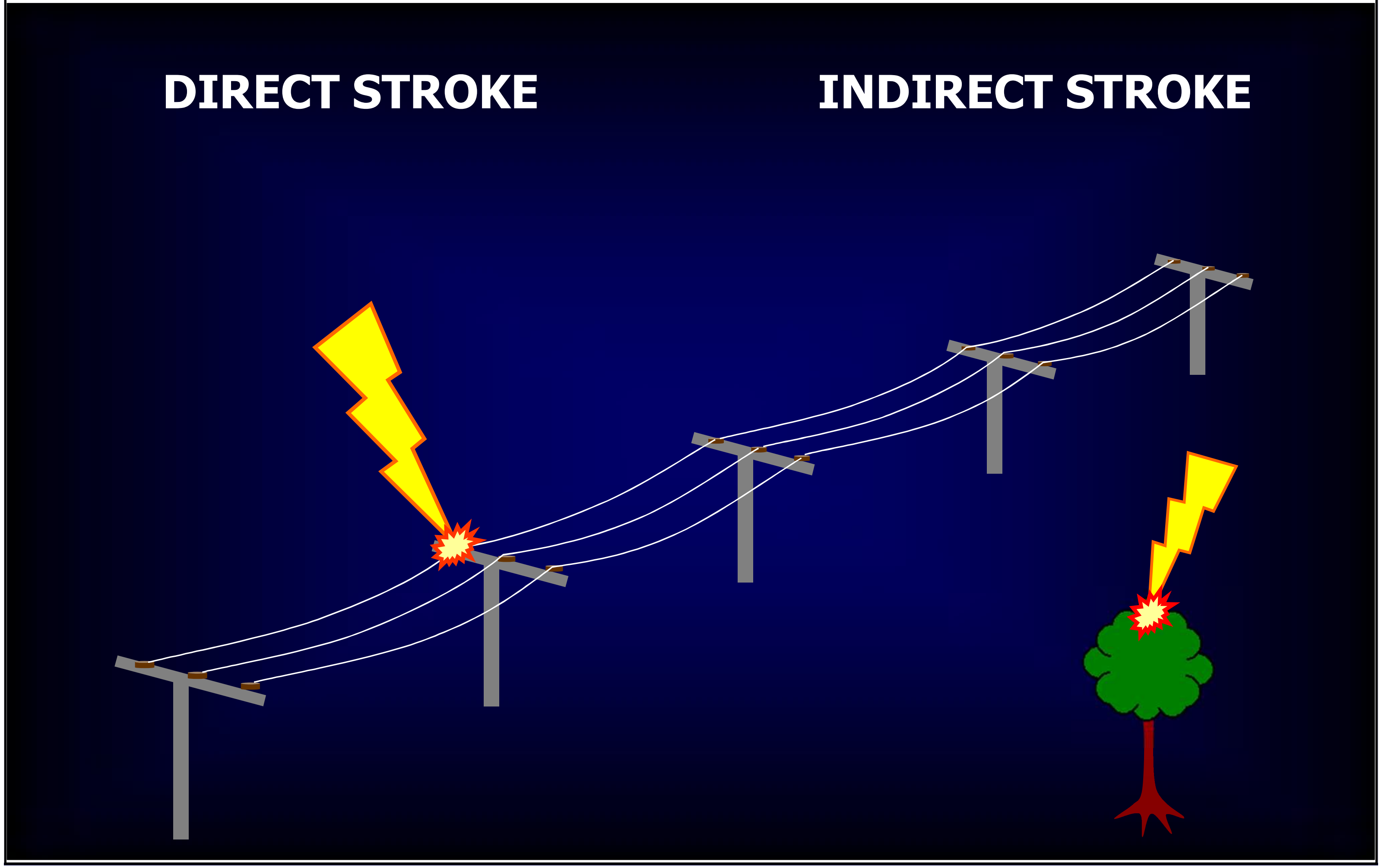
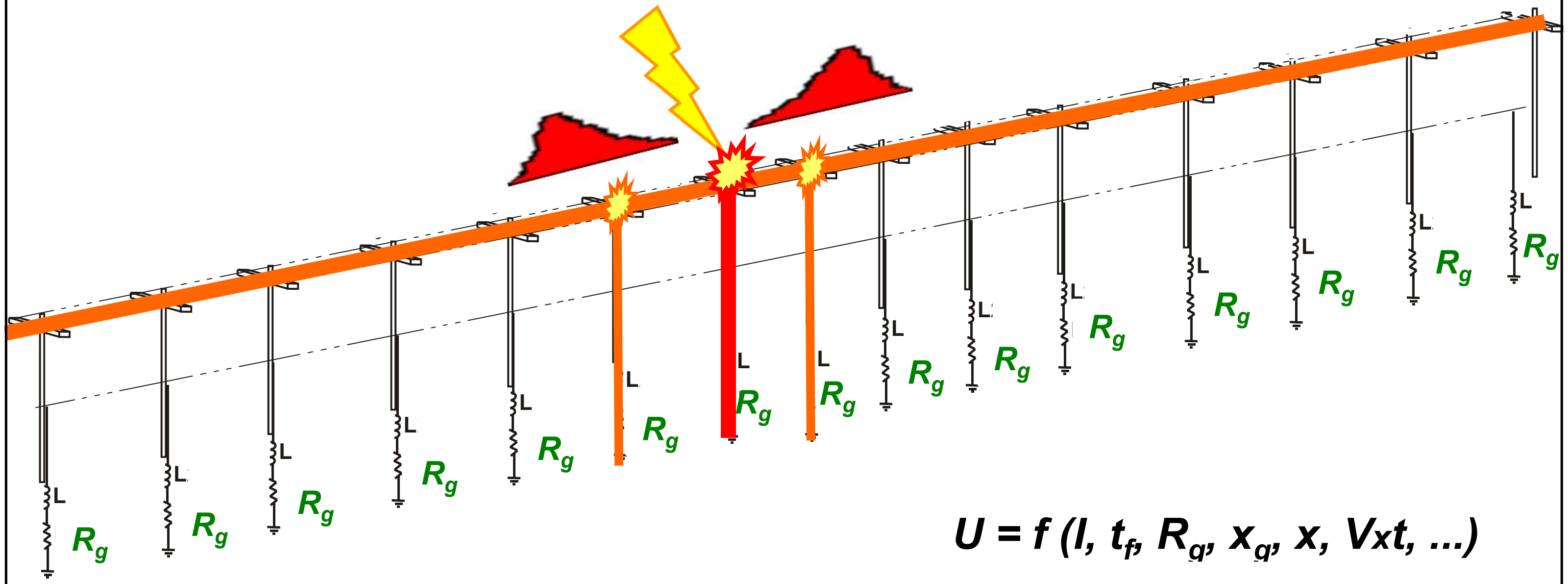
- Conclusions

LIGHTNING OVERVOLTAGES IN MV SYSTEMS



DIRECT STROKES

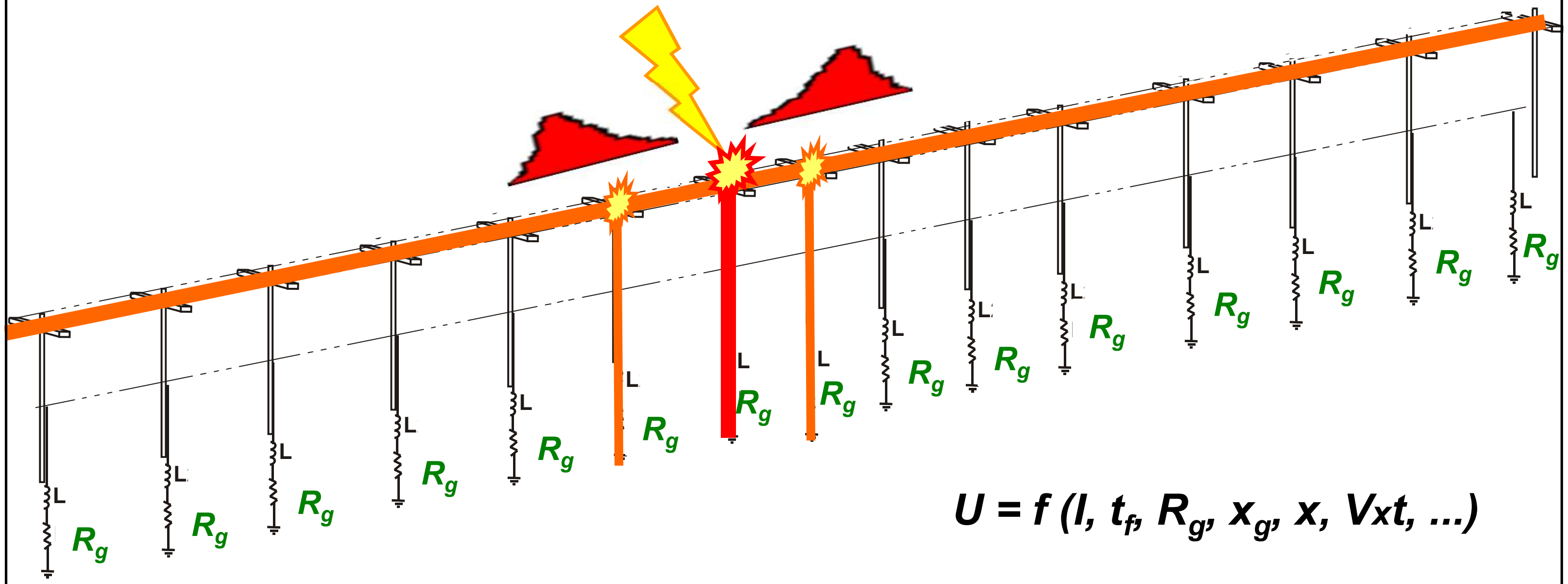


$U = f\,(I,\, t_f,\, R_g,\, x_g,\, x,\, Vxt,\, \ldots)$

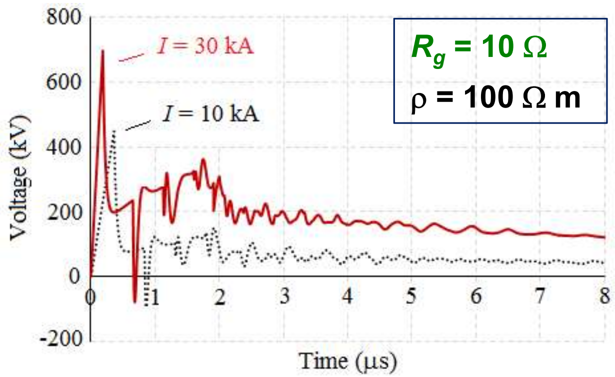
- Overvoltages are characterized by a few very short spikes in the wavefront, produced by multiple line insulation flashovers, followed by a slower wave.

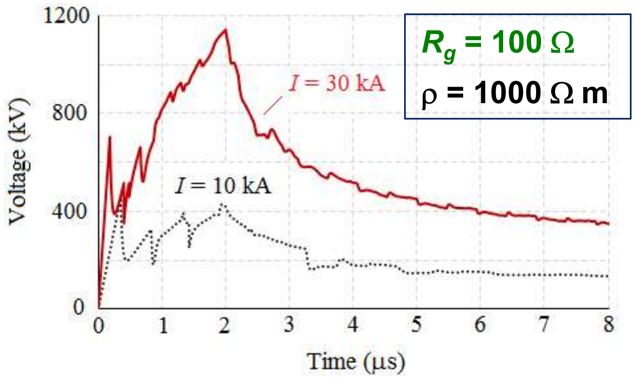
The prospective magnitudes are in the MV range and, therefore, in almost all the cases a direct strike to a distribution line without SW or SA's will cause multiple flashovers.

DIRECT STROKES

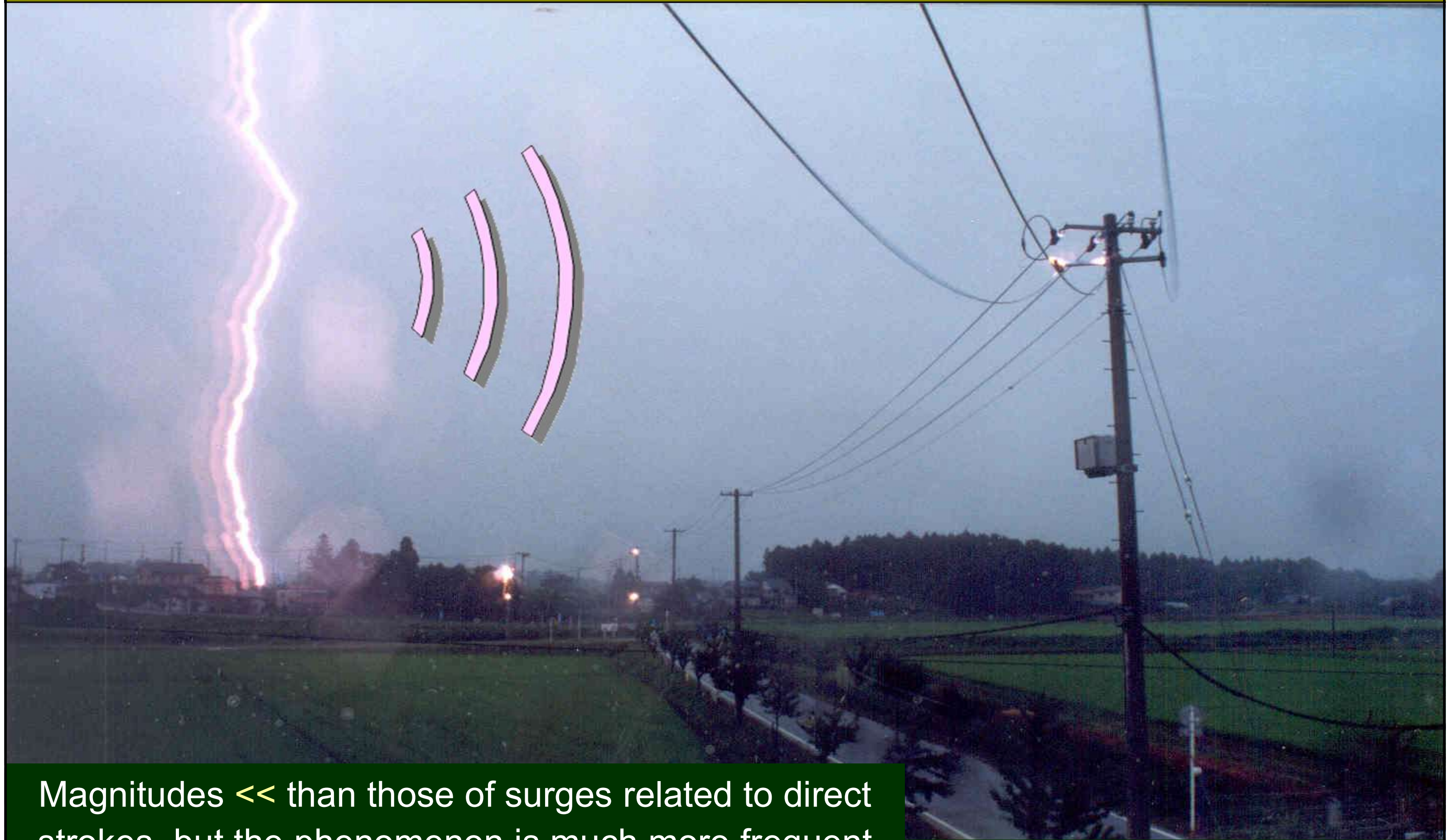


$$U = f\,(I,\ t_f,\ R_g,\ x_g,\ x,\ Vxt,\ \ldots)$$





INDIRECT STROKES



Magnitudes << than those of surges related to direct strokes, but the phenomenon is much more frequent → greater no. flashovers (≤ 15 kV).

Courtesy: Prof. S. Yokoyama

MAIN PARAMETERS

Shorter durations in comparison with the overvoltages caused by direct strokes.

- Magnitude, front time, and propagation velocity of the stroke current
- Distance between the line and the lightning strike point
- Upward leader / elevated object
- Line configuration (horizontal or vertical, rural or urban)
- Conductors' heights, presence of a shield wire or neutral conductor
- Observation point
- Position of the stroke channel relative to the line
- Soil resistivity and ground resistance
- Grounding / surge arresters' spacing
- Surge arrester V/I characteristic, nearby buildings

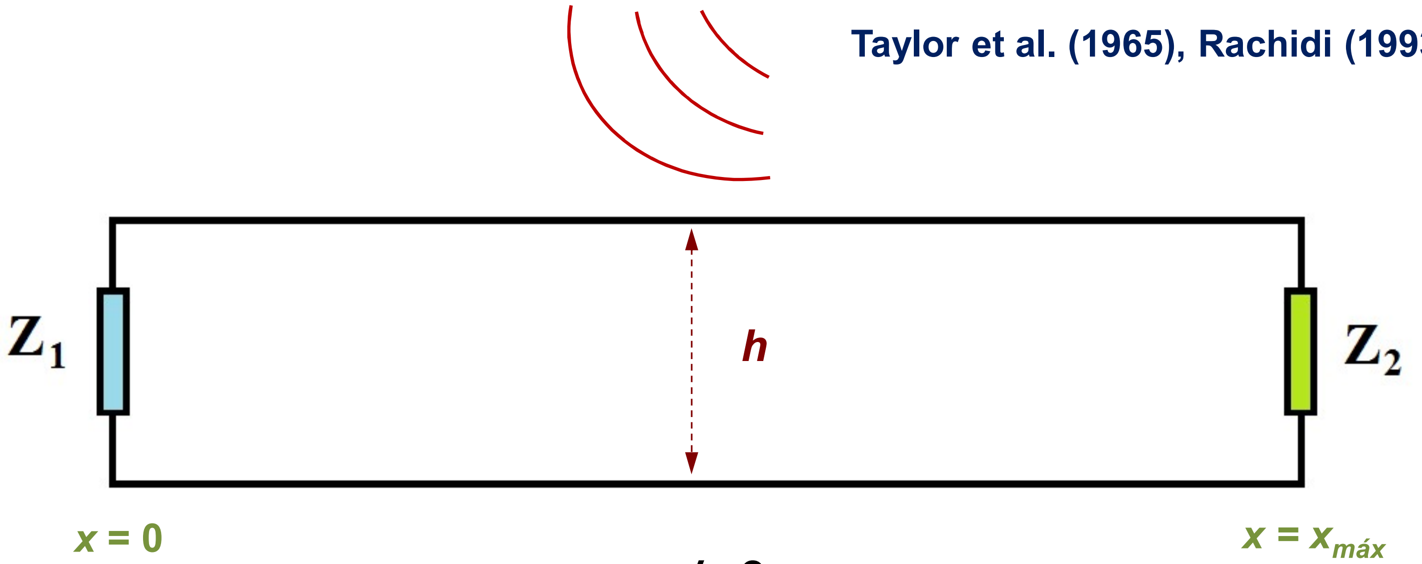
THE EXTENDED RUSCK MODEL (ERM)

$$\begin{cases} \dfrac{\partial V^s(x,t)}{\partial x} + \displaystyle\int_0^t \xi_g'(t-\tau)\,\frac{\partial}{\partial \tau} I(x,\tau)\,d\tau + L\frac{\partial I(x,t)}{\partial t} = -\dfrac{\partial \Phi^i(x,h,t)}{\partial x} - \dfrac{\partial A_x^{\,i}(x,h,t)}{\partial t} \\[2ex] \dfrac{\partial I(x,\,t)}{\partial x} + C\,\dfrac{\partial V^{\,s}(x,\,t)}{\partial t} = 0 \end{cases}$$

Inducing electric field (horiz. component)

Agrawal et al. (1980)

Taylor et al. (1965), Rachidi (1993)



$\rho \neq 0$

THE EXTENDED RUSCK MODEL (ERM)

$$\begin{cases} \dfrac{\partial V^s(x,t)}{\partial x} + \displaystyle\int_0^t \xi_g'(t-\tau)\,\dfrac{\partial}{\partial \tau} I(x,\tau)\,d\tau + L\dfrac{\partial I(x,t)}{\partial t} = -\dfrac{\partial \Phi^i(x,h,t)}{\partial x} - \dfrac{\partial A_x^{\,i}(x,h,t)}{\partial t} \\ \dfrac{\partial I(x,\,t)}{\partial x} + C\,\dfrac{\partial V^s(x,\,t)}{\partial t} = 0 \end{cases}$$

$$U(x,t) = V^s(x,t) + h\dfrac{\partial A_z^{\,i}(x,h,t)}{\partial t}$$

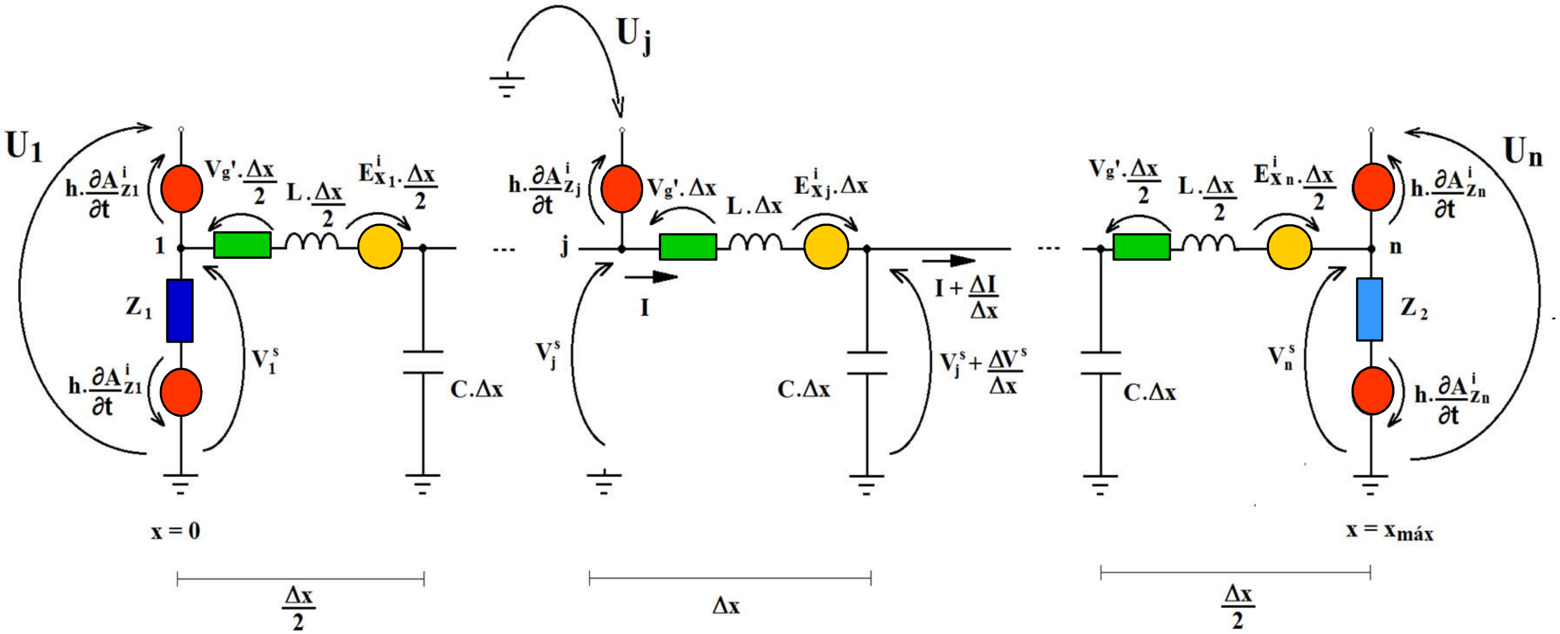
$$\begin{cases} V^s(0,t) = -Z_1.I(0,t) - h\dfrac{\partial A_z^{\,i}(0,t)}{\partial t} \\ V^s(x_{máx},t) = Z_2.I(x_{máx},t) - h\dfrac{\partial A_z^{\,i}(x_{máx},t)}{\partial t} \end{cases}$$

$$U(x,t)_{(\rho \neq 0)} = U(x,t)_{(\rho = 0)} + VEx_I(x,t)$$

A. Piantini, "Extension of the Rusck model for calculating lightning-induced voltages on overhead lines considering the soil electrical parameters," *IEEE Trans. Electromagnetic Compatibility*, vol. 59, no. 1, pp. 154-162, 2017.

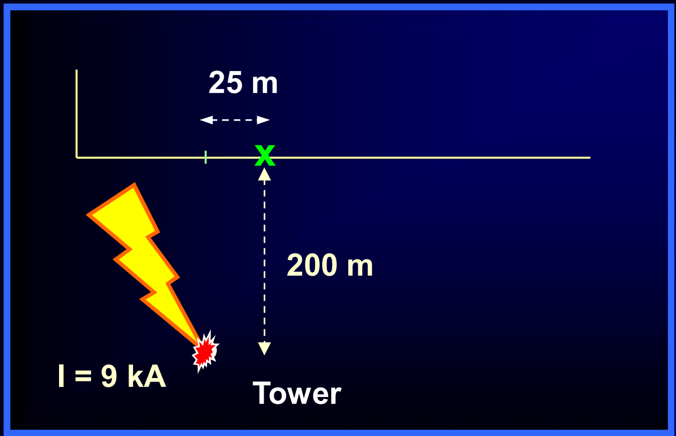
THE EXTENDED RUSCK MODEL (ERM)

Equivalent circuit:

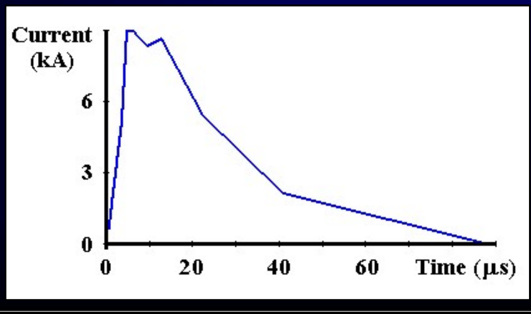


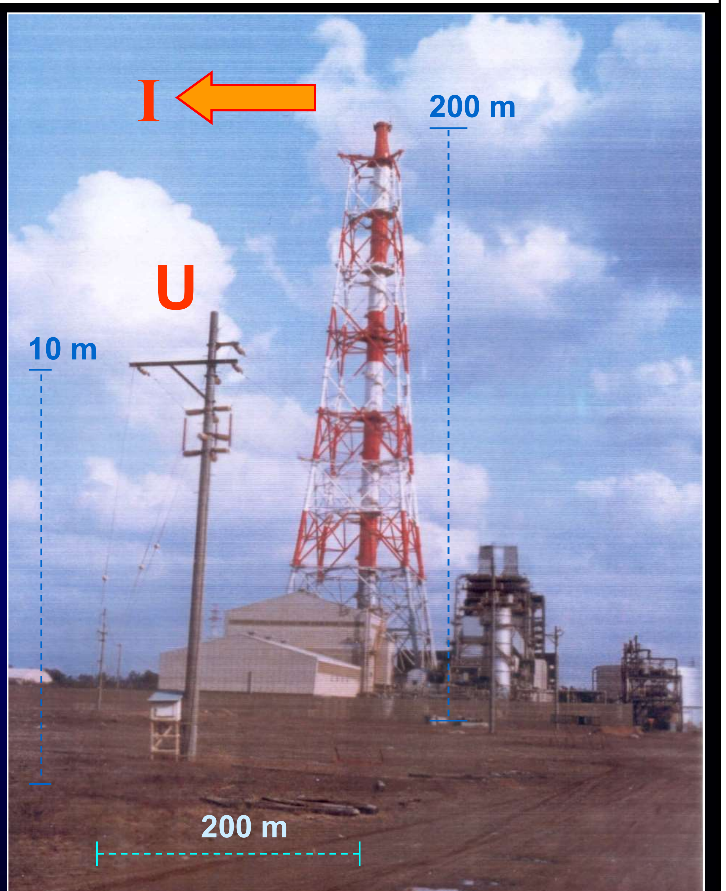
MODEL VALIDATION – Exp. data from Japan

Top view



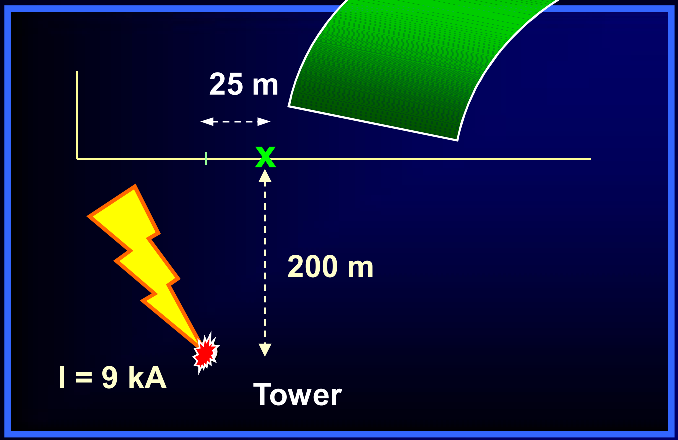
Natural lightning (CRIEPI, Japan)





Courtesy: Prof. S. Yokoyama

MODEL VALIDATION – Exp. data from Japan



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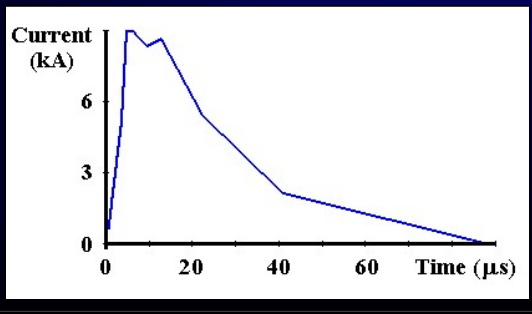
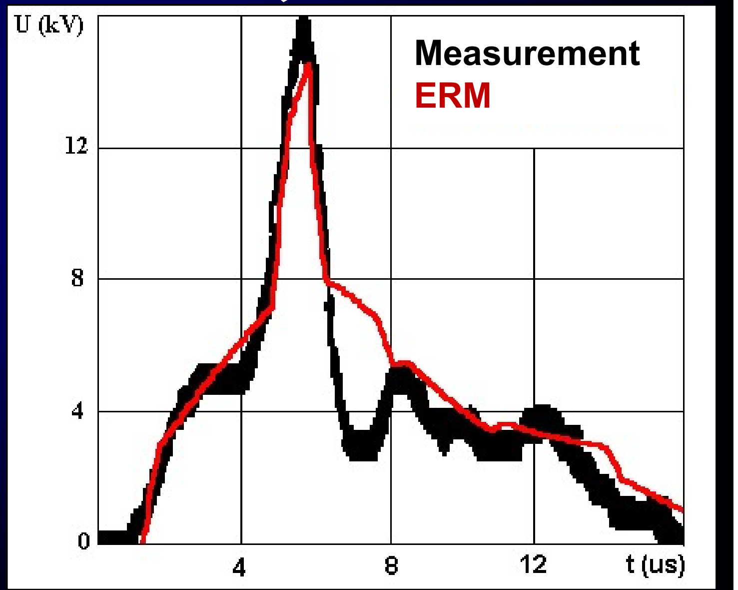
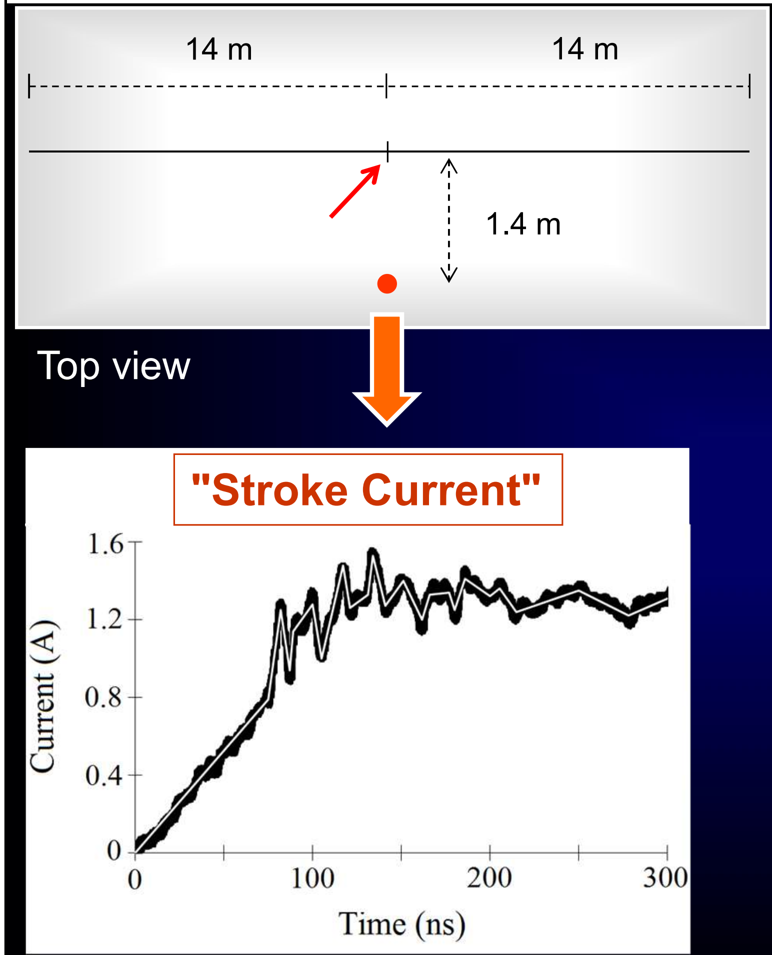
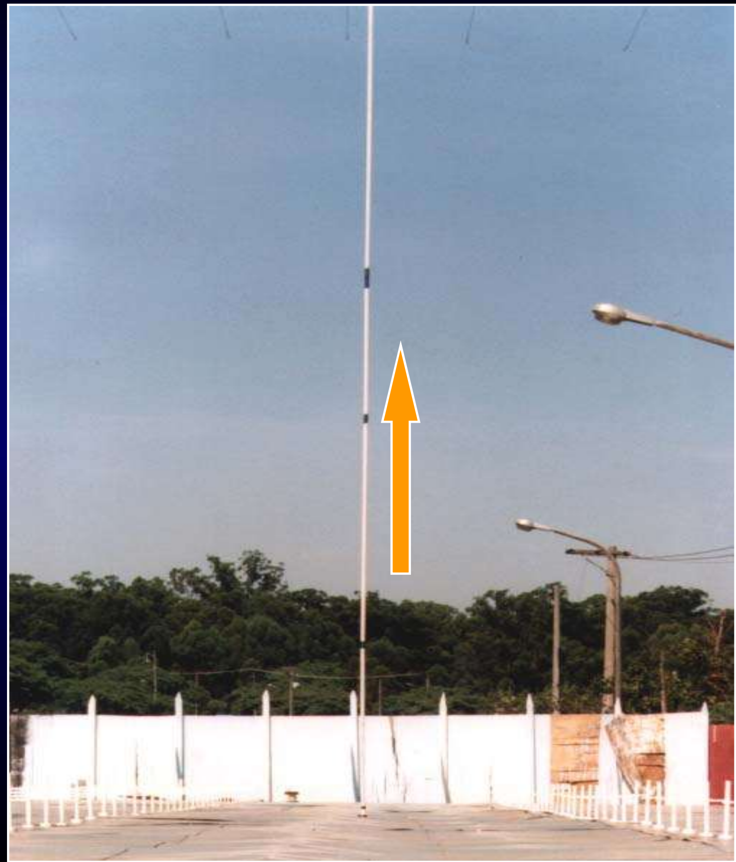




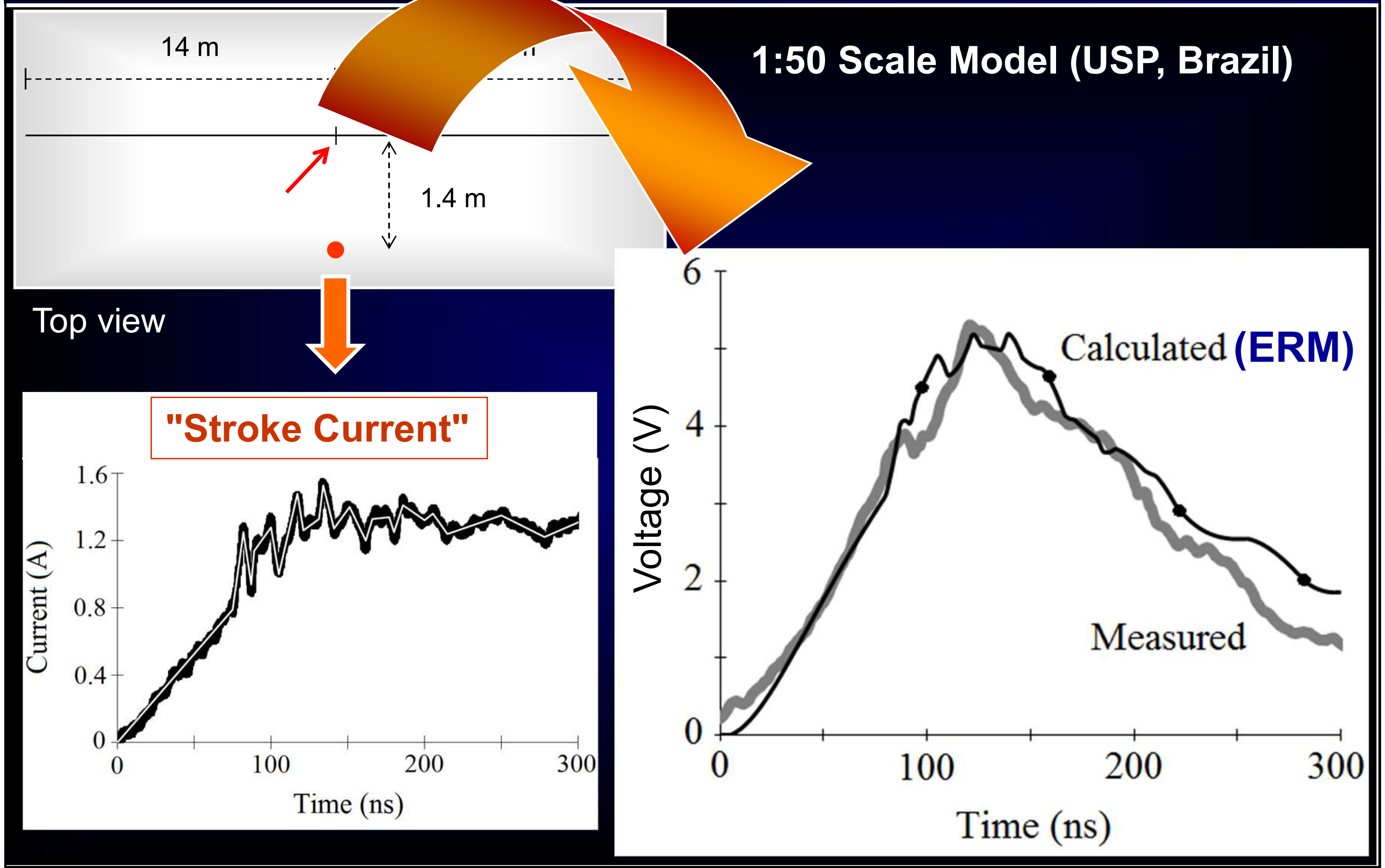
MODEL VALIDATION – Exp. data from Brazil



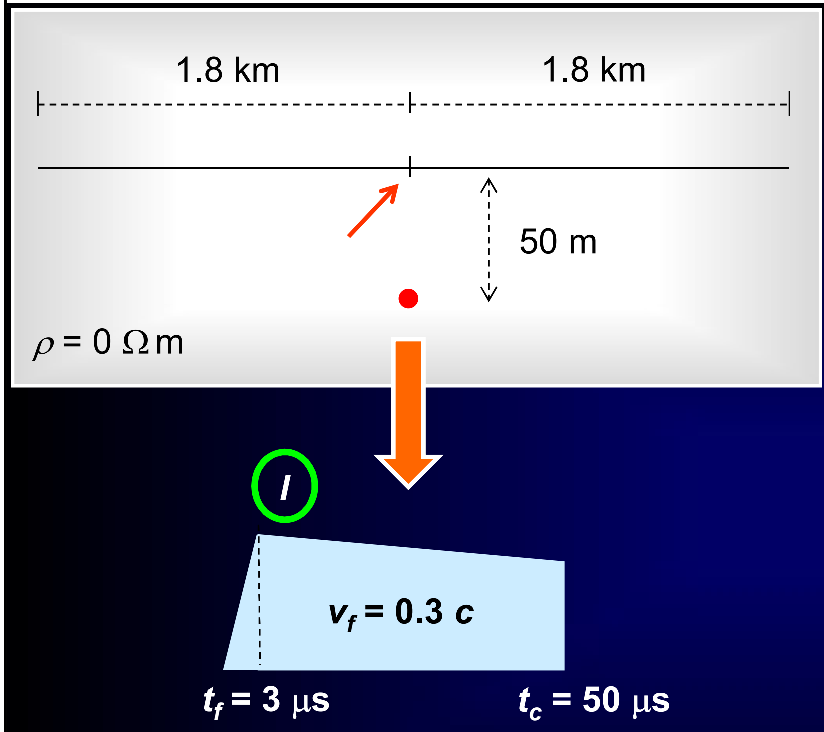
1:50 Scale Model (USP, Brazil)



MODEL VALIDATION – Exp. data from Brazil



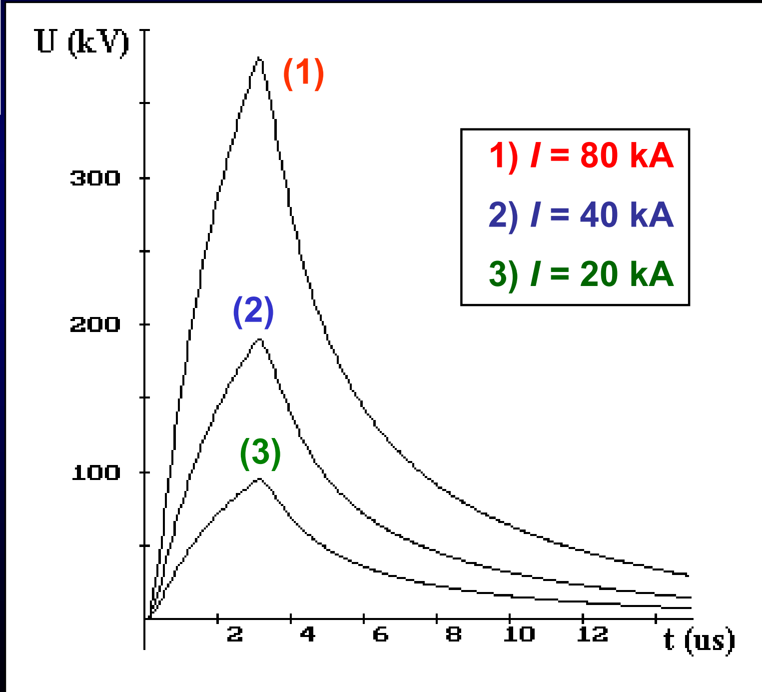
Stroke current amplitude *(I)*



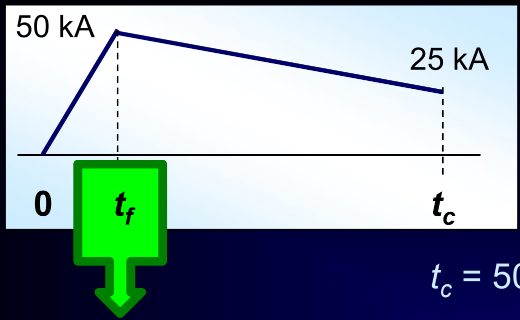
- Non-linear devices not present
- Corona is disregarded

→ U α I

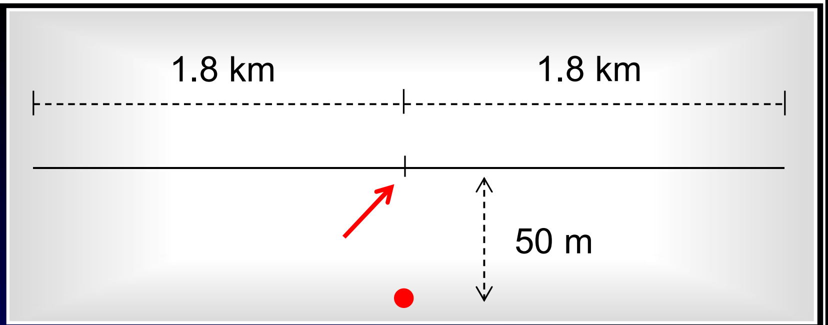
Line: single-phase, matched

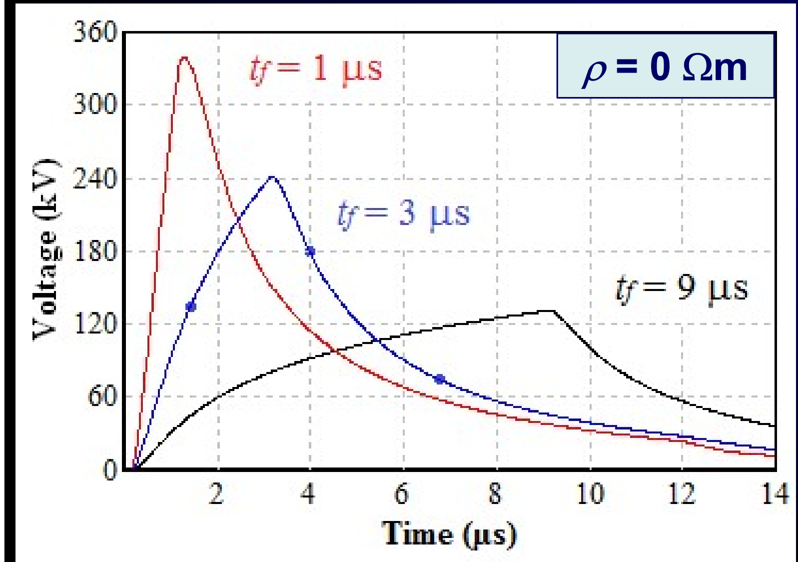


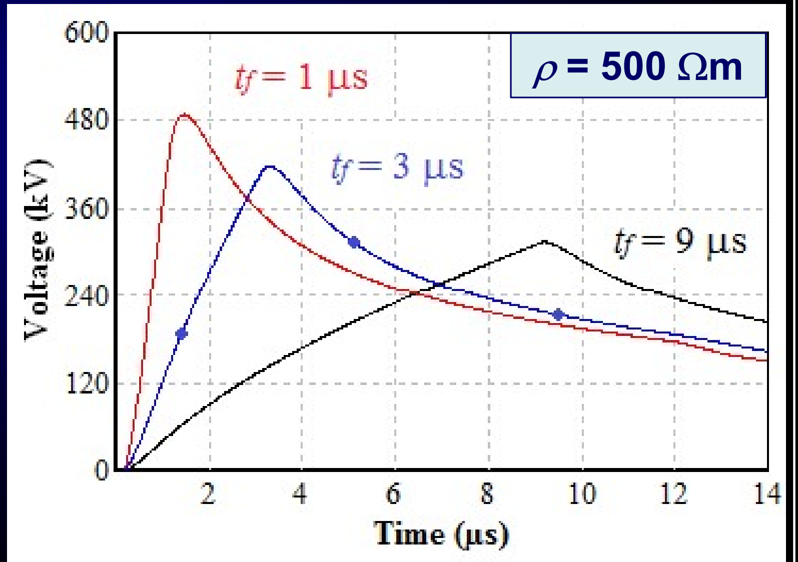
Stroke current waveshape *(t_f, t_c)*



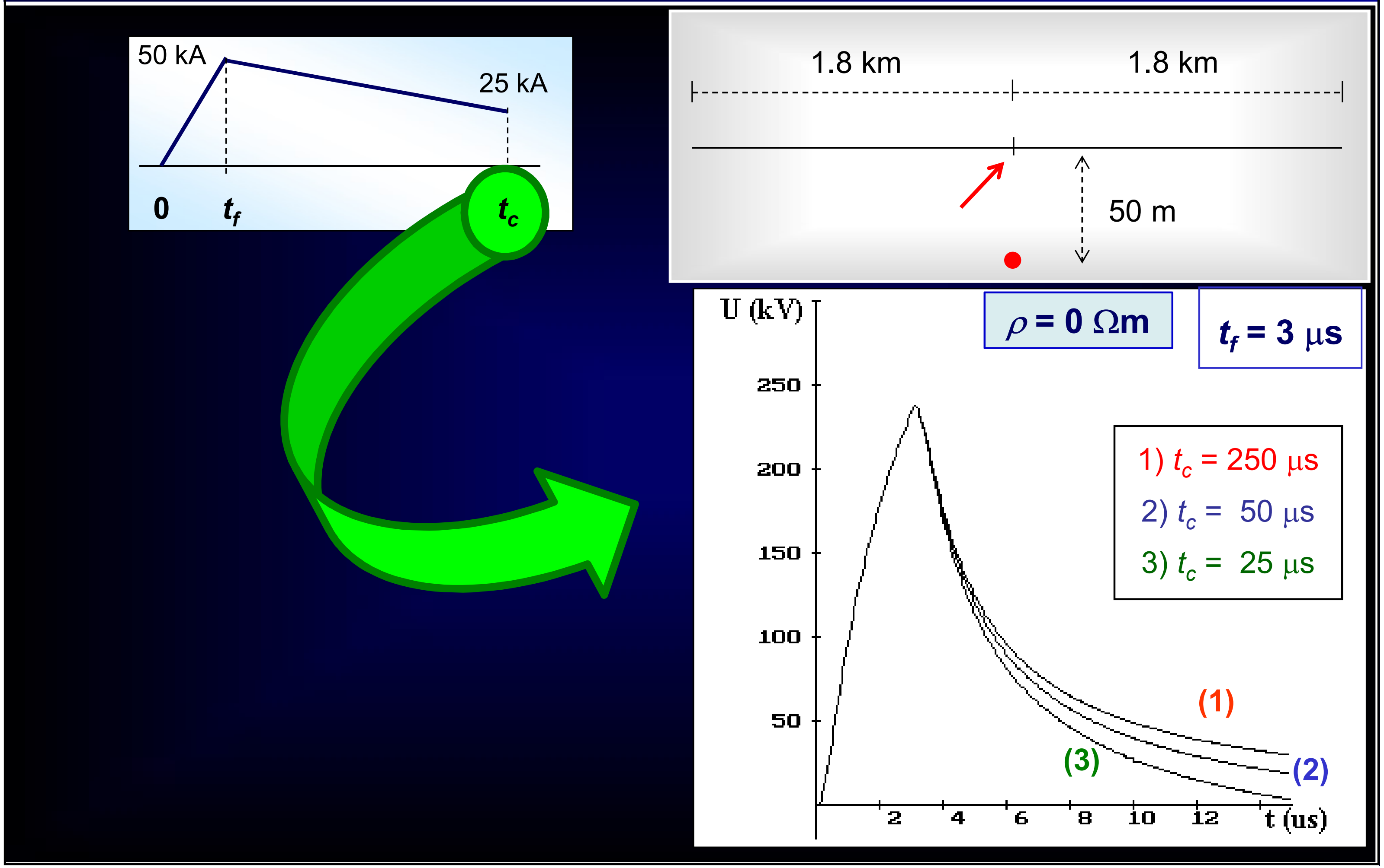
t_c = 50 μs



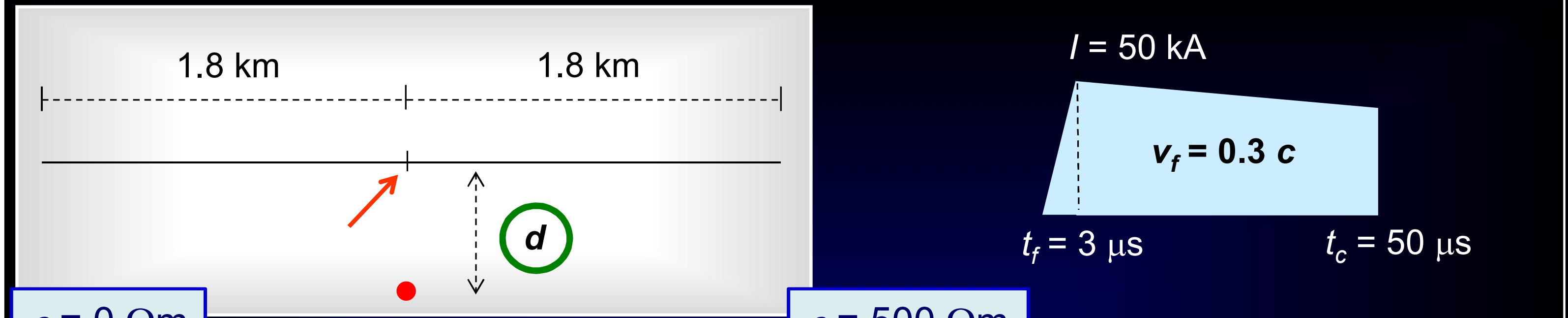




Stroke current waveshape (t_f, t_c)

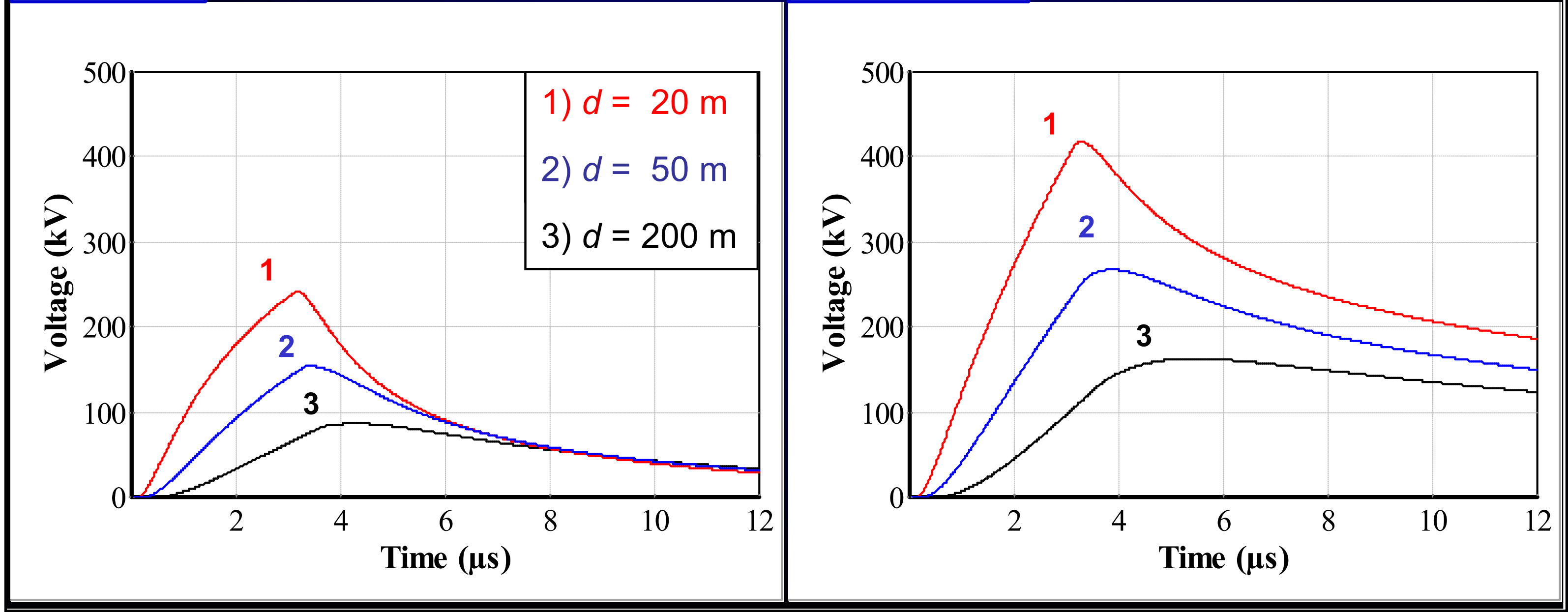


Distance line - stroke location *(d)*

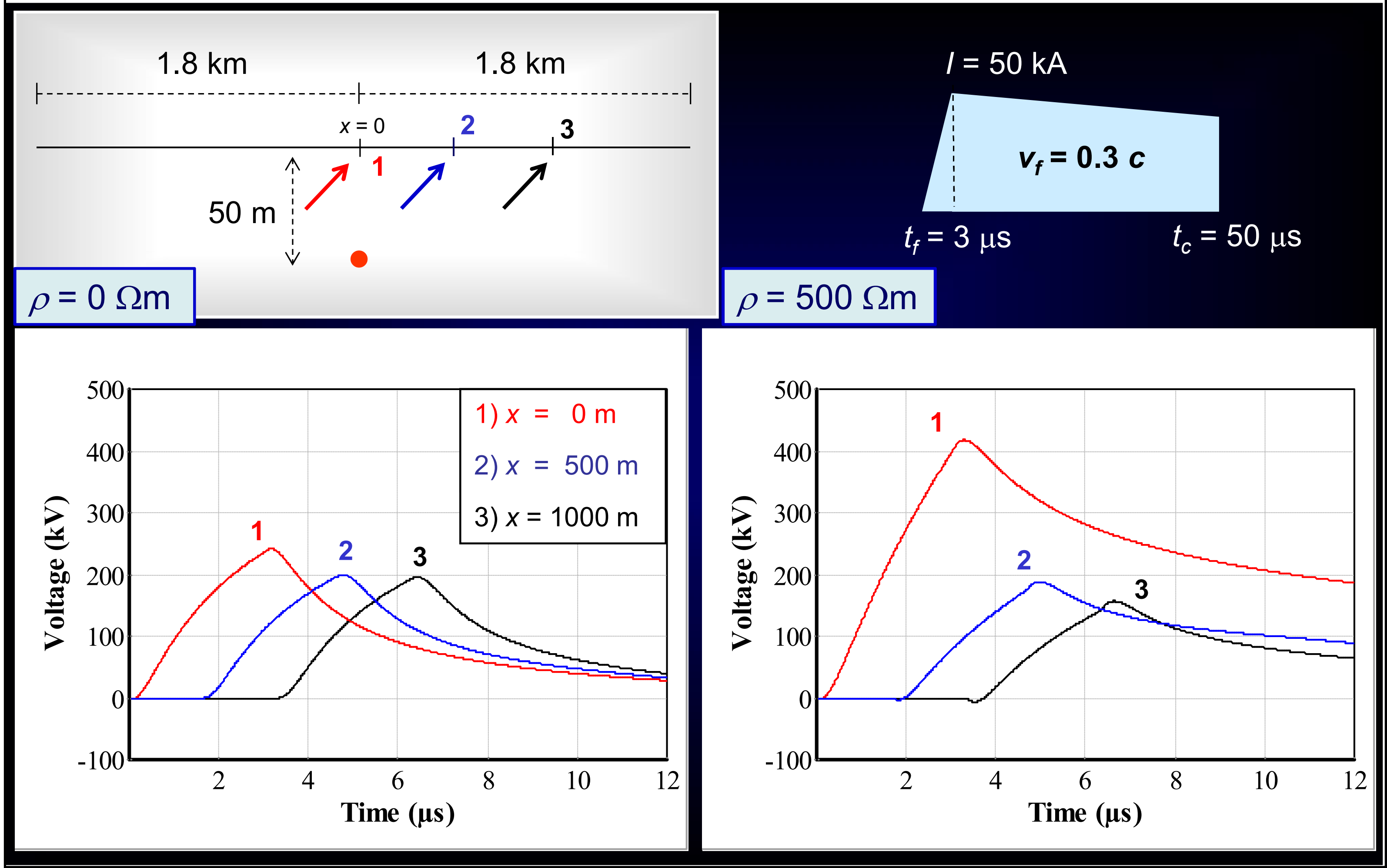


ρ = 0 Ωm

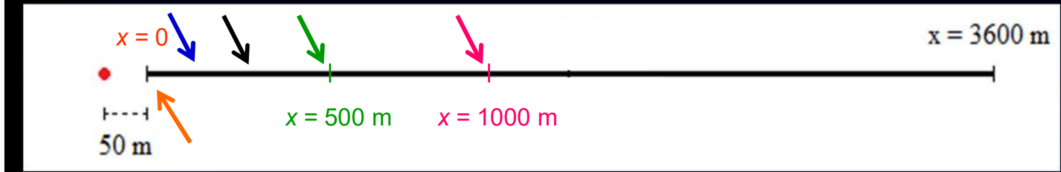
ρ = 500 Ωm



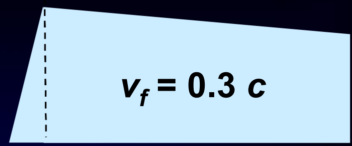
Soil resistivity *(ρ)* and Observation point *(x)*



Soil resistivity *(ρ)* and Observation point *(x)*

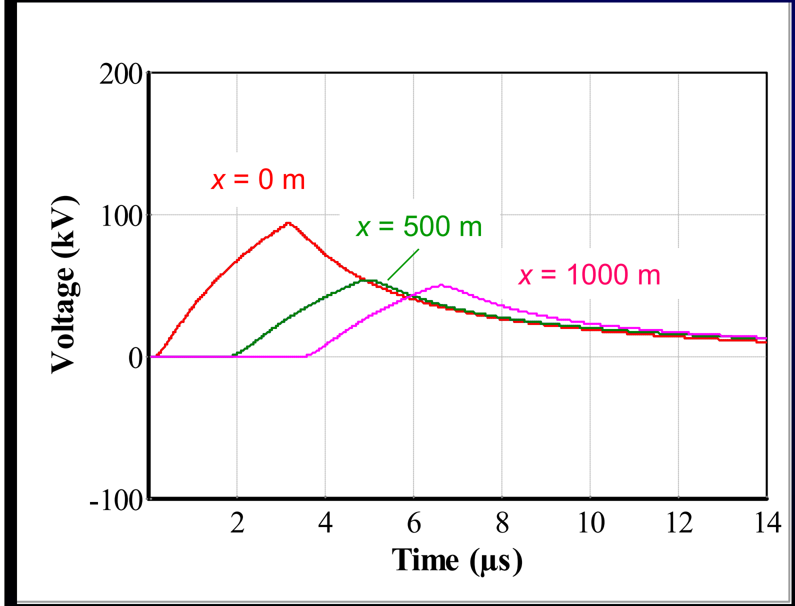


I = 50 kA

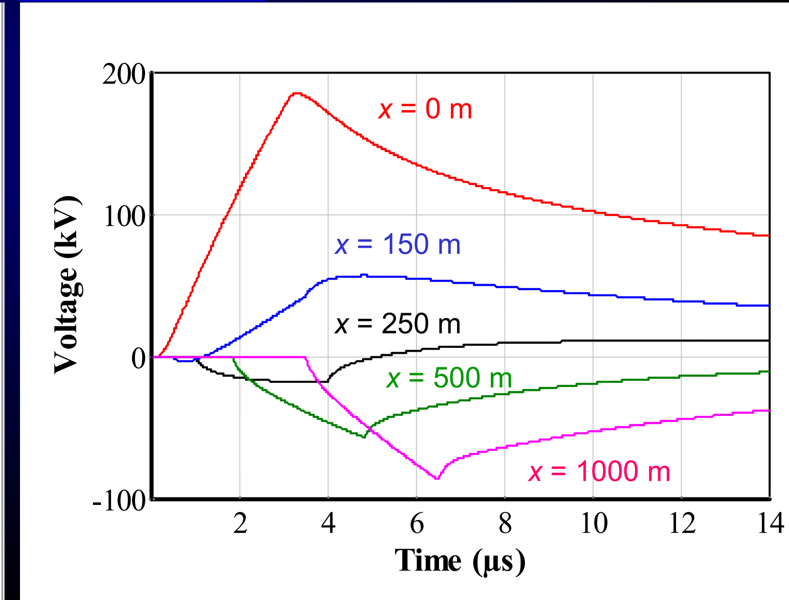


t_f = 3 μs t_c = 50 μs

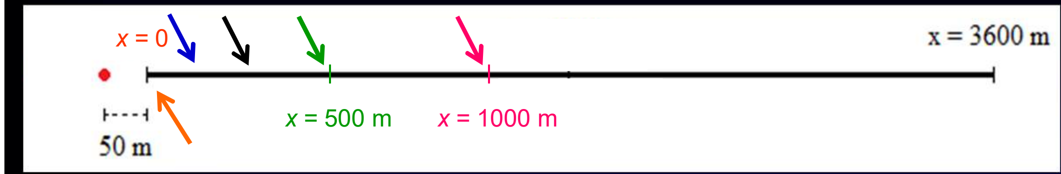
ρ = 0 Ωm



ρ = 500 Ωm



Soil resistivity *(ρ)* and Observation point *(x)*



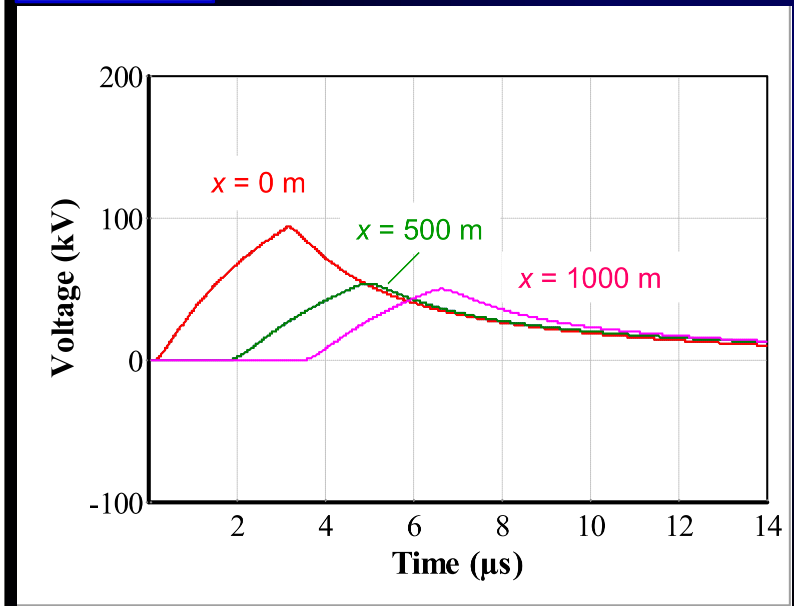
Effect of *ρ*:

- **observation point**
- **relative position line-l.s.p.**

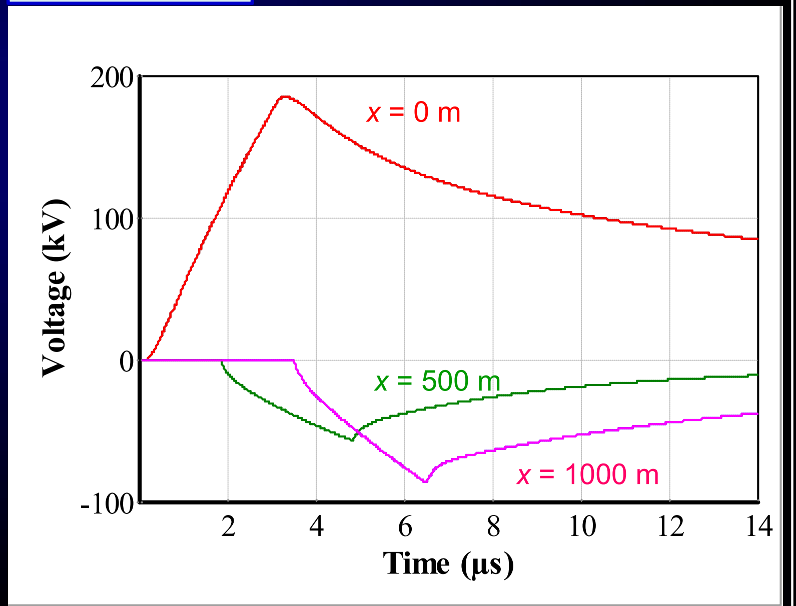
$t_c = 50\ \mu s$

***U* may ↑, ↓, or change polarity**

$\rho = 0\ \Omega m$



$\rho = 500\ \Omega m$



OUTLINE

- Introduction
- Lightning Phenomenon (main processes)
- Transmission Lines
- Medium-Voltage Lines
- **Low-Voltage Networks**
- Conclusions

LIGHTNING OVERVOLTAGES IN LV SYSTEMS

- Cloud flashes
- Direct strikes to the LV system
  - LV conductors
  - LV power installations
- Nearby strikes
  - "direct" induction
  - interception of the stroke current by neutral groundings
- Transference from the MV system
  - direct strikes to the primary
  - nearby strikes

CLOUD FLASHES

Sweden

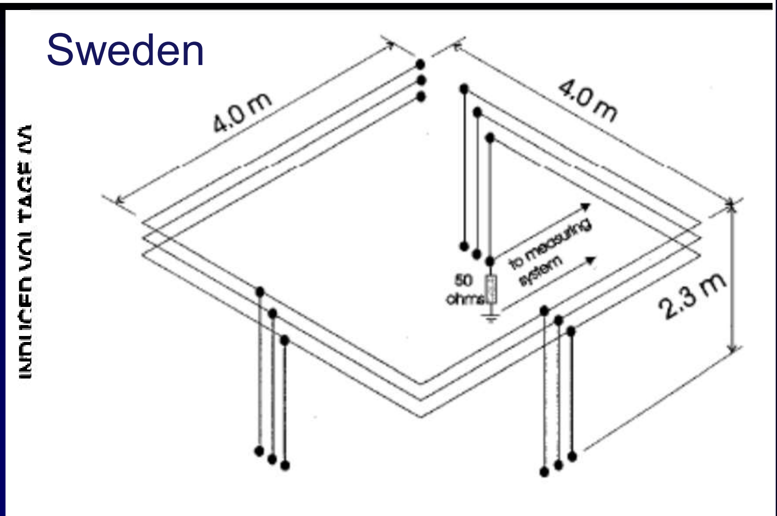


Fig. 1. Electrical arrangement of the simple electrical circuit.

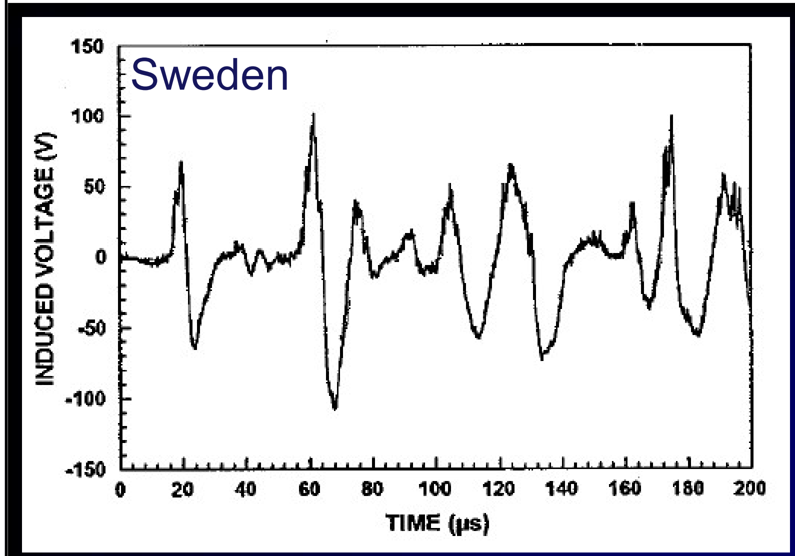
Galván et al. (1998), Silfverskiöld et al. (1999)

75% of the global lightning activity.

No. of studies relatively scarce in comparison with that bearing on CG flashes.

Discharge events that take place inside the cloud, preceeding CG and IC flashes → bipolar pulses with very fast rise times

CLOUD FLASHES



The pulse trains associated with such processes may induce voltages with magnitudes of the same order of (and even higher than) those induced by the return stroke itself.

Galván et al. (1998), Silfverskiöld et al. (1999)

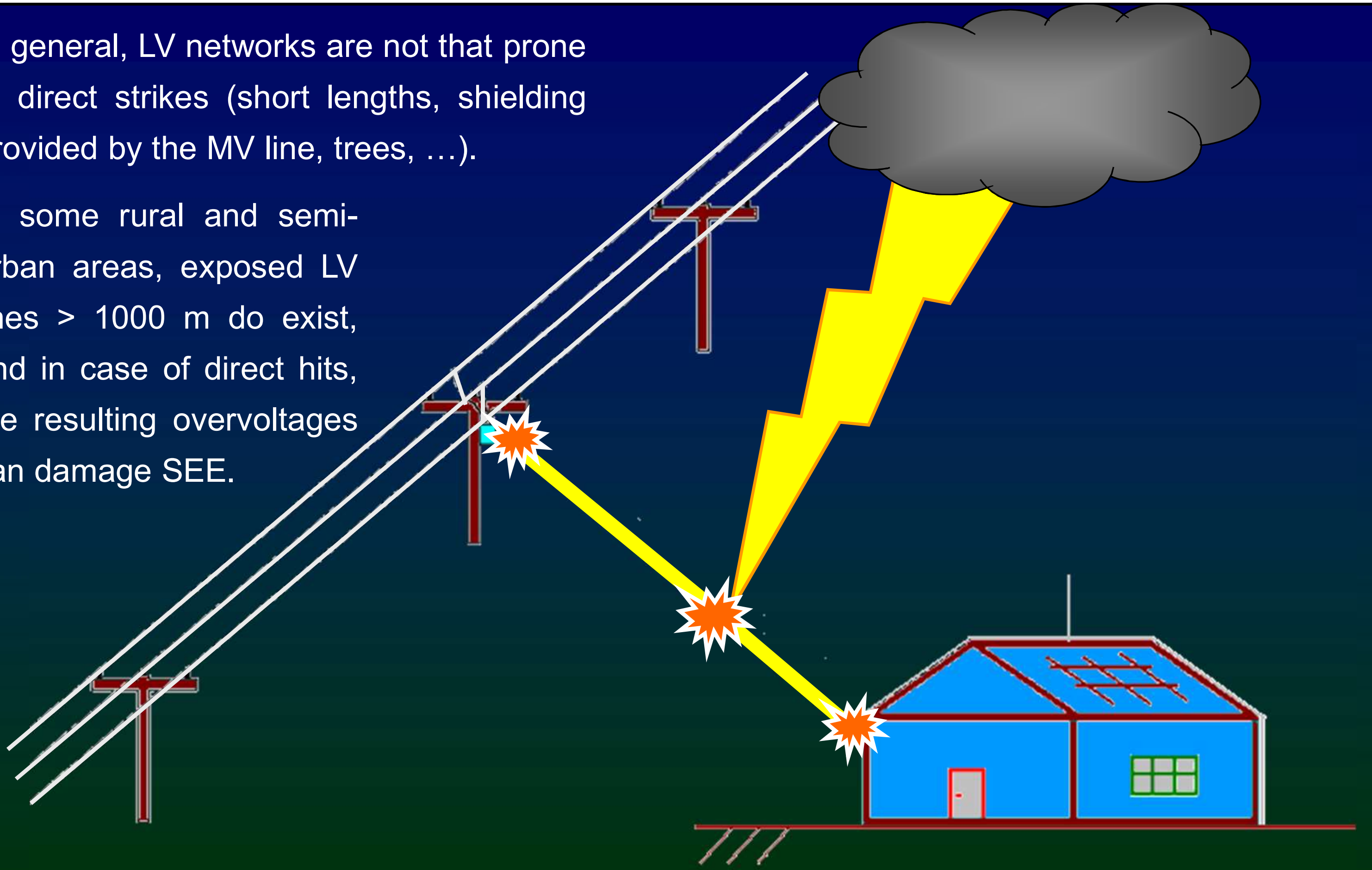
These events are therefore important and should be taken into account in the evaluation of the interference problems caused by LEMPs.

Short interval between the induced voltage pulses → degradation, damage, and failure of electronic components of sensitive apparatus connected to the LV power supply

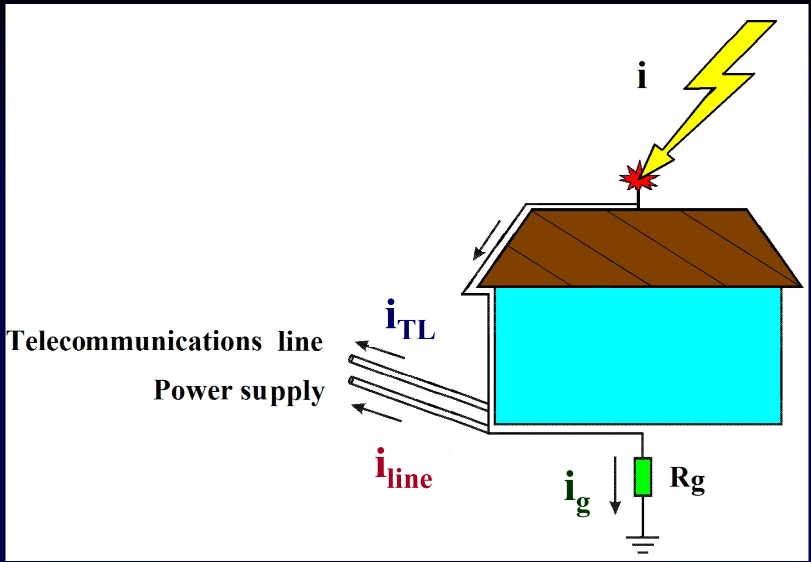
DIRECT STRIKES TO THE LINE

In general, LV networks are not that prone to direct strikes (short lengths, shielding provided by the MV line, trees, …).

In some rural and semi-urban areas, exposed LV lines > 1000 m do exist, and in case of direct hits, the resulting overvoltages can damage SEE.



DIRECT STRIKES TO A LVPI



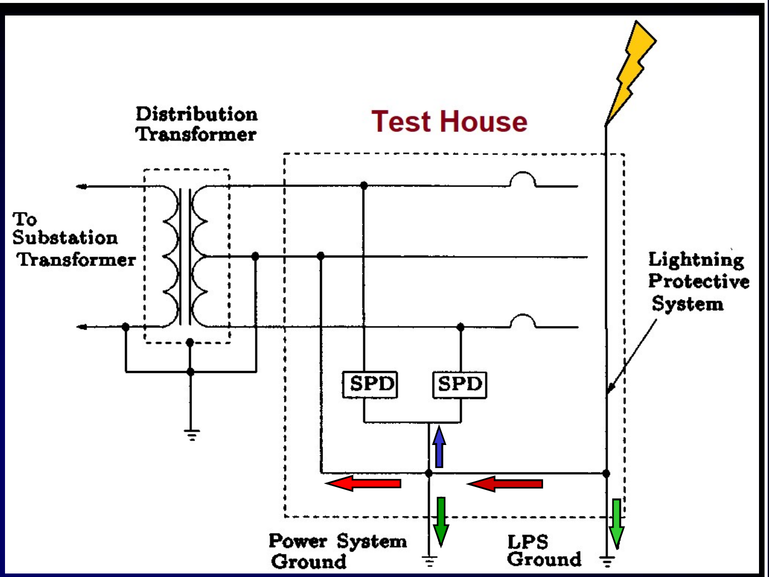
Ground potential rise → operation of SPDs / flashovers
→ a portion of i is injected into the line → overvoltages

i_{line} = f (relative impedance of the line with respect to the impedances of all the other possible current paths)

DIRECT STRIKES TO A LVPI

International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida (rocket-triggered lightning technique)

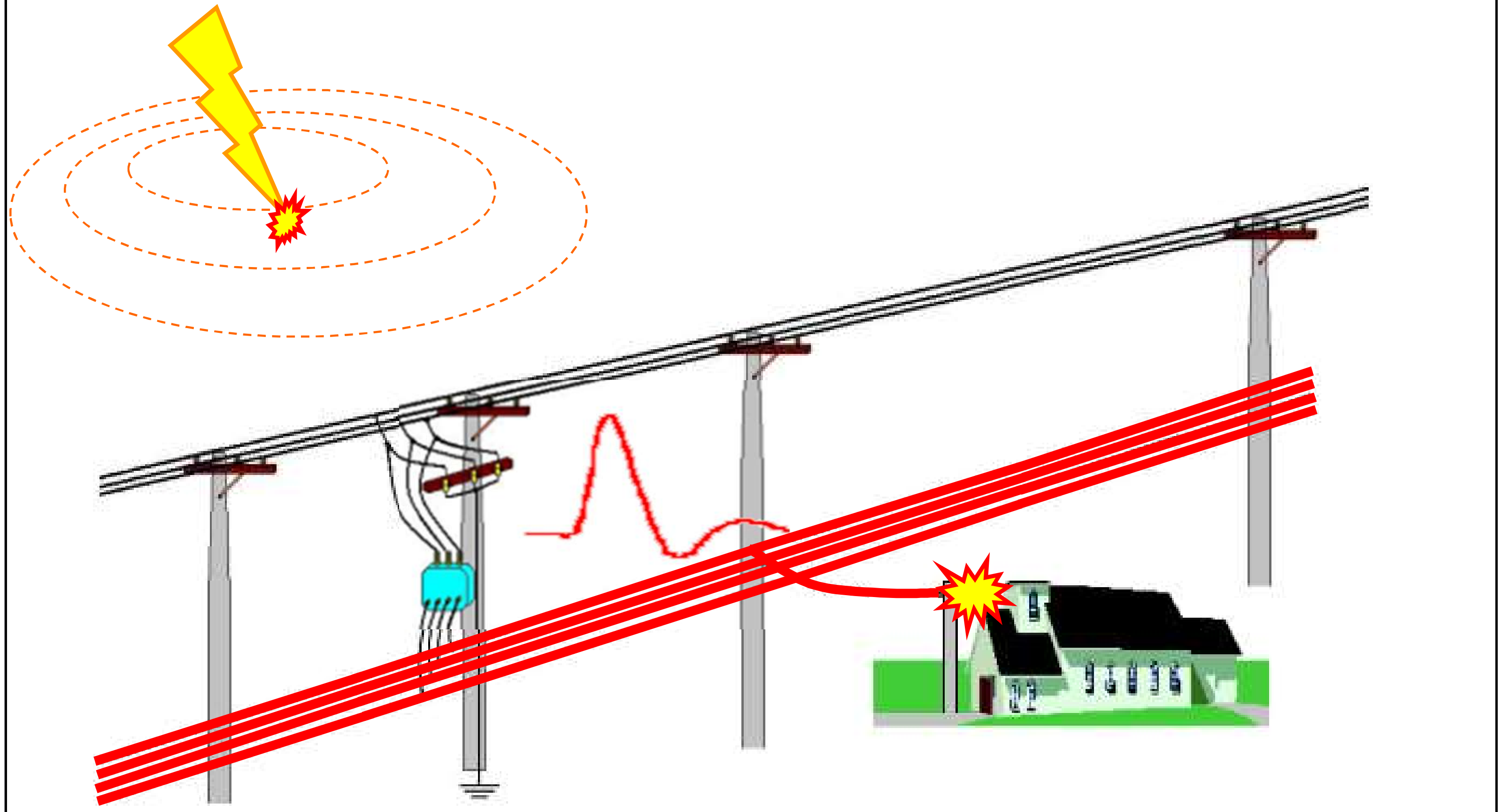
B.A. De Carlo, V.A. Rakov et al. (ICLP, 2006)
V.A. Rakov et al. (IEEE T. PWRD., 2002)



The current waveshapes in the ground rods of the test house differed markedly from the waveshapes in other parts of the system. The ground rods appeared to filter out the higher freq. components of the stroke current, allowing the lower freq. components to enter the house's electrical circuit.

The mean value of the peak current entering the electrical circuit neutral varied from about 22% to over 80% of the injected lightning current peak, depending on the test config. (lightning current injection point, no. down conductors, grounding system, and use of SPDs).

INDIRECT STROKES



Interception of the stroke current by neutral groundings

Camp Blanding (rocket-and-wire technique to trigger lightning): when the strike point is at tens of meters from the line, an appreciable fraction of the total current enters the system from the neutral groundings.

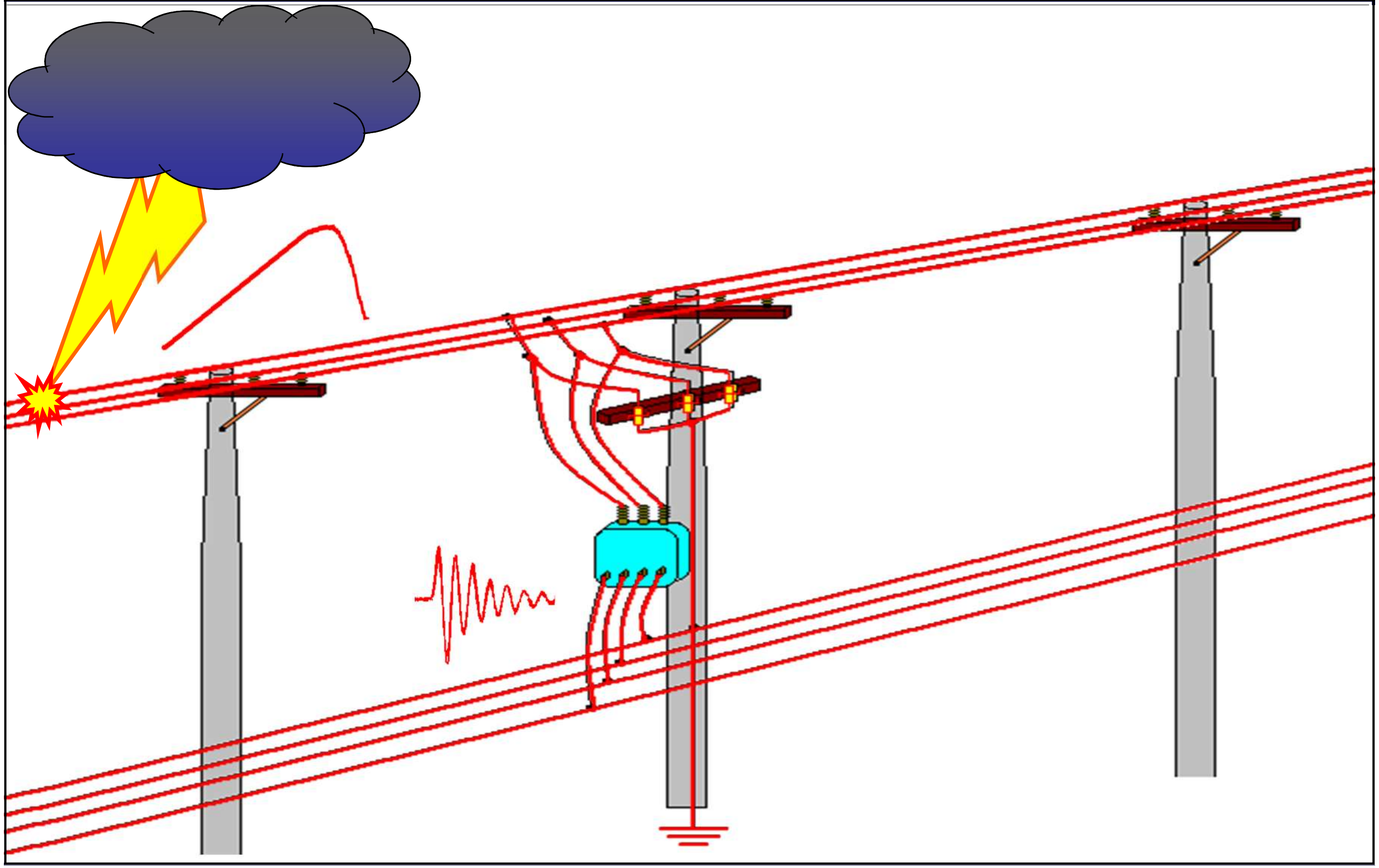
In three cases reported (d = 60, 40 and 19 m), the observed peak values of the currents entering the system from its ground connections varied from 5% to 18% of the stroke current peak.

Rakov V.A. and Uman M.A. 'Artificial initiation (triggering) of lightning by ground-based activity'. Lightning: Physics and Effects (Cambridge University Press, Cambridge, 2003), Chapter 7, pp. 265–307.

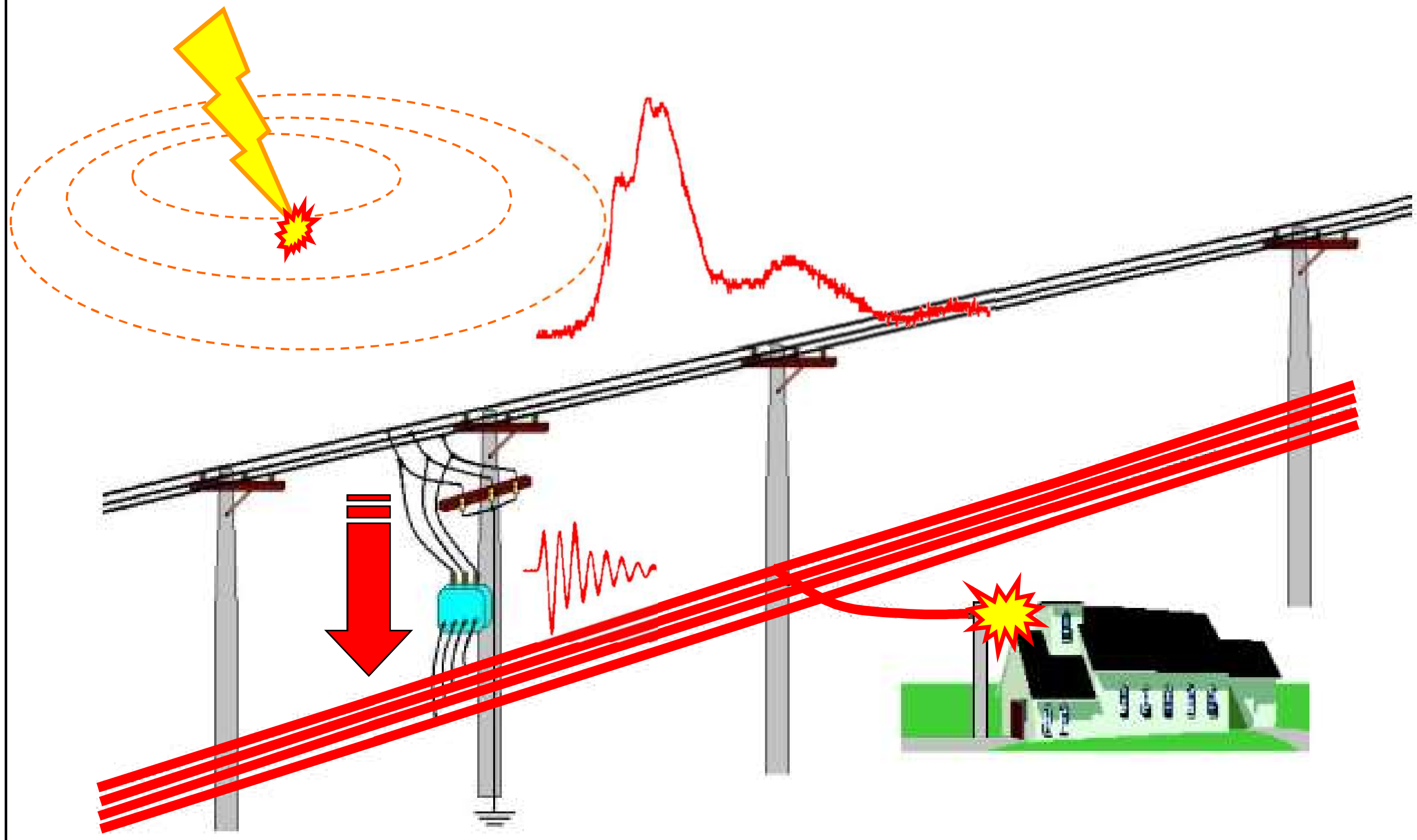
DIRECT STRIKES TO THE MV LINE

Direct strikes to the MV circuit produce overvoltages on the LV network due to transference from the distrib. transf. and to injection of current into the neutral.

DIRECT STRIKES TO THE MV LINE



INDIRECT STROKES



CONCLUSIONS (Transmission Lines)

- UHV TL's are a cost-effective solution for long distance power transmission. UHV transmission towers are > 100 m, therefore SF is a serious threat;
- SF's are the main cause for outages of UHV TL's in Japan. In China, lightning outages caused by SF reach 92% for 500 kV TL's. For TL's 500 kV and above, lightning trip-outs are mainly due to SF's;
- For TL's below 500 kV located in regions of high soil resistivity, BF governs the lightning performance. The best measure for reducing BF rates is usually the ↓ of the impedance of the grounding system.

CIGRE TB 704 (WG C 4.26) – Evaluation of Lightning Shielding Analysis Methods
for EHV and UHV DC and AC Transmission Lines (Oct. 2017)

CONCLUSIONS (MV LINES)

- Larger overvoltages are usually associated with the FS, but SS may also induce severe surges, especially in the case of low resistivity soils;
- U depends on the observation point and on several parameters related to the return stroke current, soil, and network config.;
- Line height, stroke current magnitude and front time, distance line-l.s.p., soil resistivity, nearby buildings: great influence;
- Finite length of the stroke channel, stroke current wavetail, soil permittivity: minor influence.

CONCLUSIONS (LV NETWORKS)

- Larger overvoltages are usually associated with the FS, but SS may also induce severe surges, especially in the case of low resistivity soils;
- LIOV's have a high frequency of occurrence and can often reach high magnitudes. Their severity depends on the combination of the values of the lightning, network, and soil parameters;
- P-G voltages can reach several tens of kV at different points in the network. The value of 20 kV can often be exceeded if d < 100 m. P-N voltages of several kV are common in the absence of SPDs.

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Alexandre Piantini

piantini@iee.usp.br

THANK YOU FOR YOUR ATTENTION!