Welcome to High Voltage Engineering

Please enter the rain class

Department of Electrical Engineering,
Tsinghua University

Spring 2025 High Voltage Engineering
Lecture 14

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May 29, 2025

Chapter 9 Lightning Overvoltage and Its Protection

9.1 Lightning parameters

9.2 Basic measures for lightning protection

9.3 Lightning overvoltage in overhead transmission line

9.4 Lightning overvoltage and its protection in power plant and substation

Master the principles of science
Know technical measures
Understand engineering specifications

Scientific problem: Why?
Technical problem: How?
Engineering problem: What's the best?

The core concepts of this chapter:

Lightning parameters， lightning current, lightning rod and ground wire, surge arrester, grounding device, grounding impedance , soil resistance, induced overvoltage, direct lightning overvoltage, lightning withstand level, lightning outage rate, incident wave of lightning

2025-5-21 Wuhan

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What concepts or parameters can be used to describe lightning quantitatively from the point of view of lightning protection?

The Lightning of the Great Wall in Jinshanling, Hebei Province on May 27, 2021

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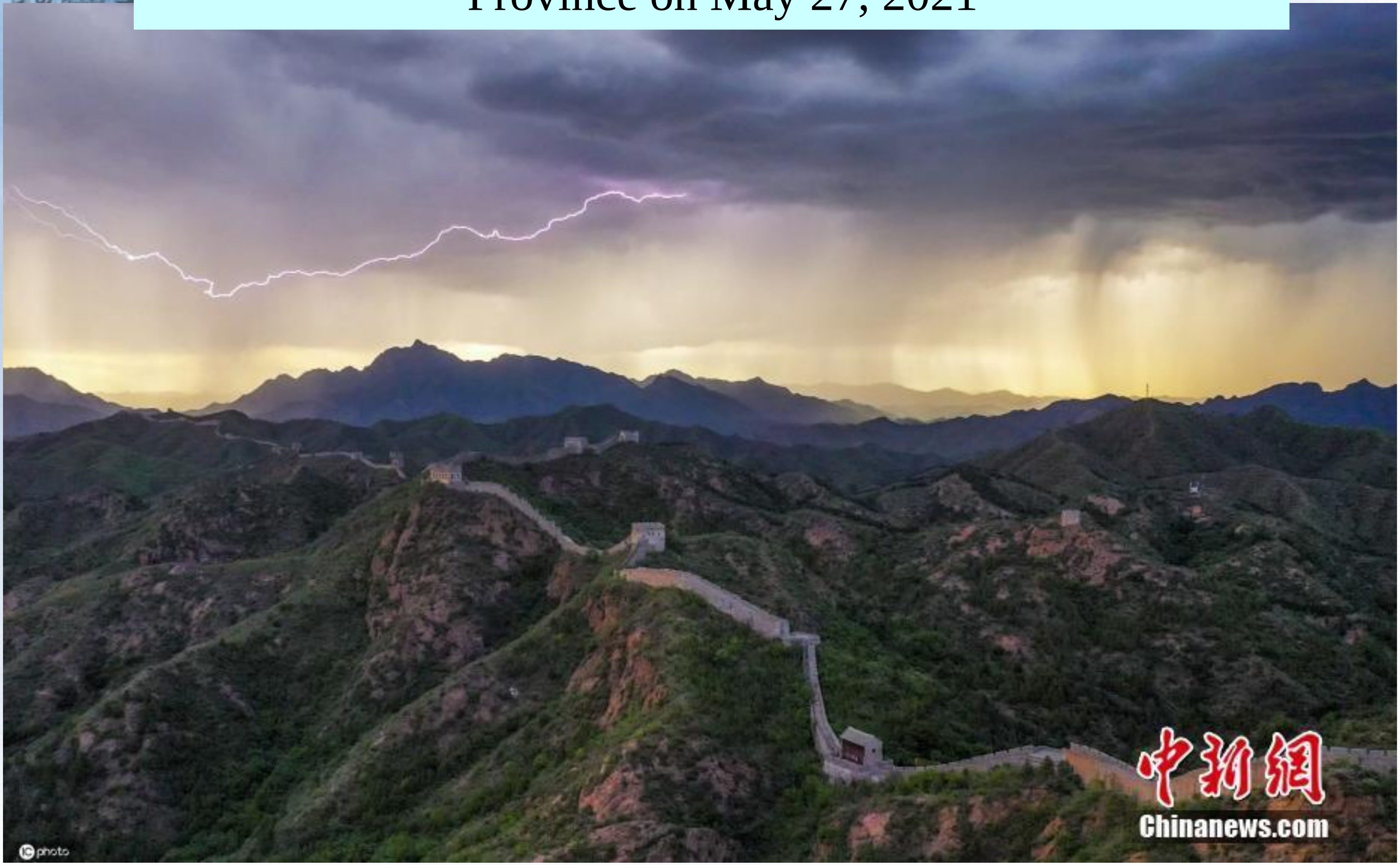
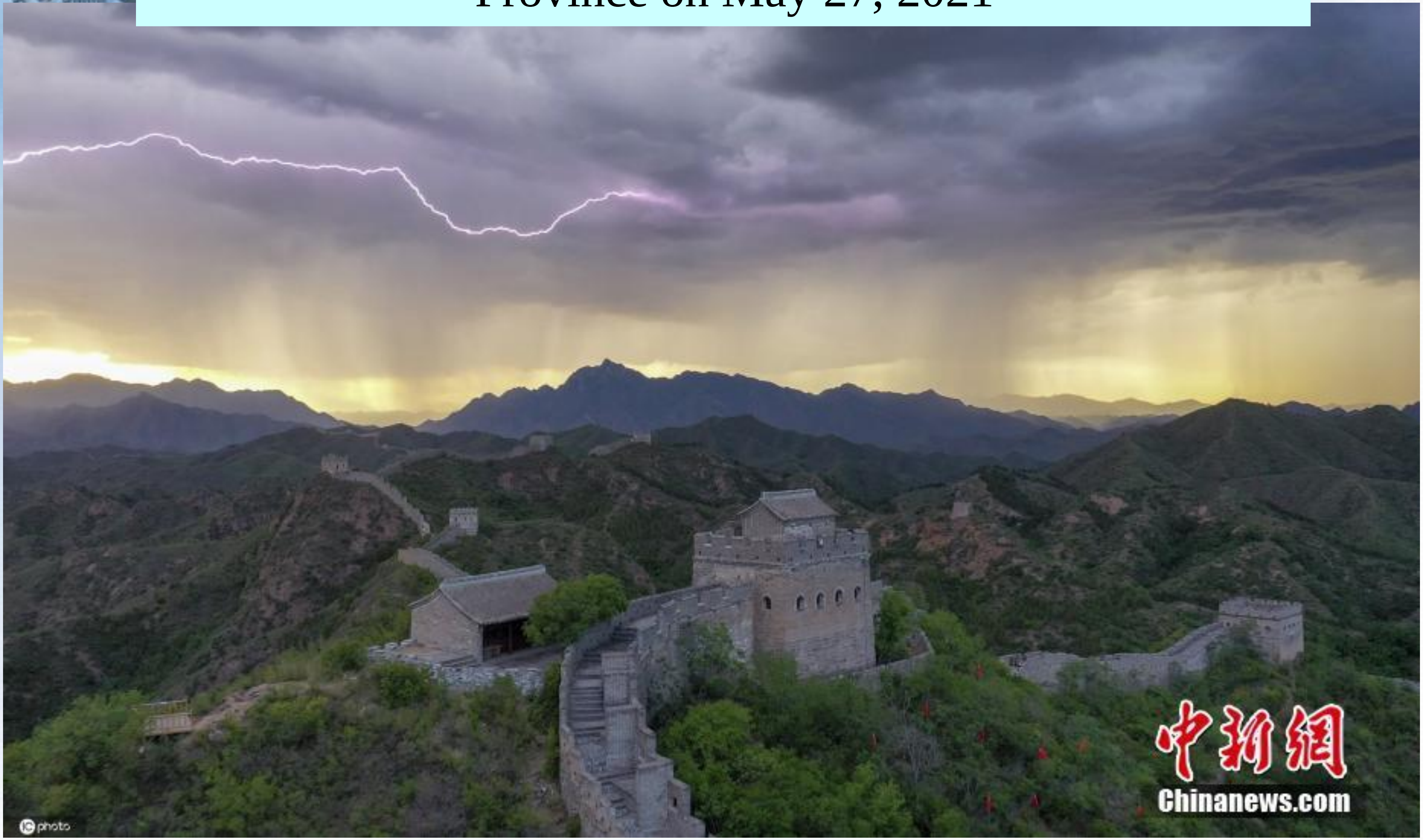


The Lightning of the Great Wall in Jinshanling, Hebei Province on May 27, 2021



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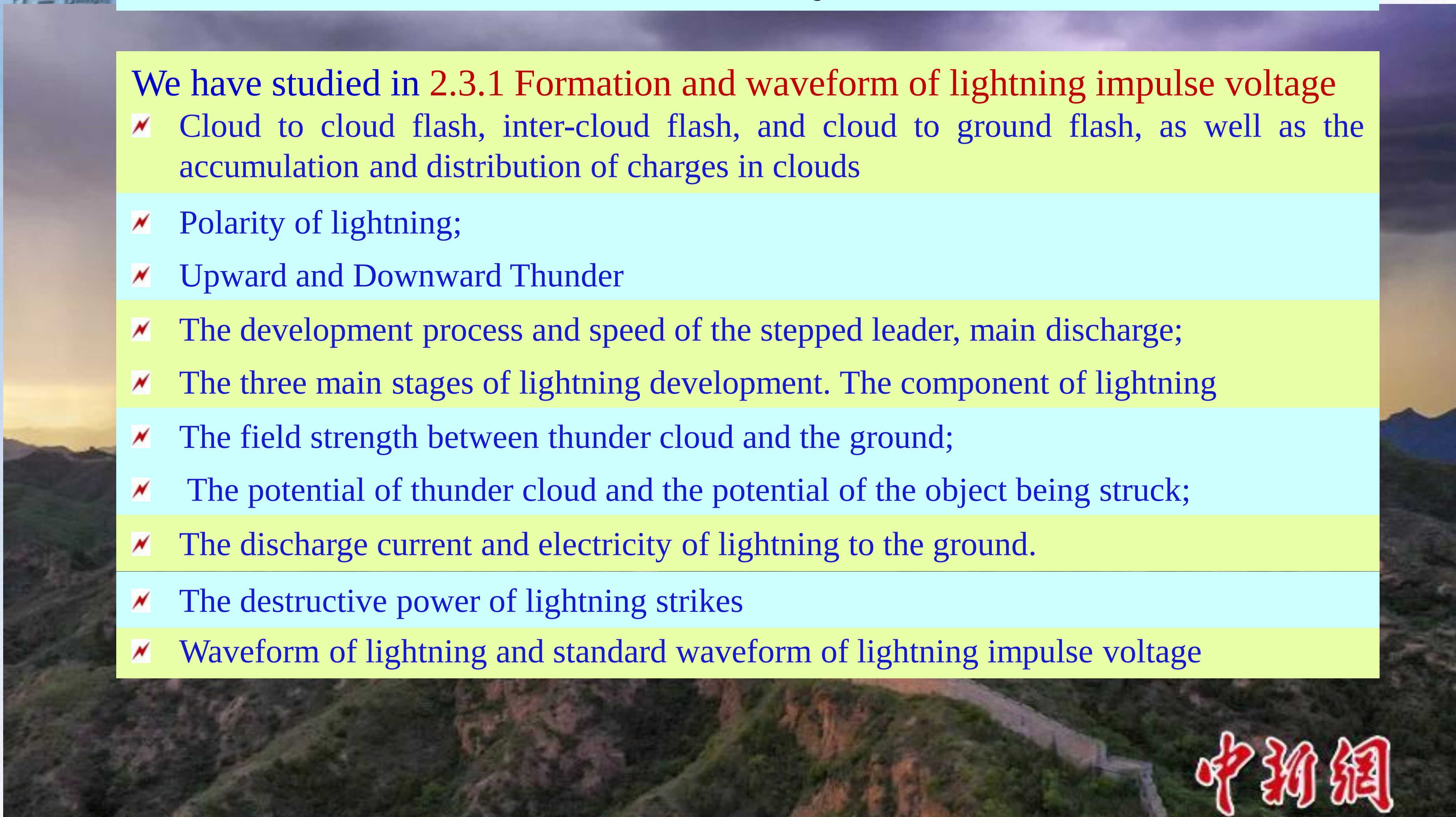


We have studied in 2.3.1 Formation and waveform of lightning impulse voltage

- Cloud to cloud flash, inter-cloud flash, and cloud to ground flash, as well as the accumulation and distribution of charges in clouds
- Polarity of lightning;
- Upward and Downward Thunder
- The development process and speed of the stepped leader, main discharge;
- The three main stages of lightning development. The component of lightning
- The field strength between thunder cloud and the ground;
- The potential of thunder cloud and the potential of the object being struck;
- The discharge current and electricity of lightning to the ground.
- The destructive power of lightning strikes
- Waveform of lightning and standard waveform of lightning impulse voltage

What concepts or parameters can be used to describe lightning quantitatively from the point of view of lightning protection?

Lightning parameters

Lightning activity (thunderstorm intensity):

lightning day, lightning hours, ground flash density

Lightning current: polarity, amplitude, steepness, waveform (wave front, wave tail)

Lightning parameters

Lightning activity (thunderstorm intensity):

lightning day, lightning hours, ground flash density

Lightning current: polarity, amplitude, steepness, waveform (wave front, wave tail)

9.1 Lightning parameters

9.1.1 Waveform and polarity of the lightning current

- The impulse lightning current wave is with unipolarity (75% to 90% are negative polarity).
- Use the negative lightning impulse wave for analysis of lightning protection and insulation coordination.

If there are mainly negative lightnings over the world, will there be too much negative charge on the earth?

9.1 Lightning parameters

9.1.2 Amplitude, steepness, waveform of lightning current

National standard GB/T 50064-2014 “Code for design of overvoltage protection and insulation coordination of AC electrical installations” :

- $\log P = -I / 88$, namely $I \geqq 88$ kA with a probability of 10%
- For the northwest areas with few thunderstorms: $\log P = -I / 44$

✓ *I*: the lightning current amplitude in kA

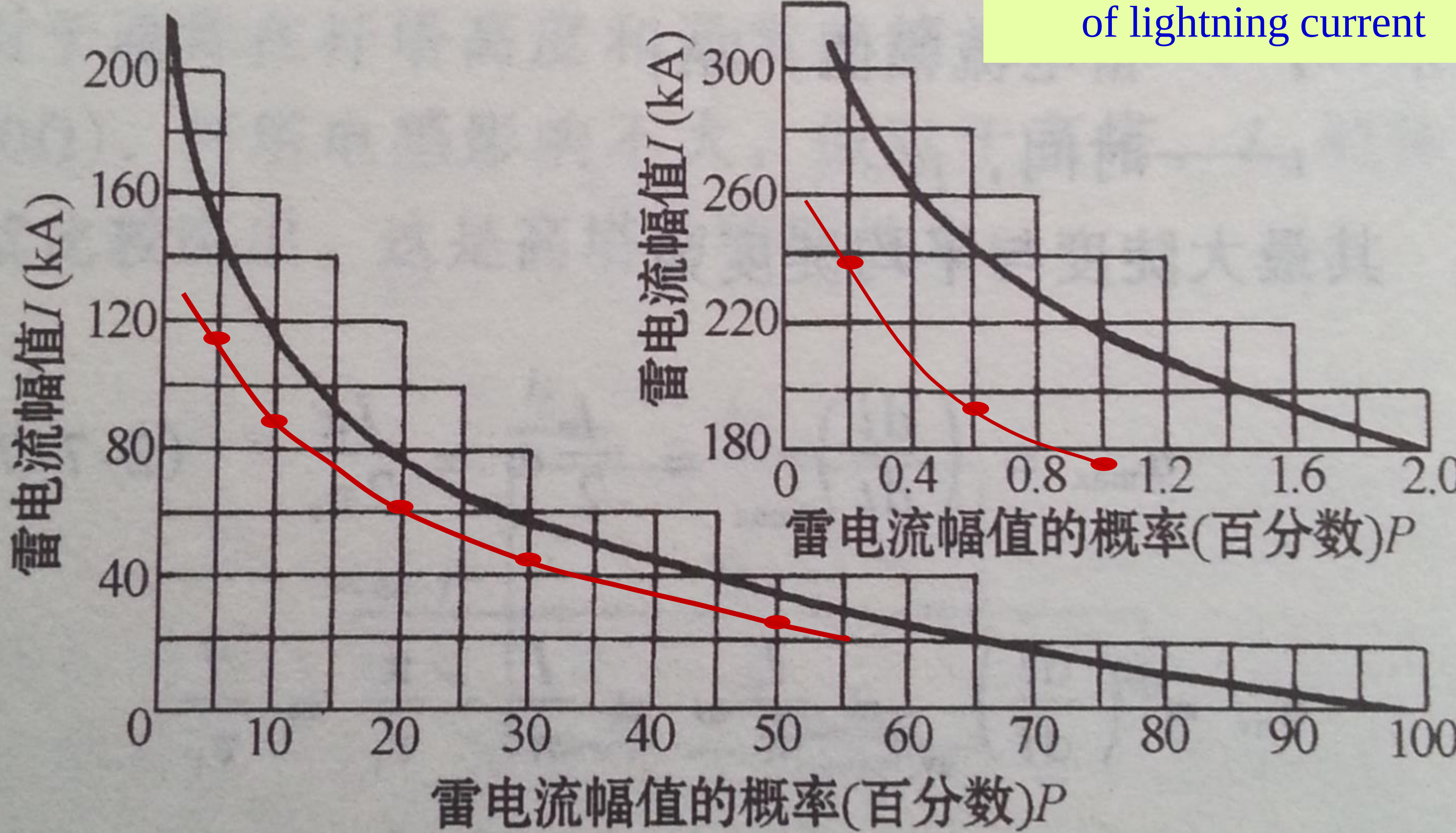
✓ *P:* the probability that the lightning current amplitude exceeding *I*.

The current measured by the device mounted at the lightning strike point with very small grounding resistance is the lightning current in above formula

How is the amplitude of the lightning current determined?

The main discharge of lightning propagates along the stepped lead channel. Surge impedance *Z* of the channel is generally regarded as 300~3000Ω in calculation.

Probability of the amplitude of lightning current



$$\log P = -\frac{I_m}{108}$$

Previous standard

current standard

$$\log P = -\frac{I_m}{88}$$

9.1.2 Amplitude, steepness, waveform of lightning current

- The amplitude of lightning current measured in different countries/regions varies greatly, but the waveform is basically the same.
- The wave front is mostly at 1μs ~ 5μs, with an average of 2μs ~ 2.5μs.
- In the lightning protection design in China, the wave front of lightning current is specified as 2.6μs, and the waveform is 2.6μs/50μs.

Why is the standard waveform of lightning impulse voltage 1.2/50μs?

9.1.2 Amplitude, steepness, waveform of lightning current

- Direct measurement of the steepness of lightning current is even more difficult.
- In China, with a specified wave front of 2.6μs, the average steepness of lightning current a (kA/μs) and lightning current amplitude I (kA) are linearly related:

$$\boldsymbol{a = I / 2.6}$$

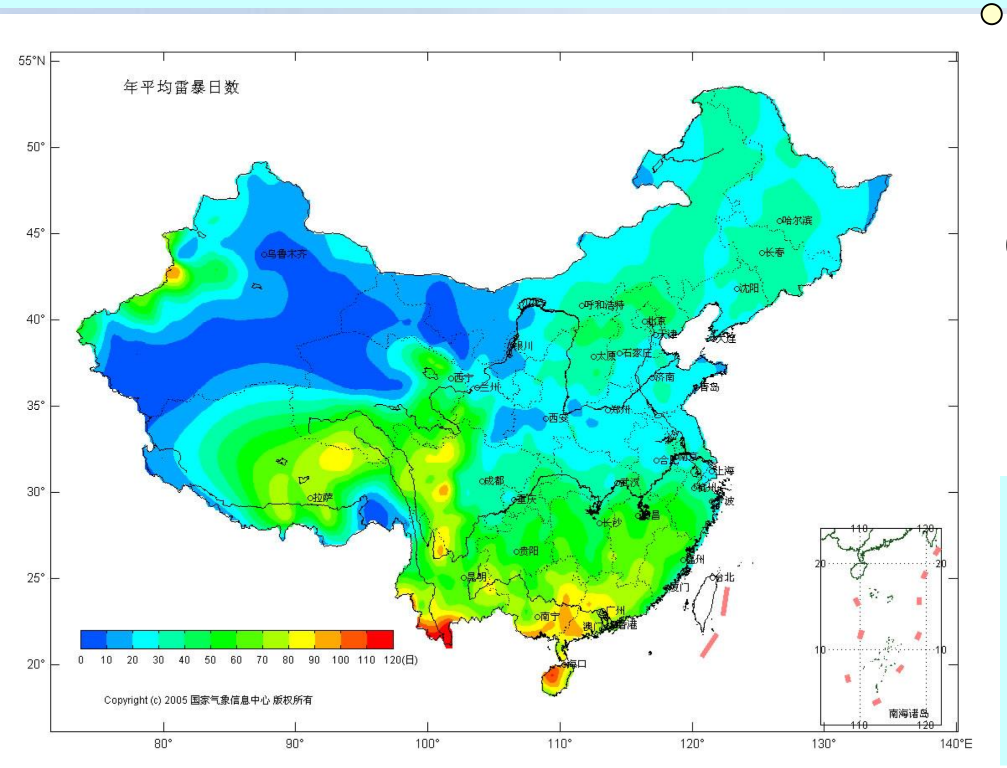
Empirical formula: $\log P_a = -a / 36$

Where P_a is the probability of a lightning current with a steepness not less than a, namely the possibility of $a \geq 36$kA/μs is 10%

9.1 Lightning parameters

9.1.3 Lightning day, lightning hour and ground flash density (lightning activity)

- **Lightning day T_d** refers to the number of days in a year to hear lightning discharge (whether between cloud thunder or ground flash).
- The country is divided into strong lightning area, multiple lightning area, medium lightning area and few lightning area according to the range of T_d.



Why is the intensity of lightning activity roughly divided like this way? Need it to be more precise?

- < 15 days: few lightning area
- 15-40 days: medium lightning area
- 40-90 days: multiple lightning area
- > 90 days: strong lightning area

9.1 Lightning parameters

9.1.3 Lightning day, lightning hour and ground flash density (lightning activity)

- **Lightning hour:** the number of hours to hear more than one thunder within an hour (whether between cloud thunder or ground flash), the average of each lightning day has about 3 lightning hours in China.
- The ratio of cloud-cloud to cloud-ground discharge is about 1.5 ~ 3.0 in the temperate zone and 3 ~ 6 in the tropics.

Ground flash density ***γ*:** the number of ground flashes per km^2 per lightning day.
In DL/T620-1997, China takes γ = 0.07 flashes/(lightening day • km^2).
For areas with T_d=40, the number of lightning strikes to OHL per 100km per year is $N_L=0.28(b+4h)$.

For normal 220kV OHL, the width of ground wire is b=11.6m, and the average height of ground wire is h=24.5m, then N_L=30.7 strikes/100 km year.
For normal 500kV OHL, b=18.6m, h=27.25m, then N_L=35.7 strikes/100 km year.

9.1 Lightning parameters

9.1.1 Waveform and polarity of the lightning current

9.1.2 Amplitude, steepness, waveform of lightning current

9.1.3 Lightning day, lightning hour and ground flash density

9.1.4 Monitoring of lightning activity by lightning location system

Why is there no voltage in the lightning parameters?

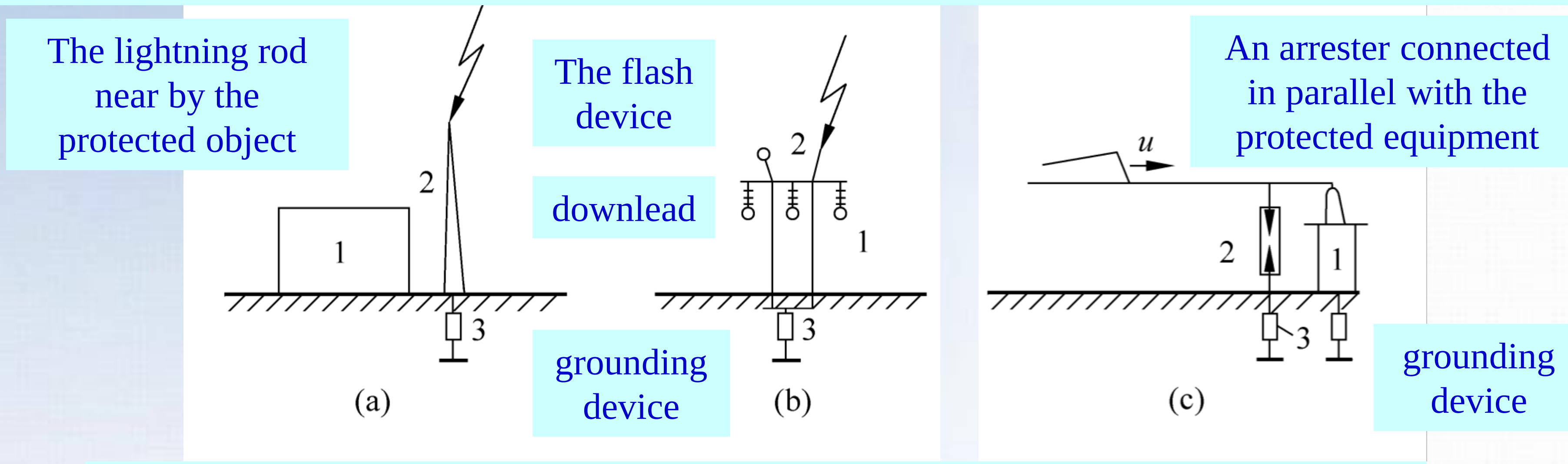
How high is the potential of the object subjected to a lightning strike?
How to determine?

9.2 Basic measures for lightning protection

Lightning discharge is hard to stop. **Try to avoid and reduce** its destructiveness, i.e., to take lightning protection measures.

Adopting the correct lightning protection measures is very important!

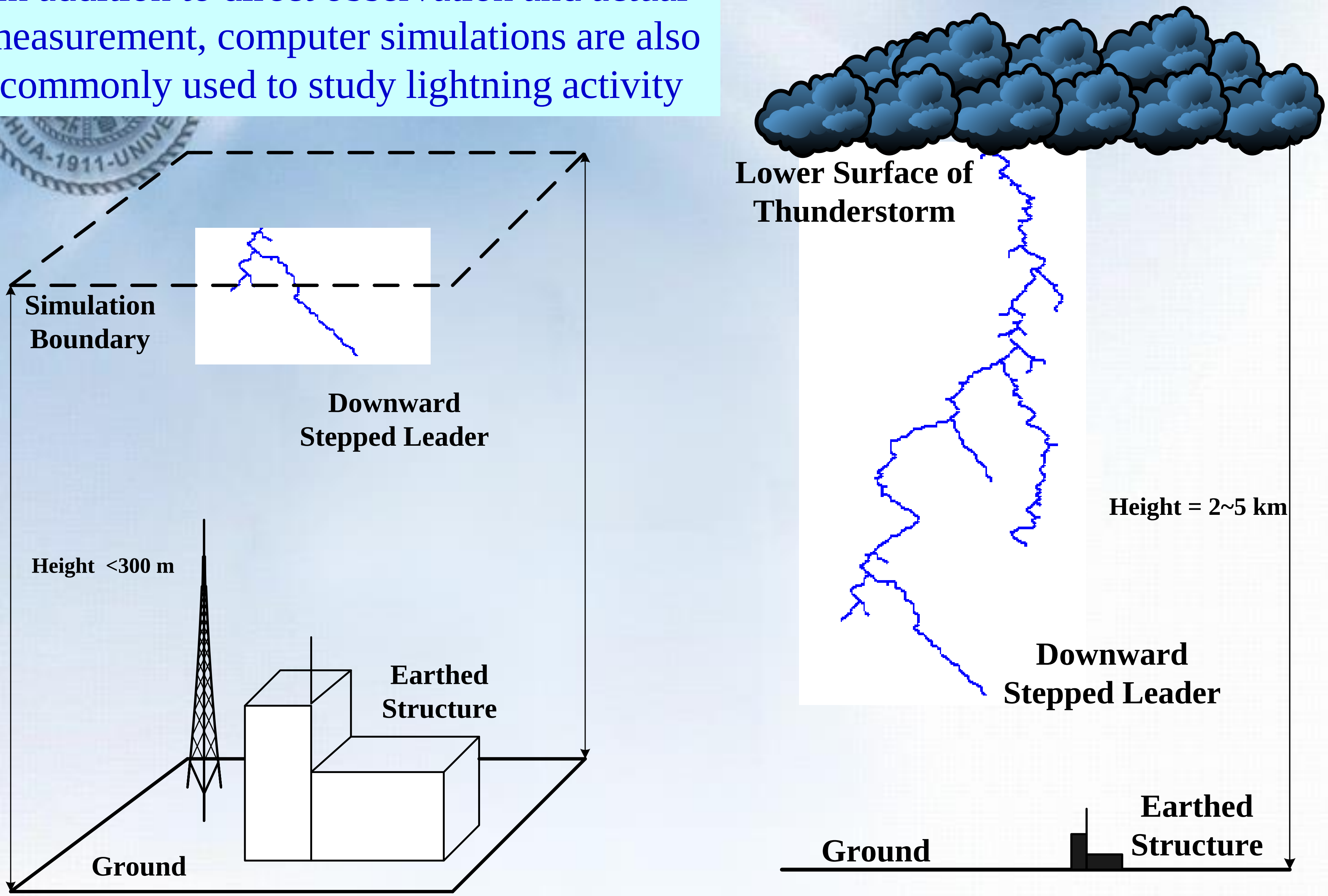
Basic measures: (lightning rod, ground wire, surge arrester) + grounding device



1-protected object	1- conductor	1-electrical equipment
2-lightning rod	2- ground wire	2-surge arrester
3-grounding device	3-grounding device	3-grounding device

Schematic diagram of basic lightning protection measures

In addition to direct observation and actual measurement, computer simulations are also commonly used to study lightning activity



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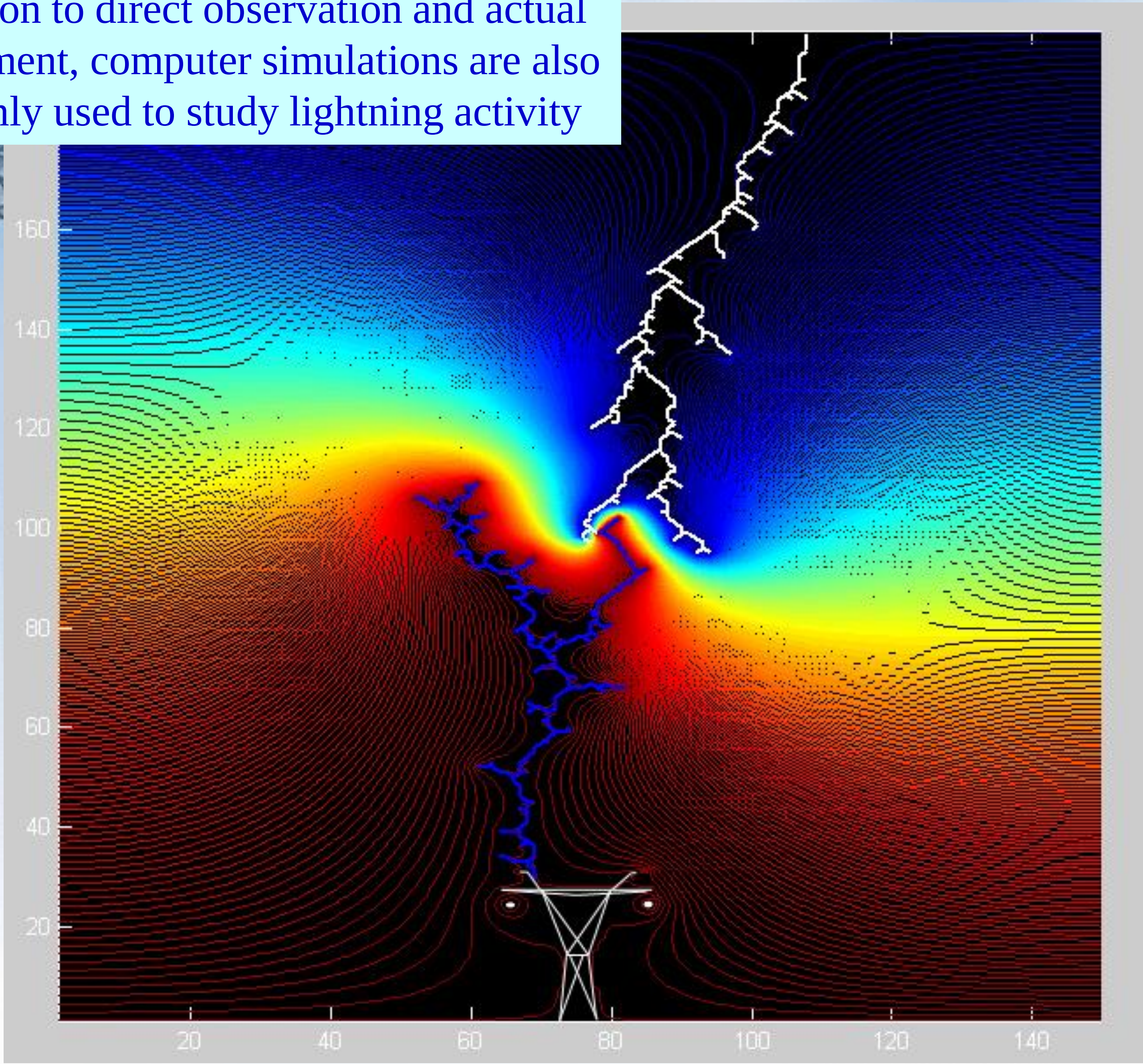
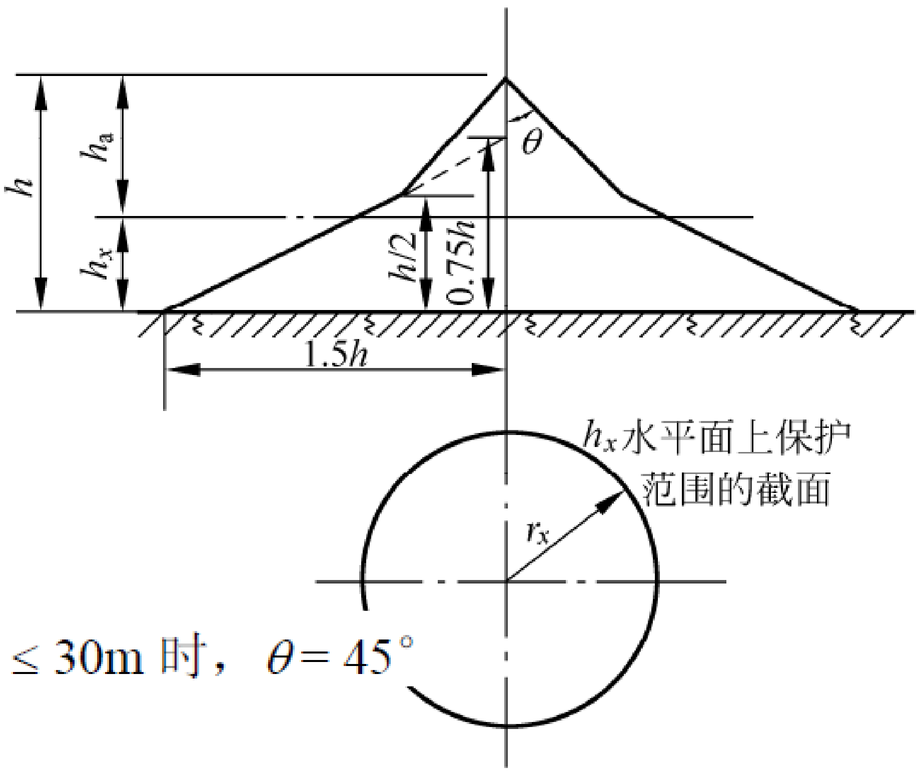


9.2 Basic measures for lightning protection

9.2.1 Lightning rod: Directional height, protection range (99.9% protection probability)



$h \leq 30$m 时， $\theta = 45°$

$$\left.\begin{array}{ll} r_x = (h - h_x)p = h_a p, & h_x \geq h/2 \\ r_x = (1.5h - 2h_x)p, & h_x < h/2 \end{array}\right\}$$

式中 h、h_x、h_a、r_x的单位均为 m

p 是避雷针的高度影响系数，

$h \leq 30$m 时， ······ $p = 1$

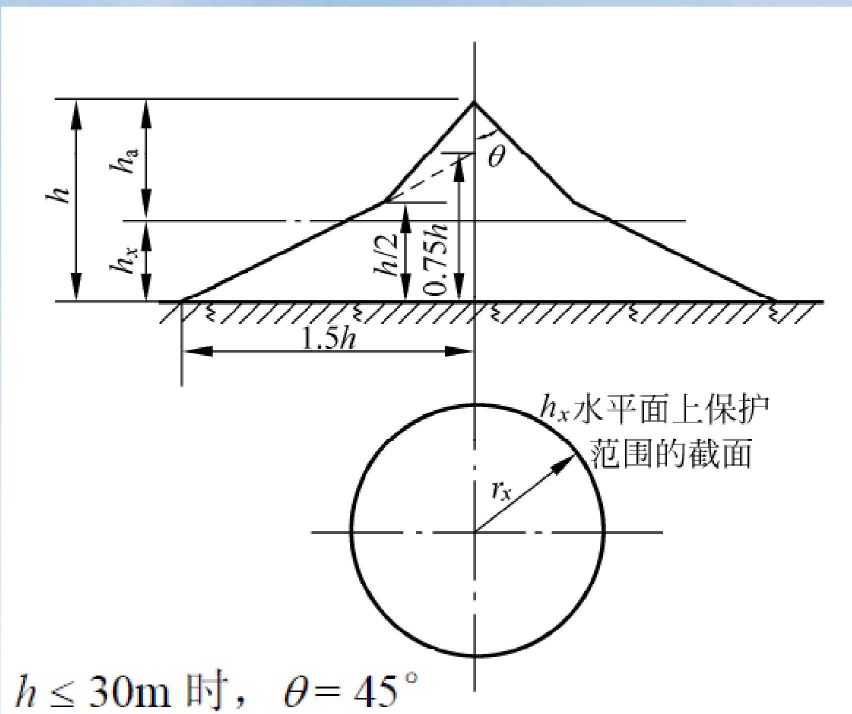
30m $< h \leq$ 120m 时， $p = 5.5/\sqrt{h}$

h>120m 时， p 按照 120m 时计算

Protection range of a single lightning rod

9.2 Basic measures for lightning protection

9.2.1 Lightning rod: Directional height, protection range (99.9% protection probability)



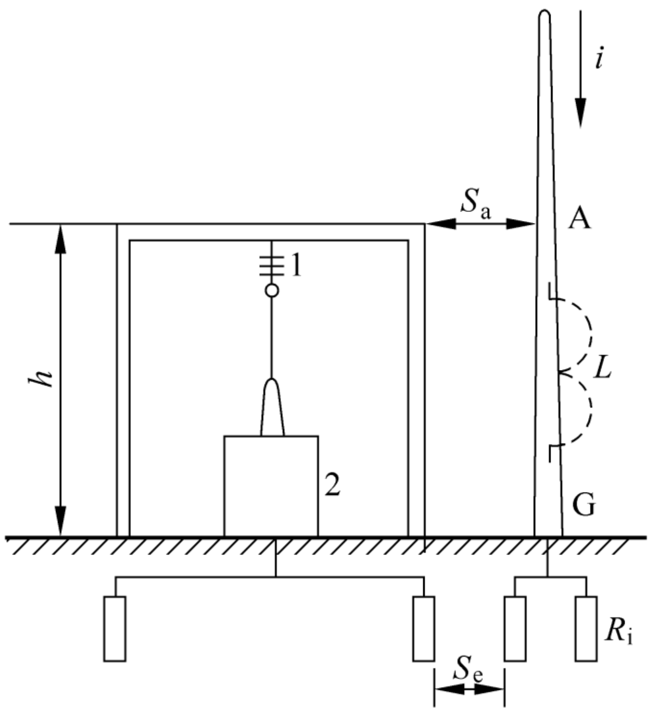
Protection range of a single lightning rod

Lightning rods normally mounted at the corner (**why not at the center?**) of substation and other places with concentrated equipment to prevent direct lightning strikes

9.2 Basic measures for lightning protection

9.2.1 Lightning rod: Directional height, protection range (99.9% protection probability)

- Keep sufficient clearance S_a between the lightning rod and the protected object!
- The grounding device of the lightning rod and the protected object is underground. They must keep a sufficient insulation distance S_e!



Once there is an impulse current through the lightning rod, the lightning rod is no longer with ground potential, and the potential for different parts of the lightning rod is no longer equal!

Once the "back stroke" occurs, the grounding grid of the low voltage equipment will have a significant potential rise! Great harm!

9.2 Basic measures for lightning protection

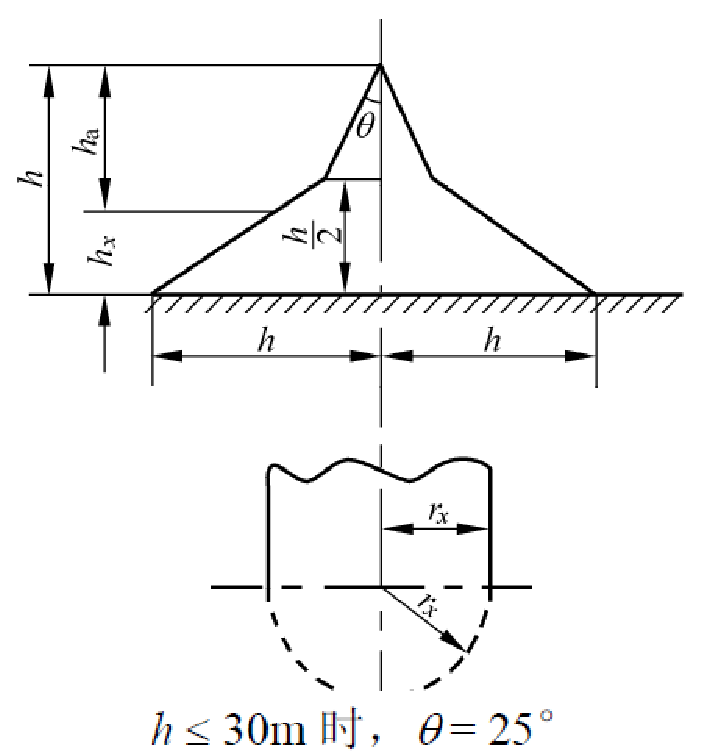
9.2.1 Lightning rod: Directional height, protection range (99.9% protection probability)

If the substation is large, is the protection range of corner mounted lightning rod safe enough?

Lightning rods normally mounted at the corner (**why not at the center?**) of substation and other places with concentrated equipment to prevent direct lightning strikes

9.2 Basic measures for lightning protection

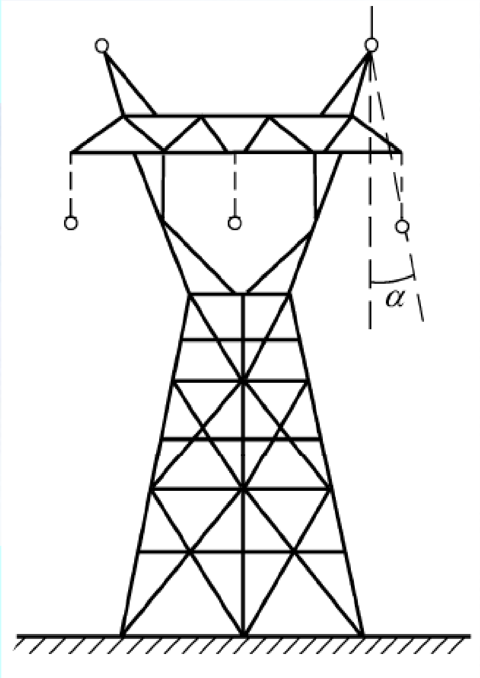
9.2.2 Ground wire: protection angle, protection range



Protection range
of a single ground wire

$$
\left.\begin{aligned}
r_x &= 0.47(h - h_x)p, \quad h_x \geq h/2 \\
r_x &= (h - 1.53 h_x)p, \quad h_x < h/2
\end{aligned}\right\}
$$

OHLs of higher voltage level are normally equipped with ground wires in the whole line



Protective angle
of ground wire

Protective angle α= 20º – 30º for normal HV OHL

For 220kV - 330kV OHL α is around 20º

For 500kV OHL α is < 15º

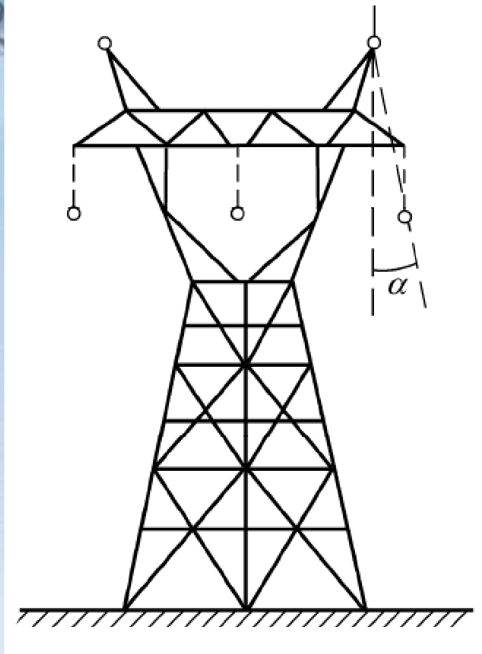
Smaller angle will be used for OHLs in mountain areas

When the lightning protection requirement is very high,

the negative protection angle can also be used

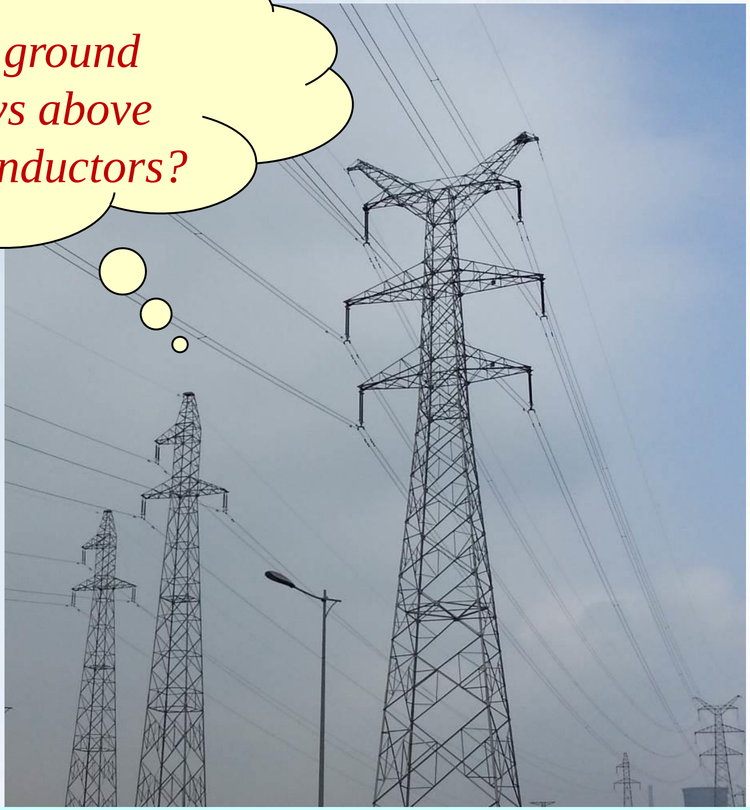
9.2 Basic measures for lightning protection

9.2.2 Ground wire: protection angle, protection range



Protective angle of the lightning conductor

Are all the ground wires always above HV phase conductors?



- OHLs of higher voltage level are normally equipped with ground wires in the whole line
- When the lightning protection requirement is very high, the negative protection angle can also be used

9.2 Basic measures for lightning protection

The lightning protection belt at building roof, lead line to ground and grounding device

9.2 Basic measures for lightning protection

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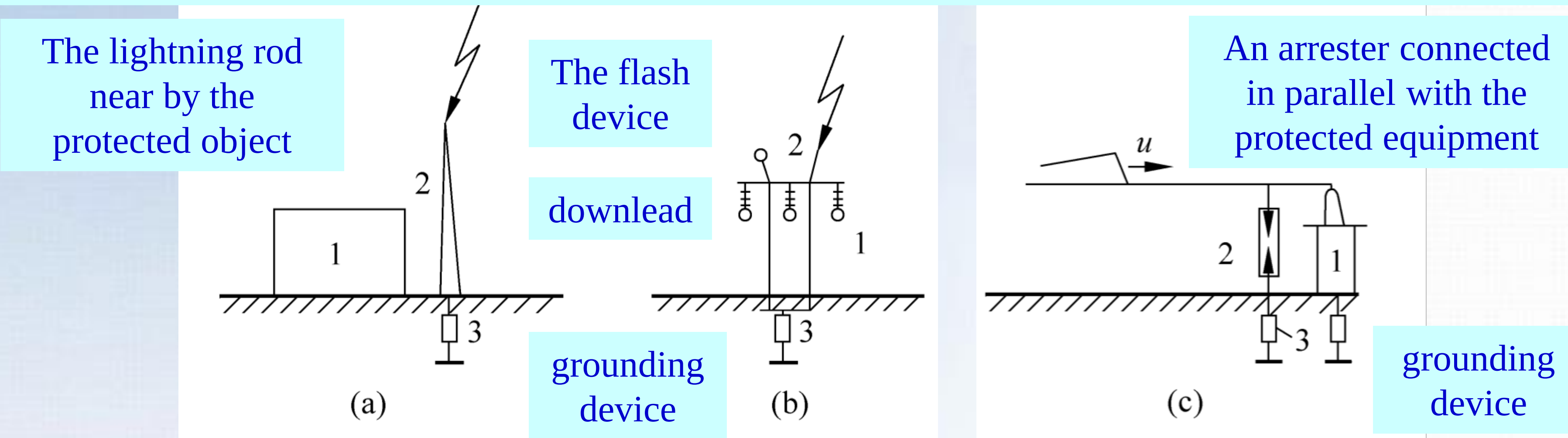
Basic measures: (lightning rod, ground wire, surge arrester) + grounding device



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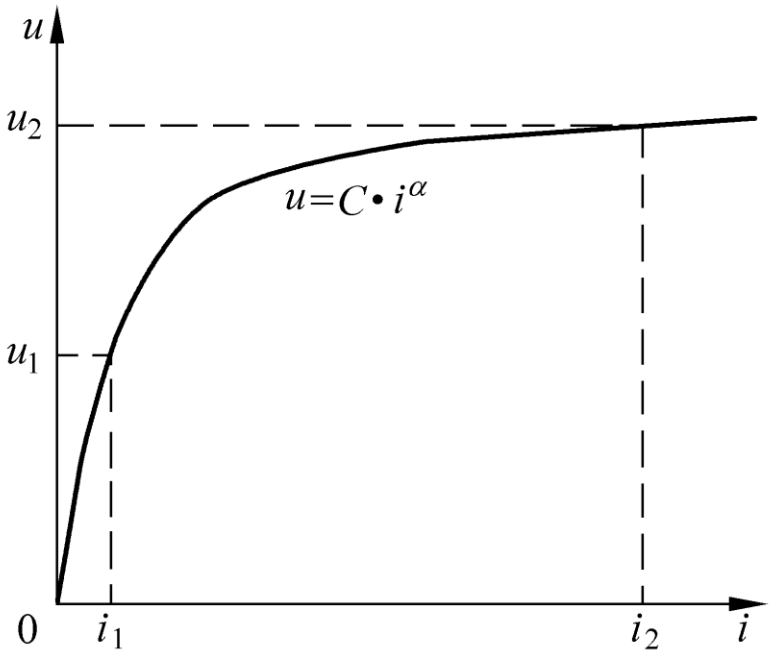
Schematic diagram of basic lightning protection measures

9.2 Basic measures for lightning protection

9.2.3 Surge Arrester:

Nonlinear volt-ampere characteristics, residual voltage, follow up current

Operating principle of silicon carbide (SiC, with series gaps), metal oxide arrester MOA (ZnO, without series gap)



Surge arrester and the protected equipment are installed in parallel nearby.

Under normal circumstances surge arrester is not conducted.

When the lightning overvoltage is higher than the action voltage of arrester, the large current flows into the ground.

Static *u*-*i* characteristics of non-linear resistance disc

i_1- follow up current, u_1-power frequency voltage

i_2-lightning current, u_2-arrester residual voltage

non-linear resistance of SiC and ZnO
Low resistance to high current
And high resistance to low current

9.2 Basic measures for lightning protection

9.2.3 Surge Arrester:

Nonlinear volt-ampere characteristics, residual voltage, follow up current

Operating principle of SiC (with series gaps)， MOA (ZnO) (without series gap)

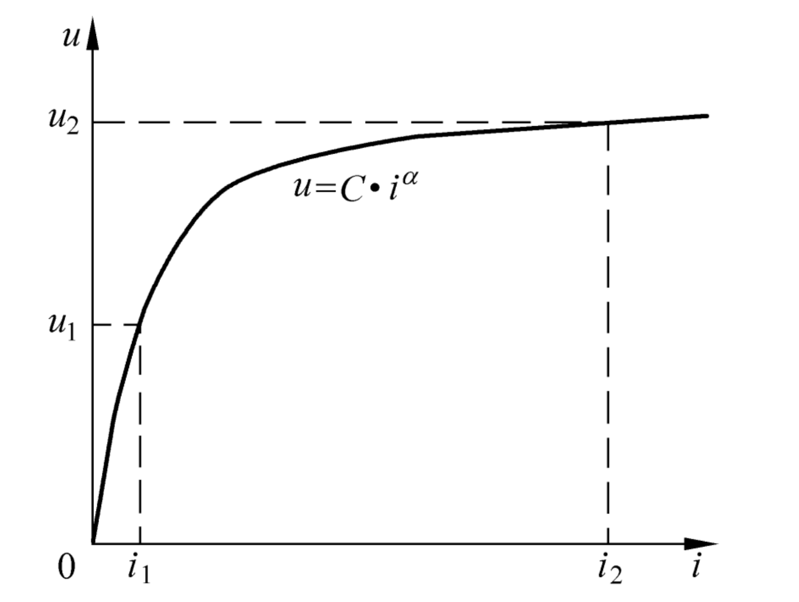
Two basic requirements for surge arrester:

(1)good *v*-*t* characteristics and low impulse current residual voltage, so as to easily achieve reasonable insulation coordination;

(2)strong ability to quickly cut off the power-flow current and automatically recover the insulation strength quickly.

The arrester generally should cut off the power frequency follow up current at the first zero current point, so that power system can continue to operate normally before HV switchgear trips off the line.

One of the function of series gaps for SiC arrester!



Static *u*-*i* curve of non-linear resistance disc

i_1-follow up current,

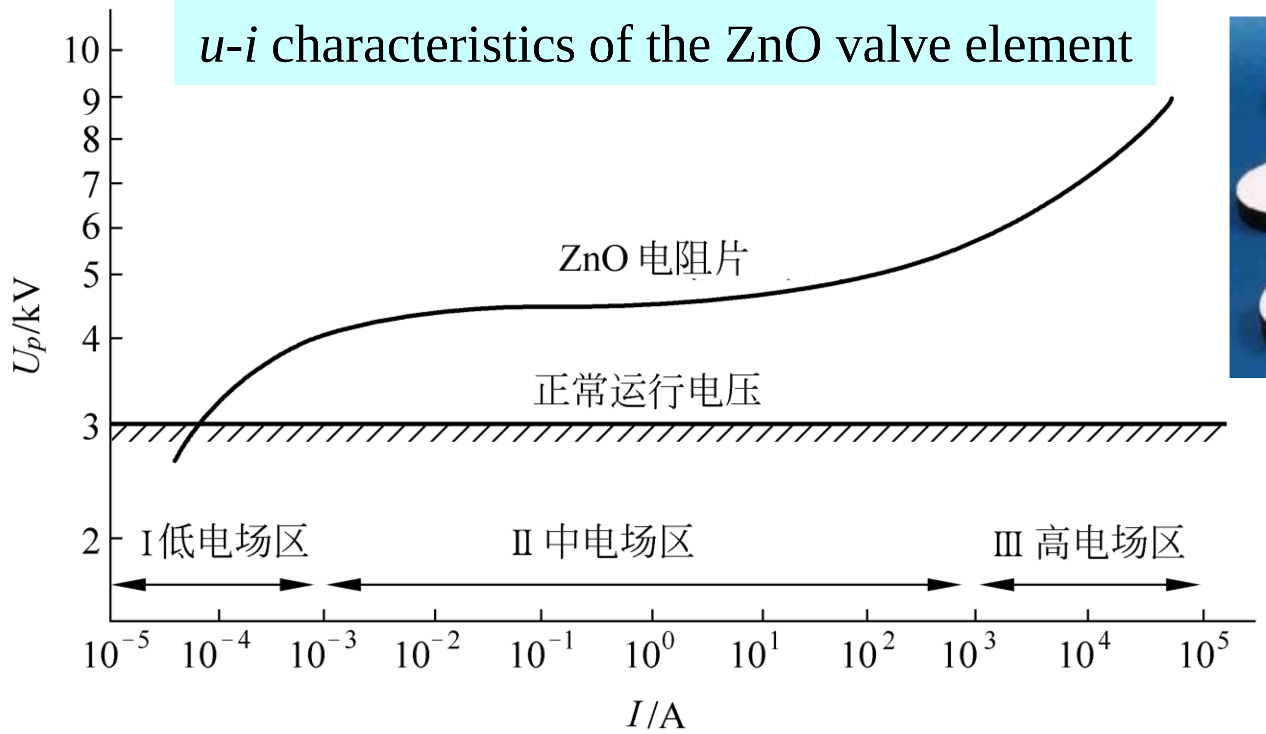
u_1-power frequency voltage

i_2-lightning current, u_2-arrester residual voltage

9.2 Basic measures for lightning protection

9.2.3 Surge arrester: working principle of the ZnO gapless surge arrester

u-*i* characteristics of the ZnO valve element



ZnO valve element

The *u*-*i* characteristics of ZnO valve element is much better than that of SiC

the nonlinear coefficient $\alpha \approx$ 0.015-0.05, therefore the series gap can be omitted

9.2 Basic measures for lightning protection

9.2.3 Surge arrester: working principle of the ZnO gapless surge arrester

The main technical parameters of ZnO arrester are:
continuous operating voltage,
rated voltage,
reference voltage,
protection level (residual voltage),
and energy absorption

例如：某种类型 500kV 瓷外套氧化锌避雷器的技术参数如下，持续运行电压 375kV（有效值）额定电压 468kV（有效值），参考电压 655kV，操作冲击保护水平 950kV。

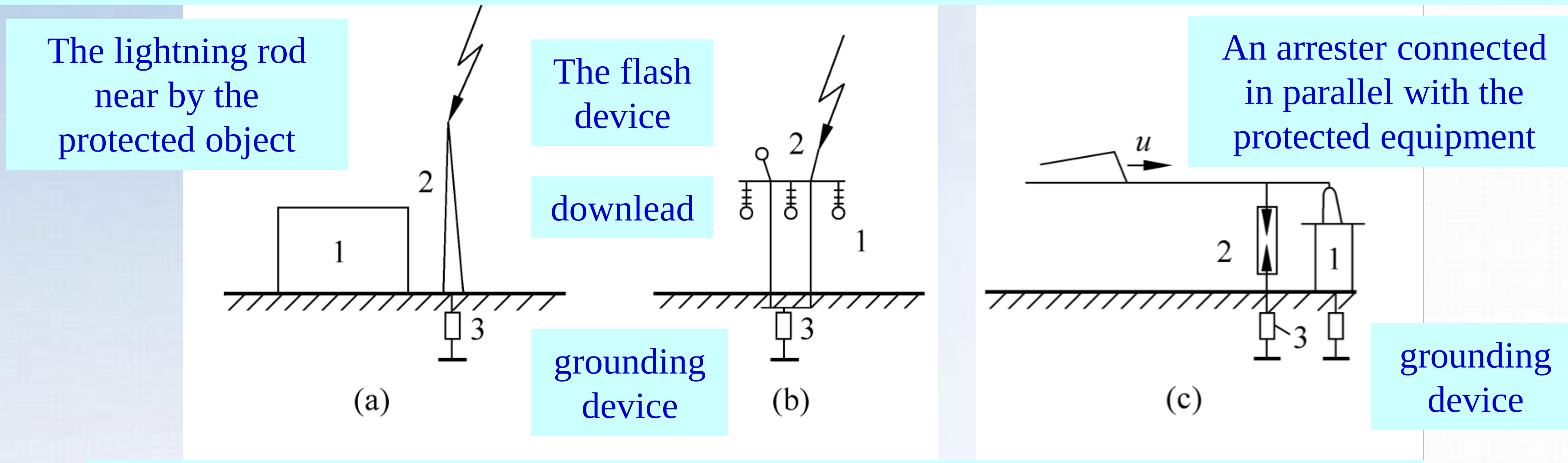
Transformer, arrester and potential transformer

9.2 Basic measures for lightning protection

Lightning discharge is hard to stop. **Try to avoid and reduce** its destructiveness, i.e., to take lightning protection measures.

Adopting the correct lightning protection measures is very important!

Basic measures: (lightning rod, ground wire, surge arrester) + grounding device



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Schematic diagram of basic lightning protection measures

9.2 Basic measures for lightning protection

9.2.4 Grounding device (grounding rod or grounding grid)

The metal grounding body buried into the ground is called a grounding device, with the function to reduce grounding resistance.

The grounding device can be classified as bellow types according to its function:

- Working grounding (e.g. neutral point grounding), 0.5 ~ 5Ω
- Protective grounding (e.g. equipment enclosure grounding),

✓ high voltage equipment 1 ~10 Ω; low voltage equipment 10 ~100 Ω

- Lightning protection grounding (e.g. grounding of lightning rod and ground wire),

✓ impulse grounding resistance ≤ 7 Ω in plain areas, and ≤ 15 Ω in mountainous areas

- Static electricity grounding

Electrical parameters of a grounding system:

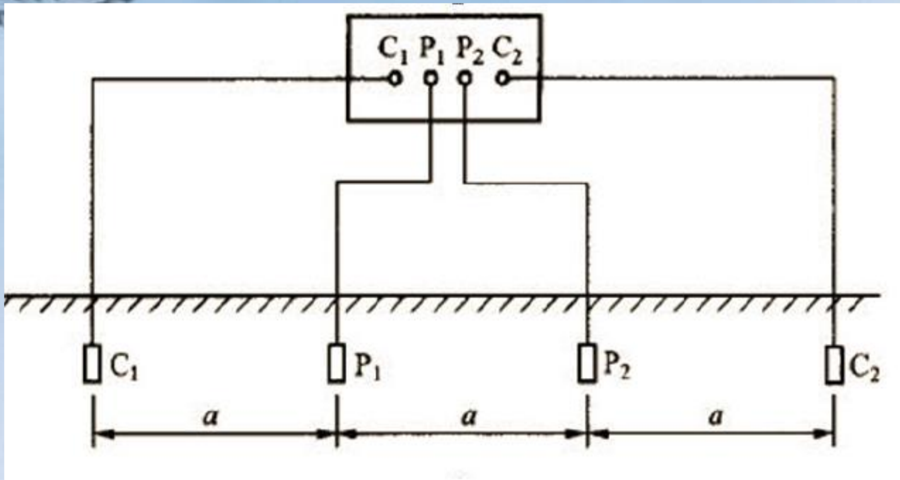
✓ grounding resistance, contact potential difference, and step potential difference.

Grounding resistance (impedance): the ratio of potential at the ground point to its current.

Soil resistivity

9.2 Basic measures for lightning protection

9.2.4 Grounding device: Soil resistivity and its measurement



$$\rho = 2\pi a R$$

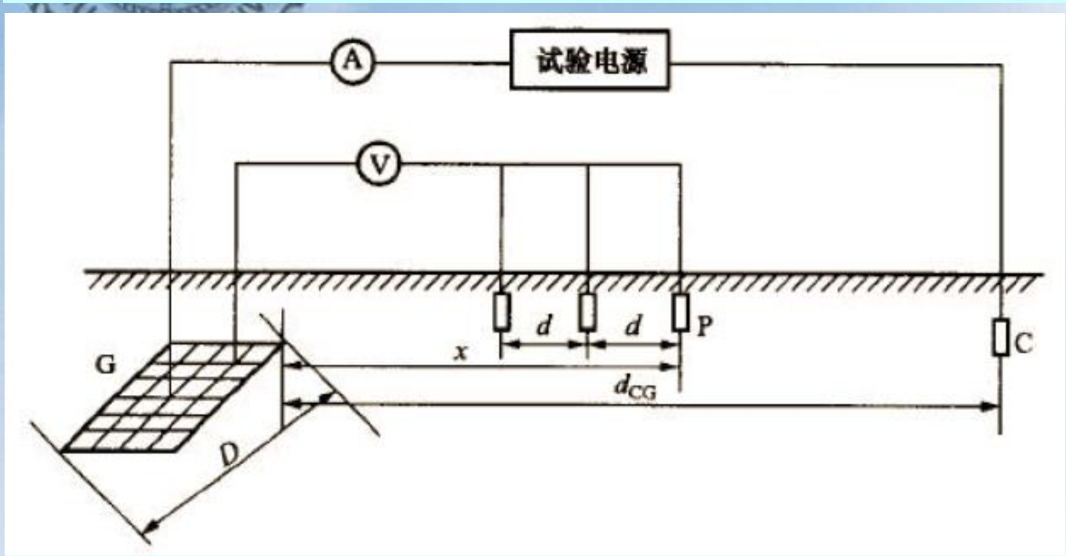
Equidistant four-electrode method for measuring soil resistivity

Resistivity of several typical soils

土壤类别	电阻率ρ / Ω·m	土壤类别	电阻率ρ / Ω·m
沼泽地	5 ~ 40	砂砾土	2000 ~ 3000
泥土、粘土、腐植土	20 ~ 200	山地	500 ~ 3000
沙土	200 ~ 2500		

9.2 Basic measures for lightning protection

9.2.4 Grounding device: Measurement of grounding resistance (impedance)



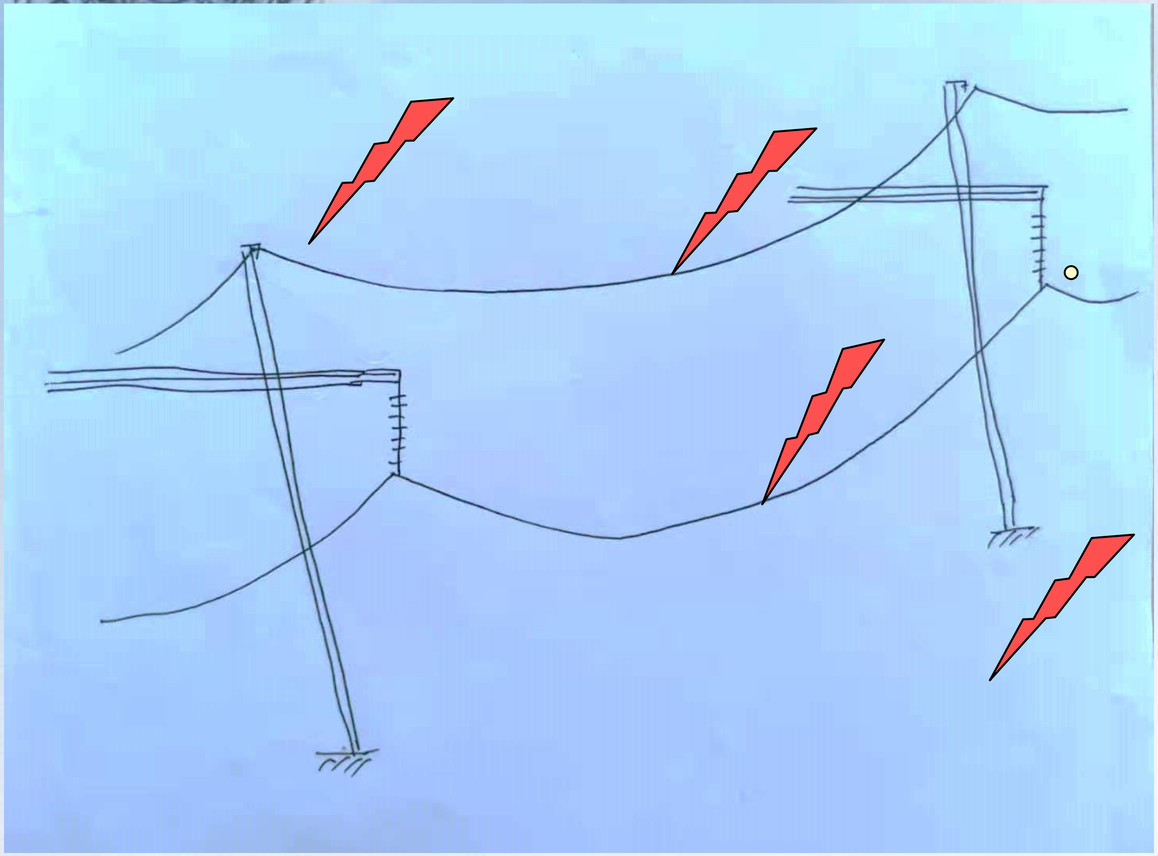
The grounding impedance presented under impulse high current is different from the grounding resistance measured under power frequency current, while it is still called grounding resistance habitually

the potential reduction method of measuring the grounding resistance of grounding device

- The current *I* generated by the test power supply changes the ground potential.
- The potential pole P moves outward from the edge of G, the potential difference *U* between P and G is tested, and the variation curve of *U* vs. *x* is drawn. The flat position of the curve corresponds to the potential zero, whose potential difference relative to the starting point of the curve is U_m.
- The grounding resistance of the grounding device $R=U_m/ I$

9.3 Lightning overvoltage of OHLs

How is the lightning overvoltage generated?



Different types of lightning overvoltage of OHL when the lightning strikes different parts of OHL

Lightning strikes different parts of OHL:

Lightning strikes tower top

strikes ground wire

strikes to phase conductor

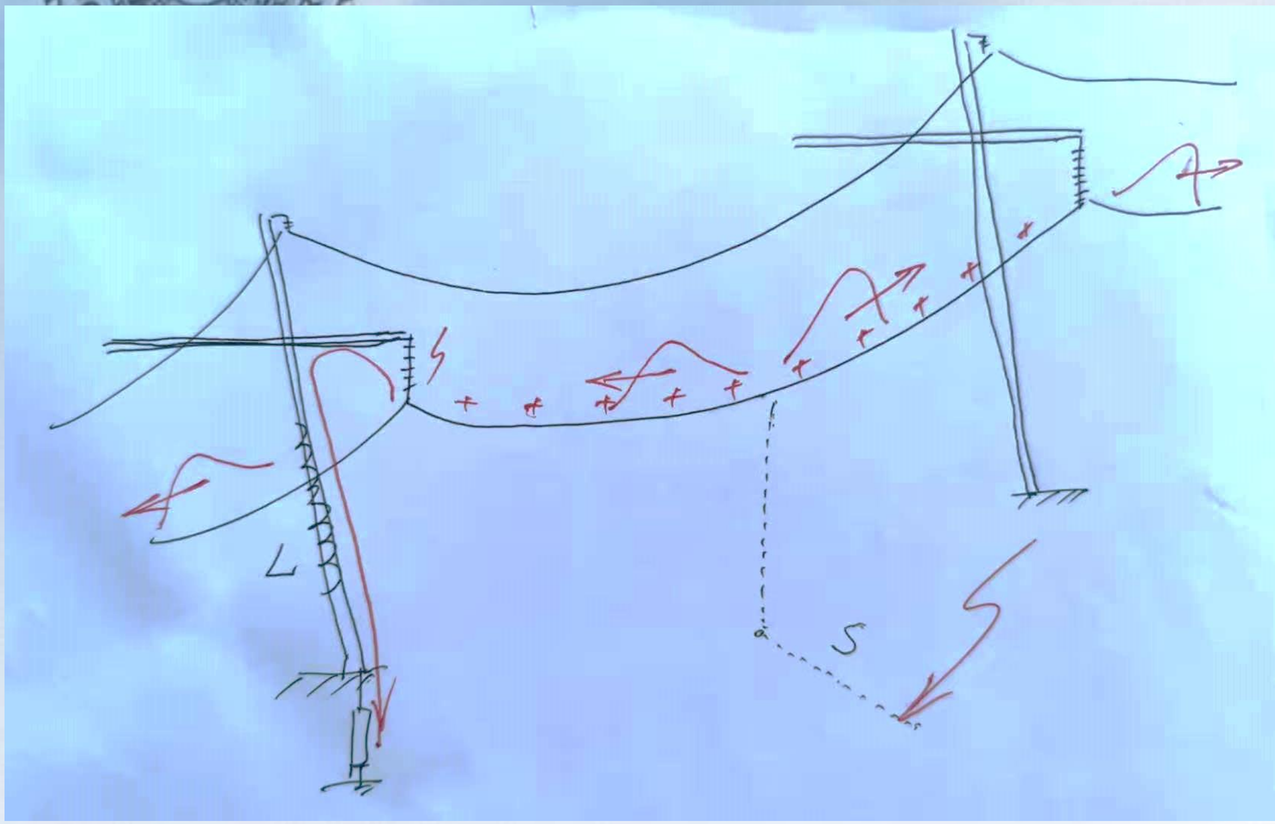
strikes ground close to OHL

Lightning protection index:

Lightning withstand level

lightning outage rate

9.3 Lightning overvoltage of OHLs



Induced overvoltage when lightning strike the ground close to OHL

Lightning strikes the ground close to OHL:

The amplitude of induced overvoltage generated on phase conductor when the lightning strikes the ground S m away from the lowest sag of span

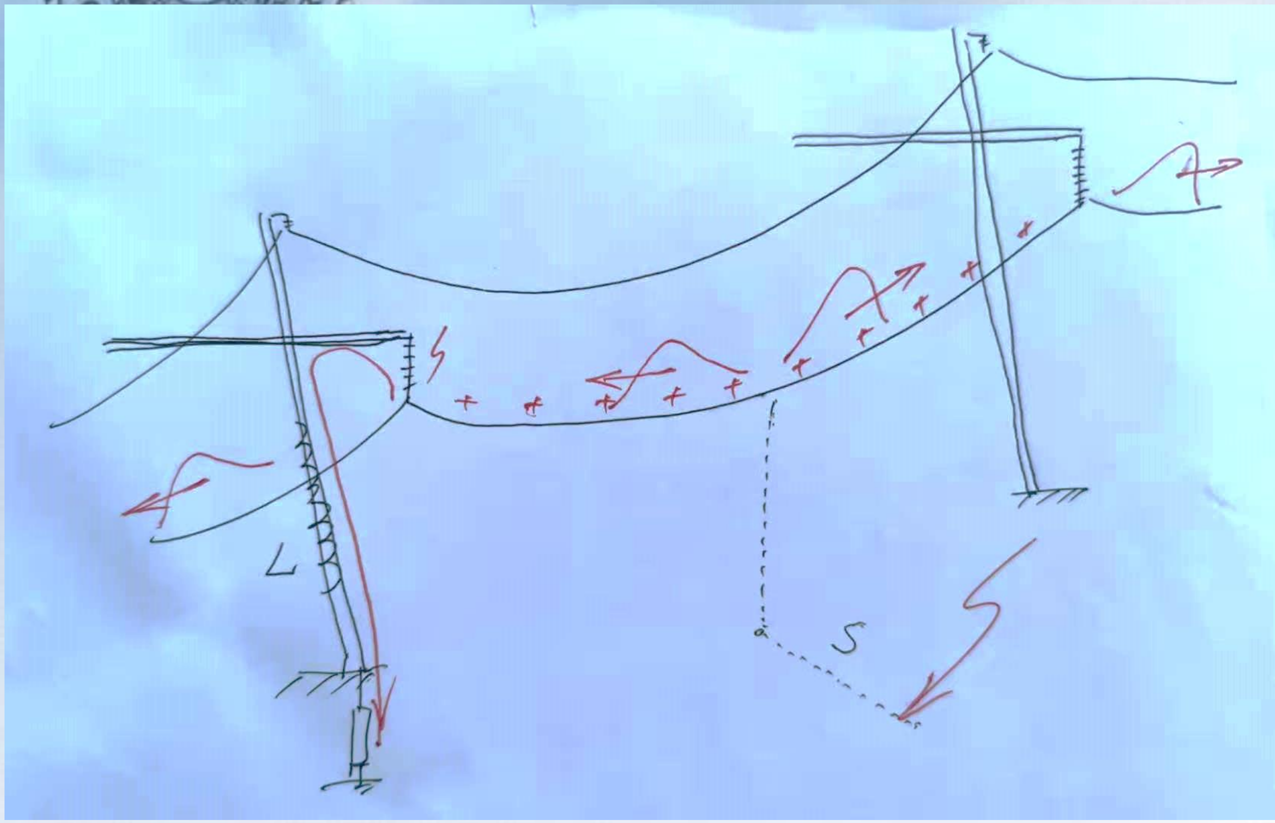
$$U \approx 25\, I\, h / S \quad \text{kV}$$

The induced overvoltage is usually only a threat to lines below 110kV

Lightning withstand level:

$$I \approx U_{50}(+)\, S / 25h$$

9.3 Lightning overvoltage of OHLs

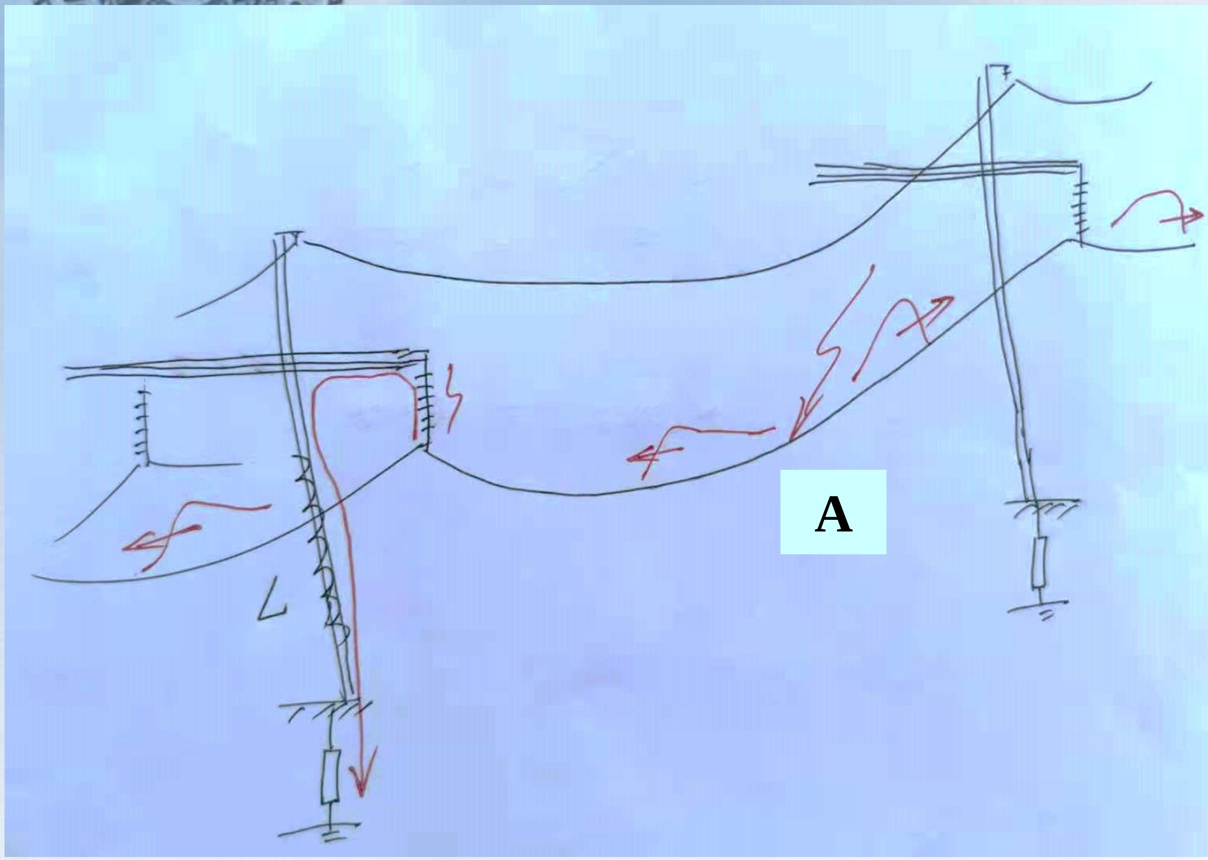


Induced overvoltage when lightning strike the ground close to OHL

The induced overvoltage is usually only a threat to lines below 110kV

- ✓ When the induced over voltage exceeds the U_{50} of insulator string, it will be an insulator flashover, and part of the induced lightning current flows into the ground.
- ✓ Then conductor is short circuit to the ground, forming a follow up current, tripping the relay protection.
- ✓ Some of the overvoltage waves continue to spread to the nearby two substations.

9.3 Lightning overvoltage of OHLs



Overvoltage by lightning direct strikes to phase conductor

If the shielding from ground wire is fail, lightning channel will directly strikes the conductor, “shielding failure” or “bypass strike"

Amplitude of overvoltage when lightning directly strikes to conductor at point A:

$$U_A \approx I Z / 4 \quad \text{kV}$$

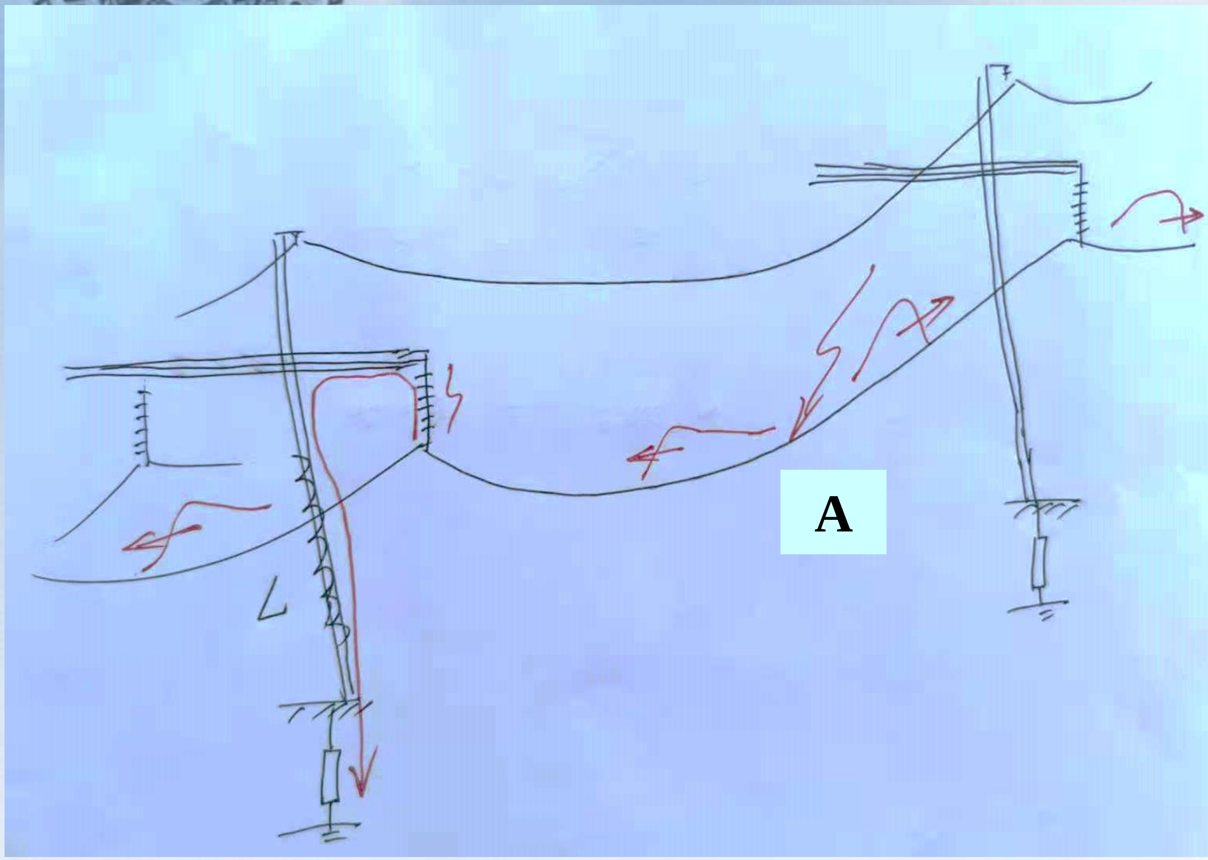
Lightning withstand level:

$$I_{耐} = 4U_{50}(-)/Z$$

$$\approx U_{50}(-)/100 \text{ kA}$$

The lightning withstand level is very low when direct strike to conductor. It is a great threat to all voltage levels!
The “shielding failure” rate must be reduced!

9.3 Lightning overvoltage of OHLs



Overvoltage by lightning direct strikes to phase conductor

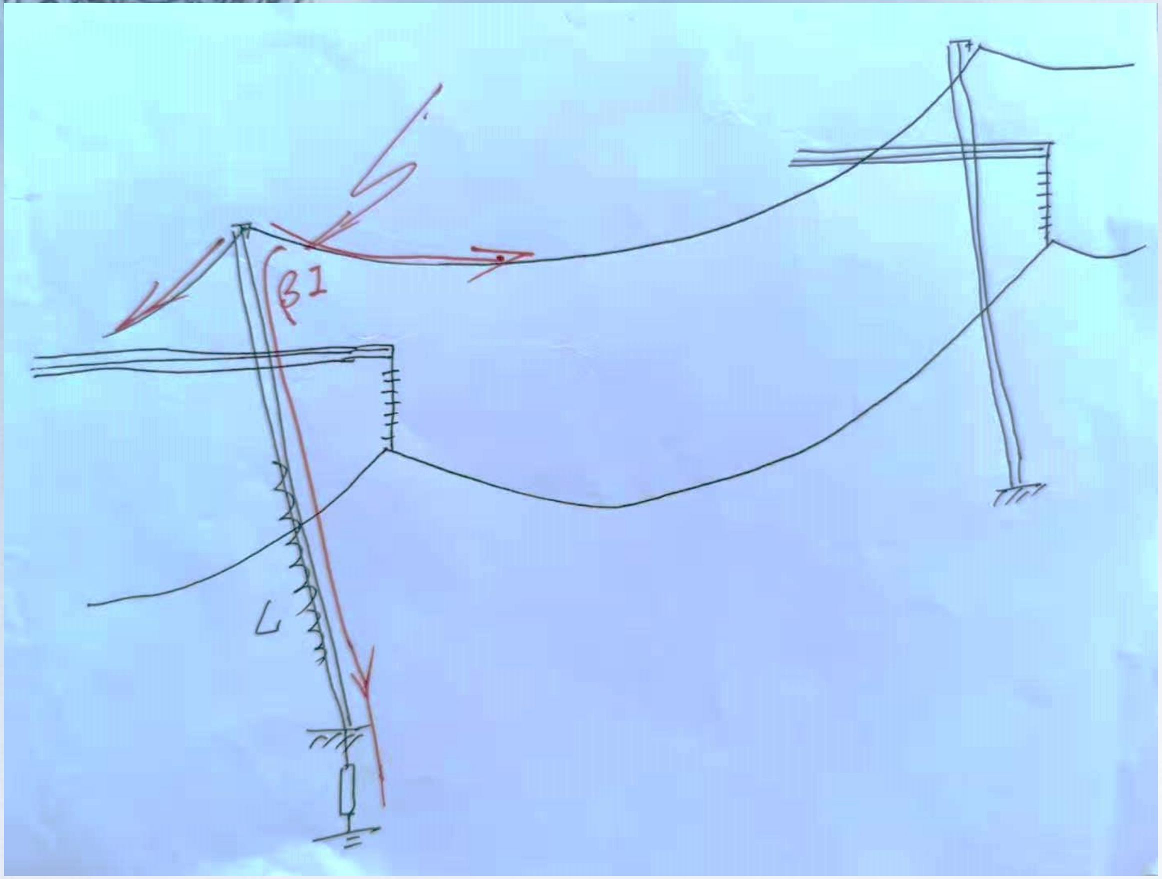
The lightning withstand level is very low when direct strike to conductor. It is a great threat to all voltage levels! The “shielding failure” rate must be reduced!

When lightning directly strikes to conductor at point A,
Lightning withstand level:

$$I_{耐} = 4U_{50}(-)/Z$$
$$\approx U_{50}(-)/100\ \text{kA}$$

- ✓ It will be an insulator flashover when overvoltage exceeds its $\boldsymbol{U}_{50}$, and part of the lightning current flows into the ground.
- ✓ Then conductor is short circuit to the ground, forming a follow up current, tripping the relay protection.
- ✓ Some of the overvoltage waves continue to spread to the nearby two substations.

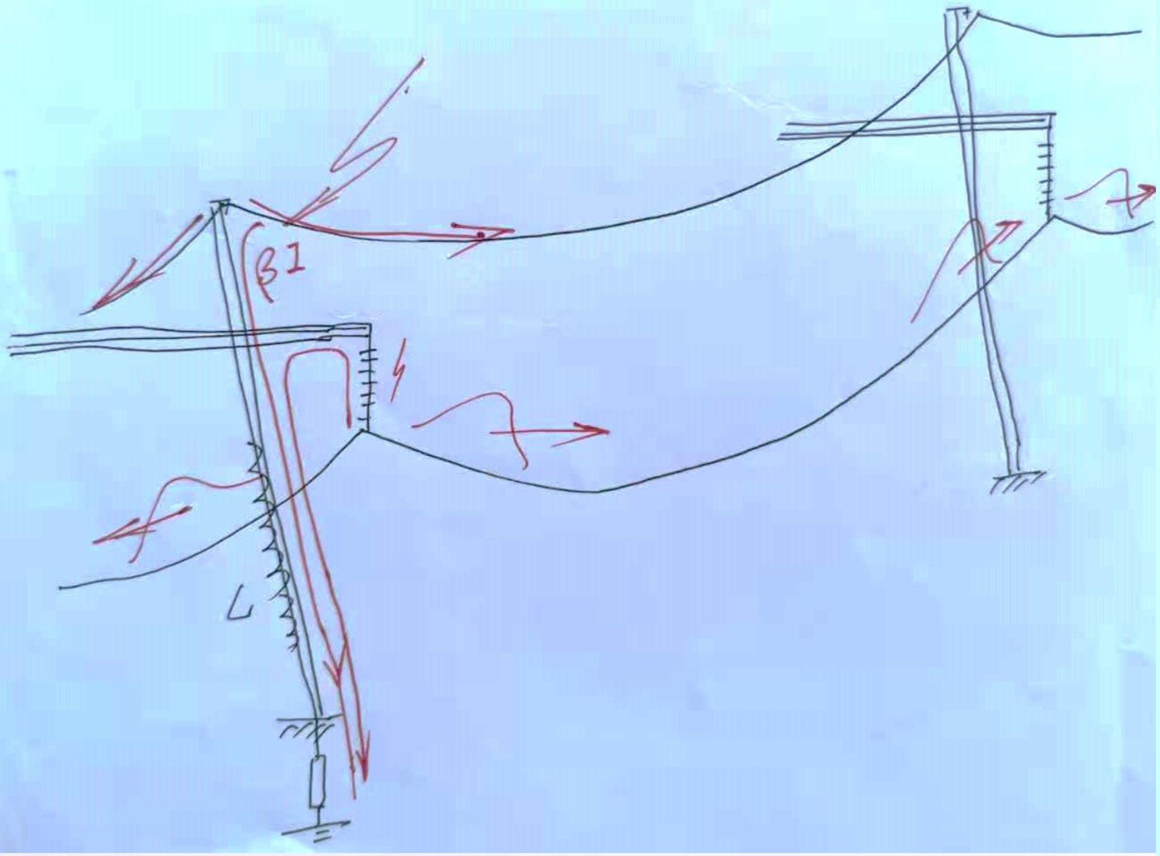
9.3 Lightning overvoltage of OHLs



Overvoltage by lightning strikes the top of tower or nearby ground wire

- ✓ When lightning strikes the top of the tower or nearby ground wire, part of the lightning current will go to nearby tower through the ground wire.
- ✓ Most of the lightning current βI flow through the grounding lead wire at tower into the grounding device at tower foot.
- ✓ The current βI forms a voltage drop in the grounding resistance R and the inductance L of grounding lead wire, leading to a voltage rise at the crossarm, called "strike back"

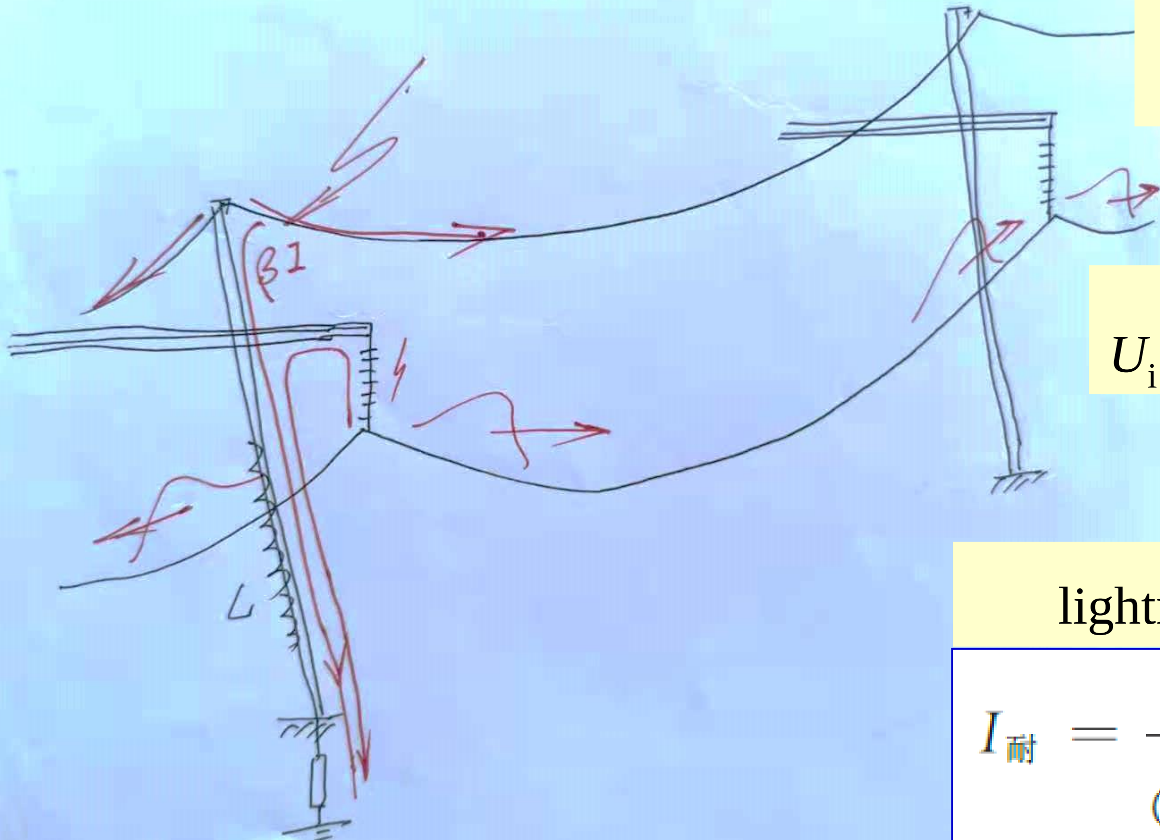
9.3 Lightning overvoltage of OHLs



Overvoltage by lightning strikes the top of tower or nearby ground wire

- ✓ When the voltage rise of "strike back" at crossarm exceeds the $\boldsymbol{U}_{50}$ of insulator string, it will result the insulator flashover.
- ✓ The conductor is then short circuit to the ground, forming a follow up current, tripping the relay protection.
- ✓ Some of the lightning waves continue to spread to the nearby two substations.

9.3 Lightning overvoltage of OHLs



Overvoltage amplitude on the insulator string when lightning strike the top of tower:

$$U_i = (1-k)\left[\beta\left(R_i + \frac{L_t}{\tau_f}\right) + \frac{h}{\tau_f}\right] \cdot I$$

lightning withstand level of OHL

$$I_{耐} = \frac{U_{50}}{(1-k)\left[\beta\left(R_i + \frac{L_t}{\tau_f}\right) + \frac{h}{\tau_f}\right]}$$

Overvoltage by lightning strikes the top of tower or nearby ground wire

9.3 Lightning overvoltage of OHLs

Lightning strikes different parts of OHL:

Lightning strikes tower top

strikes ground wire

strikes to phase conductor

strikes ground close to OHL

Lightning protection index:

Lightning withstand level

lightning outage rate

Table 9-2 The lightning withstand levels and lightning trip rates of typical towers given by DL/T 620-1997

电压等级 /kV	500	330	220	110	66	35
雷击杆塔时	125~175	100~150	75~110	40~75	30~60	20~30
耐雷水平 /kA						
平原跳闸率 (次/百公里•年)	0.081	0.12	0.25	0.83		
山区跳闸率 (次/百公里•年)	0.17~0.42	0.27~0.60	0.43~0.95	1.18~2.01		

注：跳闸率中，平原对应 R_i=7 Ω，山区两数据分别对应 R_i 为 7 Ω 和 15 Ω。

9.3 Lightning overvoltage of OHLs

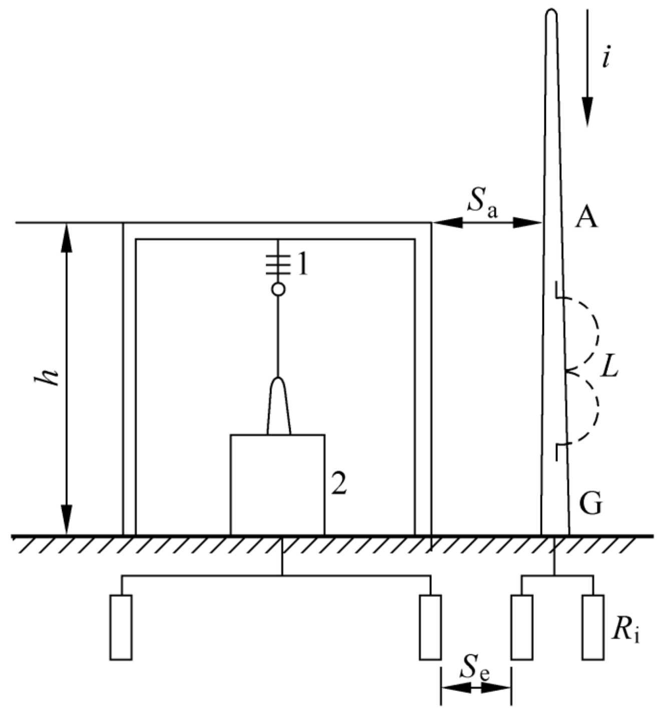
Why such a suspended arrester could prevent insulators from flashover under lightning?

Line surge arrester

9.4 Lightning overvoltage and protection of power plants and substations

9.4.1 Protection of the direct lightning strike

- Keep a sufficient clearance S_a between the lightning rod and the protected object!
- Keep a sufficient underground insulation distance S_e between grounding device of lightning rod and grounding device of the protected object !



Once there is a lightning current flow on the lightning rod, the lightning rod is no longer with ground potential, and the potential at different parts of the lightning rod is no longer equal!

Once "striking back", "high voltage running into the secondary circuit", the grounding grid of the low voltage equipment will subject to a high potential rise!

9.4 Lightning overvoltage and protection of power plants and substations

9.4.2 Protection of the incident wave from lightning

- In power plant and substation, equipment is centralized. With the lightning rod, it is effective to prevent direct lightning strike. Therefore, the incident travelling wave along the OHL becomes the main object of lightning protection in power plant and substation.
- 50% of the accidents from incident wave are caused by lightning strike to lines within 1km, and 75% are caused by those strike within 3km to the power plants and substations.
- The main measure of lightning protection in power plant and substation is to adopt surge arrester and take auxiliary measures in the incoming section to limit the lightning current amplitude and reduce the steepness of the incident wave.
- Residual voltage of surge arrester is the base of insulation co-ordination in substation. It will be introduced in Chapter 10