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Department of Electrical Engineering
Tsinghua University

High Voltage Engineering

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June 5, 2025

Chapter 10 Switching Overvoltage and Insulation Coordination

What is the main concern of this chapter?

Master the principles of science
Know the technical measures
Understand industry specifications

Core concepts of this chapter:

Multiple of switching overvoltage, breaking/closing and reclosing of circuit breaker, overvoltage by energizing or disconnecting an unloaded line, very fast transient overvoltage, closing resistance, insulation coordination, basic impulse withstand level (BIL)

Chapter 10 Switching Overvoltage and Insulation Coordination

- What is the switching overvoltage? How the switching overvoltage happened?
- What is the relation between the opening/closing of a circuit breaker and the switching overvoltage in power system?
- What are the relation between internal overvoltage and switching overvoltage?
- Are the power grid/equipment with different voltage levels face the same threat of switching overvoltage?
- Which type of switching overvoltage is more dangerous than others?
- Why engineers using the concept of permitted switching overvoltage multiples? Why not they use the amplitude (kV) of switching overvoltage?
- How many controlling and protective measures of switching overvoltage?
- What is the insulation coordination? Why we need it? and how to do it?

Ask more question to yourself

Many costs in engineering is used to deal with faults and accidents

- Classify overvoltage by the steepness of voltage:

Slow-Front Over-voltage, SFO (Switching Overvoltage)
Fast-Front Over-voltage, FFO (Lightning Overvoltage)
Very Fast Transient Over-voltage (VFTO), (Switching Overvoltage)

- Classify overvoltage by the reasons of overvoltage occurs:

Classify of overvoltage

Energizing an unloaded line (closing small capacitive current)
De-energizing an unloaded line (interrupting small capacitive current)
De-energizing an unloaded transformer (interrupting small inductive current)
Current chopping overvoltage (interrupting small inductive current)
Resonance overvoltage, Arc grounding overvoltage, system splitting overvoltage

External overvoltage (lightning overvoltage)	Internal overvoltage			
	Power frequency voltage increase (temporary overvoltage)	Resonance overvoltage	Arc grounding overvoltage	Switching overvoltage
Lightning strikes the the tower top Lightning strikes phase conductors Lightning strikes ground wire in mid of span Lightning strike the ground close to line	Caused by the capacitance rise effect of no-load long lines, Asymmetric short circuit, Sudden load shedding (load rejection), etc. *It is the basis for switching overvoltage oscillations, must be considered for insulation coordination*	Ferromagnetic resonance overvoltage and parameter resonance overvoltage (often found in distribution systems)	Caused by single-phase grounding faults in neutral isolated grounding systems	Energizing an unloaded line (including reclosing), De-energizing an unloaded line, De-energizing an unloaded transformer, Current chopping, System splitting overvoltage VFTO

Permitted switching overvoltage multiples (how many p.u.) for insulation coordination

Rated voltage level / kV	Neutral isolated grounding system		Neutral solidly grounding system				
	≤30 ~ 65	**110~ 145**	**110~ 220**	**330**	**500**	**750**	**1000**
Permitted phase to ground switching overvoltage multiple	**4.0**	**3.5**	**3.0**	**2.75**	**2.0**	**1.8**	**1.7**
The permitted phase to phase switching overvoltage is a multiple of the phase to ground switching overvoltage	**1.3 ~ 1.4**			**1.4 ~ 1.45**	**1.5**		

The magnitude of the switching overvoltage are expressed as multiples of the peak of maximum phase to ground voltage of the equipment at the point of overvoltage occurrence

For example, in a 500kV system, the permitted amplitude of the peak of maximum phase to ground voltage:

2.0 p.u. = (550×1.414/1.732) ×2.0 =898kV

The core of switching overvoltage generation is the oscillation of electromagnetic energy between capacitive and inductive elements in the circuit caused by sudden changes in the circuit parameters.

From the perspective of HV switchgear (circuit breaker), there are several situations where circuit parameters undergo sudden changes, including the following:

When the circuit breaker is opening or closing, which type of current will result a higher overvoltage?

Open: interruption of capacitive low current (cut off an unloaded line),
interruption of capacitive large current (cut off a capacitor banks),

Open: interruption of inductive low current (cut off no-load transformer, no-load motor), interruption of inductive large current (cut off fault current);

Close: closing of capacitive low current (closing no-load line),
closing capacitive large current (closing capacitor banks),

Close: closing inductive low current (closing no-load transformer, no-load motor),
closing inductive large current.

The core of switching overvoltage generation is the oscillation of electromagnetic energy between capacitive and inductive elements in the circuit caused by sudden changes in the circuit parameters.

From the perspective of HV switchgear (circuit breaker), there are several situations where circuit parameters undergo sudden changes, including the following:

When the circuit breaker is opening or closing, which type of current will result a higher overvoltage?

Open: interruption of capacitive low current (cut off an unloaded line),
interruption of capacitive large current (cut off a capacitor banks),

Open: interruption of inductive low current (cut off no-load transformer, no-load motor), interruption of inductive large current (cut off fault current);

Why is the overvoltage higher when interruption or closing low currents?

Close: closing of capacitive low current (closing no-load line),
closing capacitive large current (closing capacitor banks),

Close: closing inductive low current (closing no-load transformer, no-load motor),
closing inductive large current.

10.1 Opening and closing of high-voltage circuit breakers

The various connecting or disconnecting operations of power system are performed by HV switchgears.

Classification of different types of HV switchgears:

— **Circuit breaker:** capable of making/breaking large current during faults and load current in normal operation

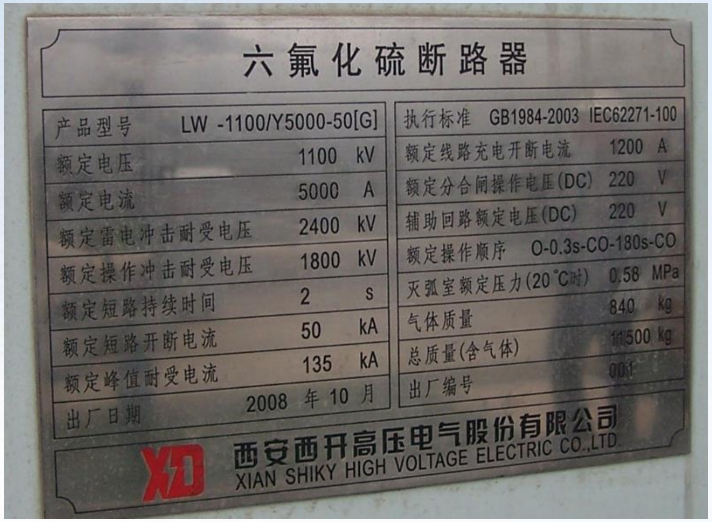
— **Load switch:** can only making/breaking load current in normal operation

— **Disconnector/Isolating switch:** When closed, it can carry normal current and specified short-circuit current. Without the need to open or close current. Isolating the live part during maintenance to ensure the safety of workers

— **Grounding switch:** Implement protective grounding for equipment or circuits under maintenance

— **Contactor:** capable of breaking, closing, and carrying normal current. Used in situations that require frequent operation and control

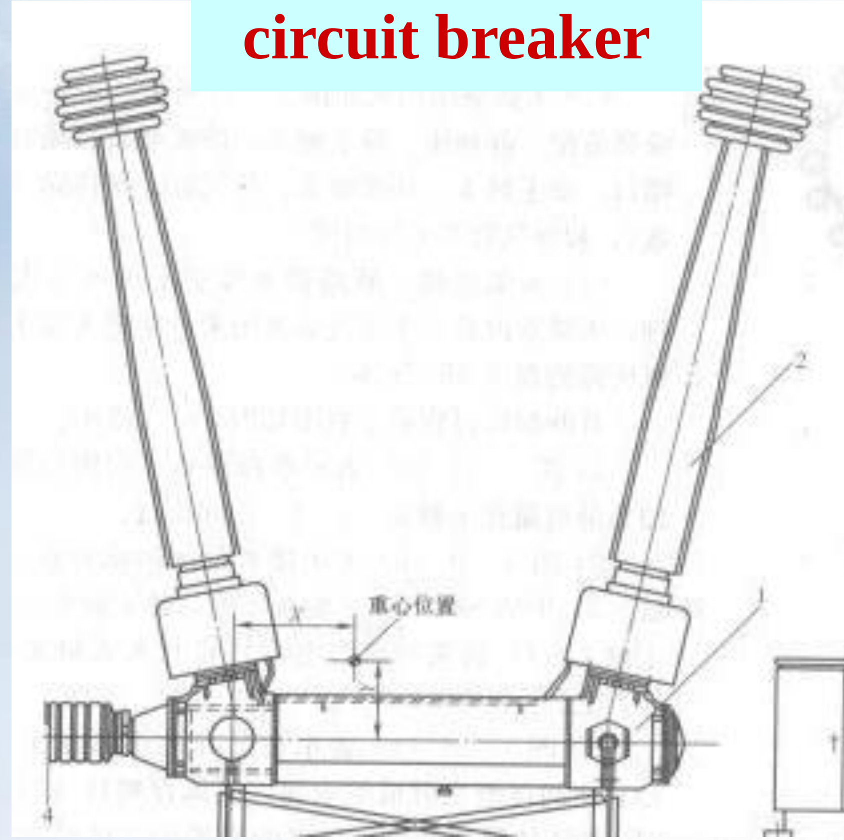
Ultra high voltage SF_6 circuit breaker

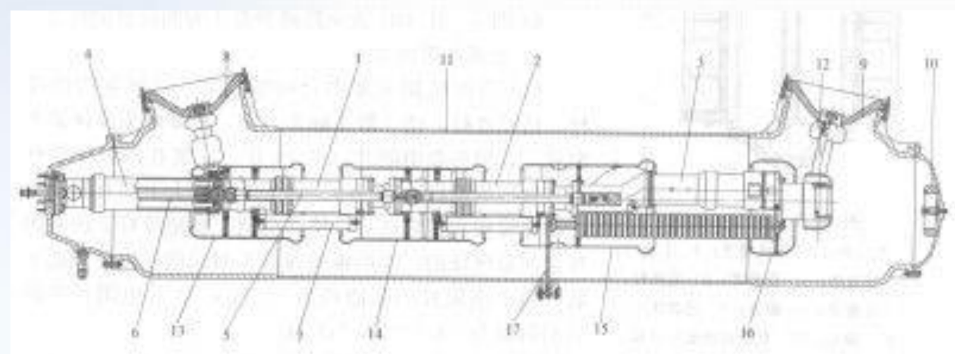


Live tank circuit breaker
(Column circuit breaker)

Dead tank circuit breaker

Dead tank circuit breaker





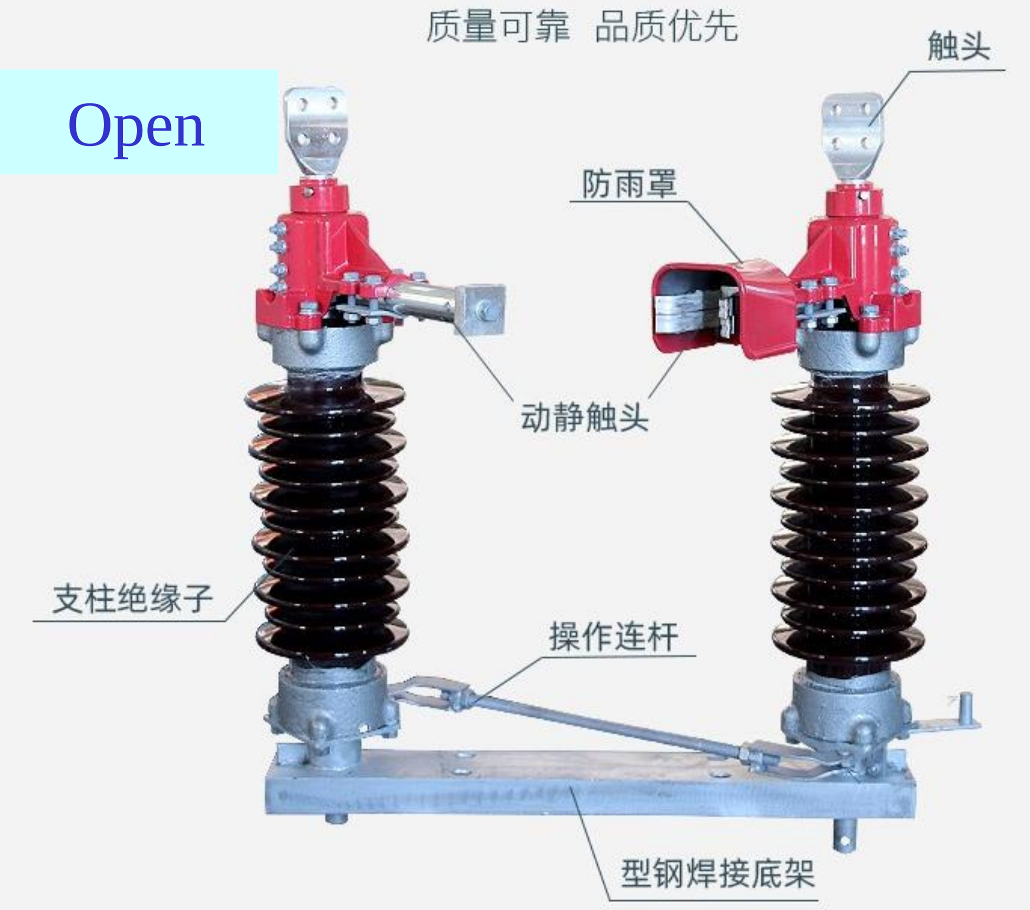
Close

Open

Isolating switch that cannot extinguish arcs,
become clearly visible disconnection points when opened

Isolating switch that cannot extinguish arcs,
become clearly visible disconnection points when opened

Open



Isolating switch that cannot extinguish arcs,
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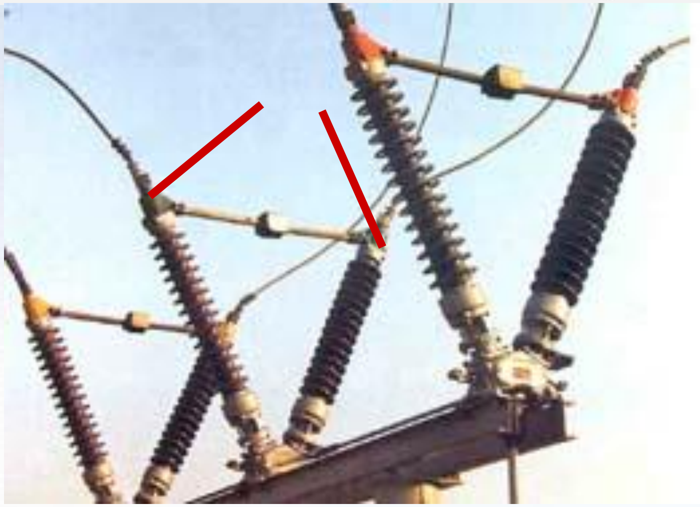


Close

Arc extinguishing is an important capability of HV circuit breakers when breaking or closing large currents.

According to arc extinguishing medium and extinguishing method, HV circuit breakers are divided into several categories: oil circuit breaker, sulfur hexafluoride (SF_6) circuit breaker, and vacuum circuit breaker, etc.

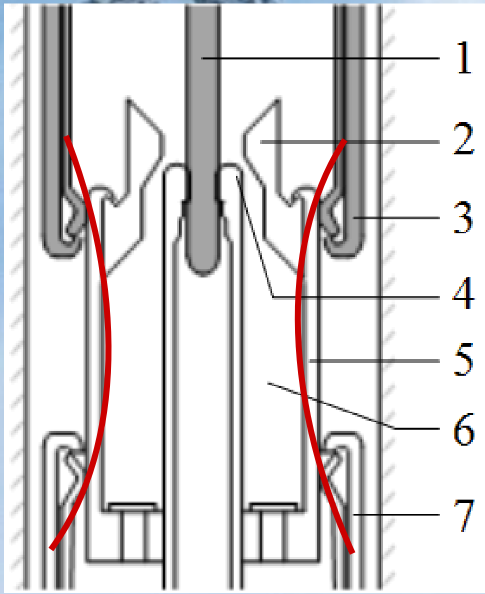
Vacuum circuit breaker: commonly used for voltage levels of 35kV and below, Vacuum circuit breakers for higher voltage level are under developing.

Oil circuit breaker: mostly used for 35kV-220kV (oil circuit breakers are flammable due to the presence of oil. Production of bulk-oil circuit breakers has long been stopped instead of low-oil circuit breaker)

SF_6 circuit breaker: commonly used for 220kV and above. Alternative gases for SF_6, are under developing to use less or no SF_6 (see textbook 2.5.7)

Circuit breaker close → circuit close

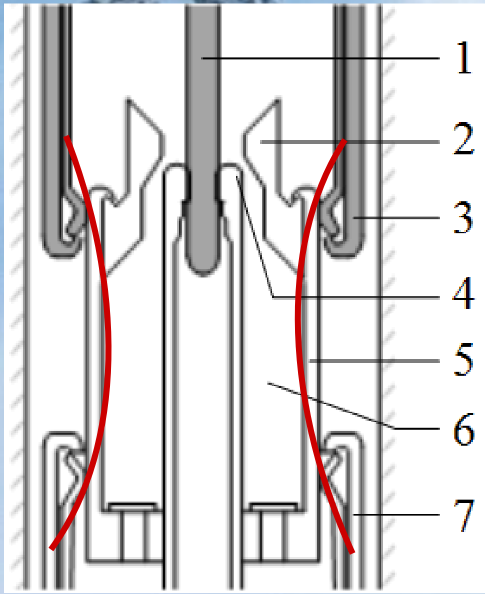
Circuit breaker open → circuit break, circuit open



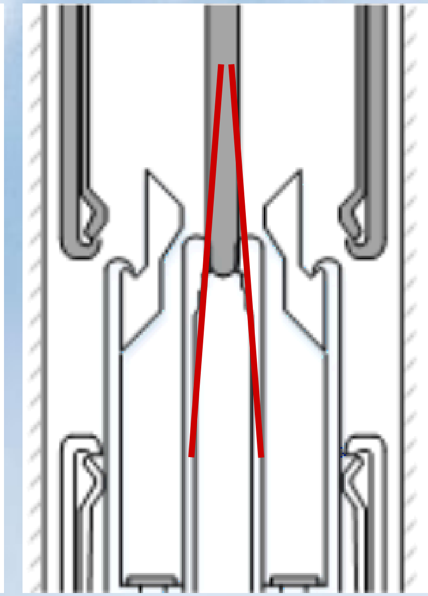
Closing position

Arc ignition and extinguishing process of circuit breaker opening

- When closing, the current mainly flows between the main contacts 5 and 3;



Closing position



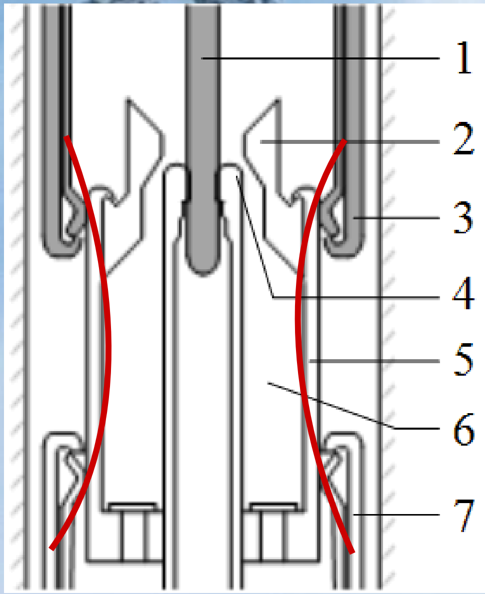
Main contact detached from contact

Static arc contact

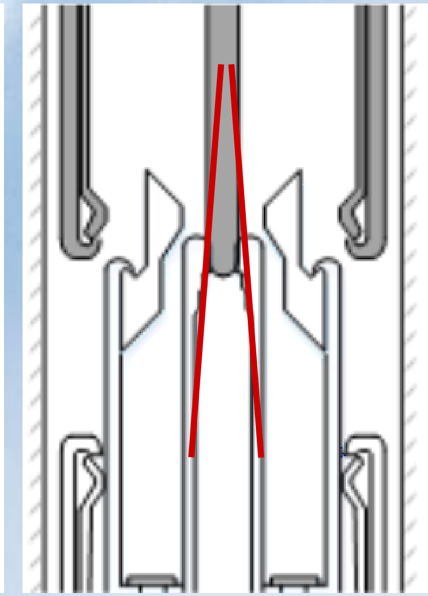
Moving arc contact

Arc ignition and extinguishing process of circuit breaker opening

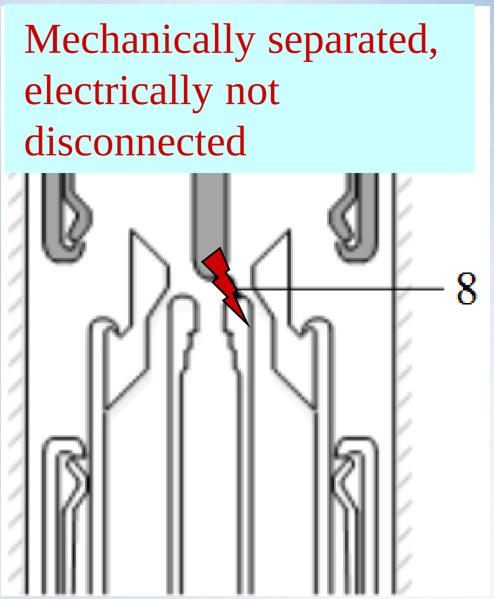
- When closing, the current mainly flows between the main contacts 5 and 3;
- When opening, 5 gradually disengages from 3 and the current flows between arc contacts 4 and 1;



Closing position



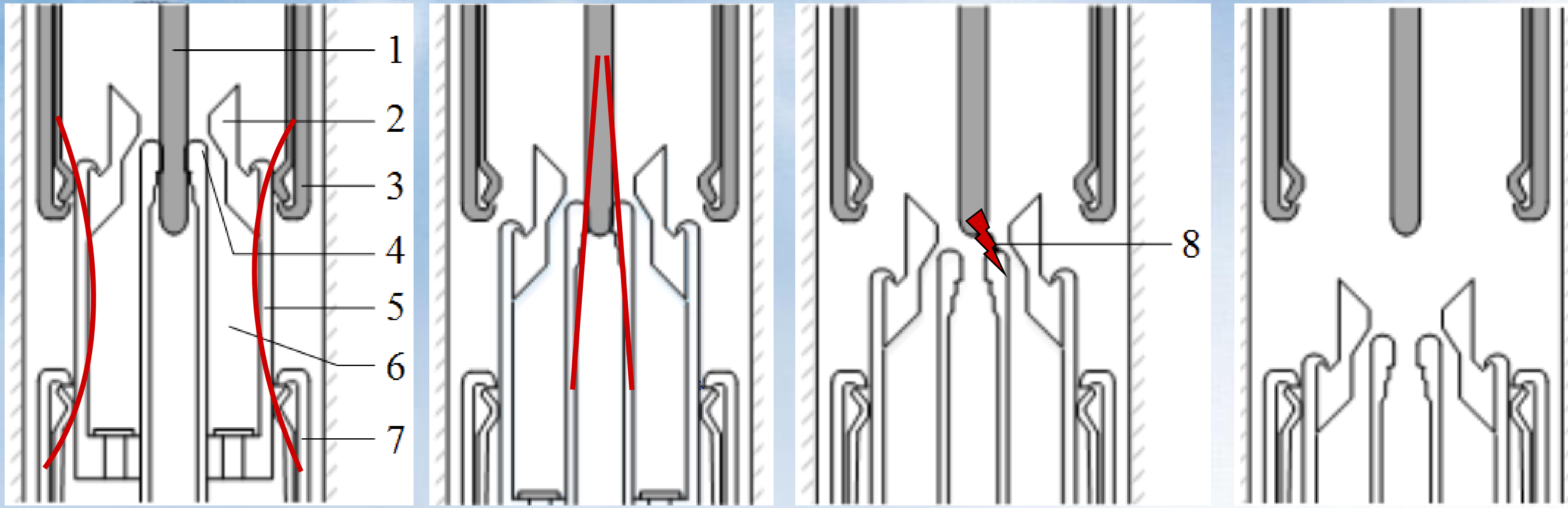
Main contact detached from contact



Arc ignition when contacts detached

Arc ignition and extinguishing process of circuit breaker opening

- When closing, the current mainly flows between the main contacts 5 and 3;
- When opening, 5 gradually disengages from 3 and the current flows between arc contacts 4 and 1;
- 4 continues to move downwards. When 4 and 1 first come out of contact, the distance between them is very small. If the current suddenly extinguish, a recovery overvoltage will be generated between them, which breakdown the gap and igniting an arc; At the same time, SF_6 sprays upwards from the center of 4

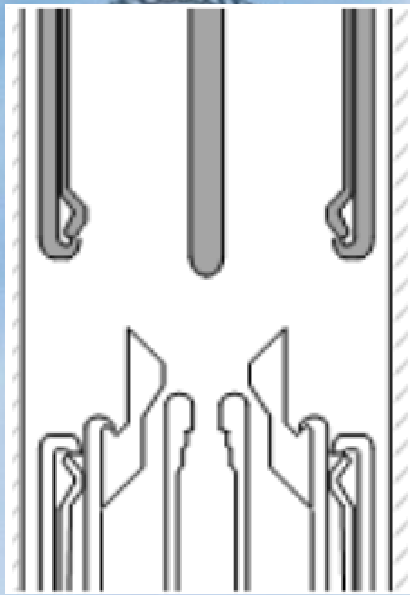


Closing position | Main contact detached from contact | Arc contact detachment generates arc | Arc extinguishing, circuit disconnected

Arc ignition and extinguishing process of circuit breaker opening

- When closing, the current mainly flows between the main contacts 5 and 3;
- When opening, 5 gradually disengages from 3 and the current flows between arc contacts 4 and 1;
- 4 continues to move downwards. When 4 and 1 first come out of contact, the distance between them is very small. If the current suddenly goes out, a recovery overvoltage will be generated between them, which breaks through the gap and generates an arc; At the same time, SF_6 sprays upwards from the center of 4
- As 4 continues to move downwards, the distance between the contacts increases, and when the arc current extinguishes at a certain zero crossing, the insulation strength between the contacts is already high enough, and arc cannot burn again after the current crosses zero. The arc is completely extinguished, the circuit is completely disconnected, and the breaking process ends.

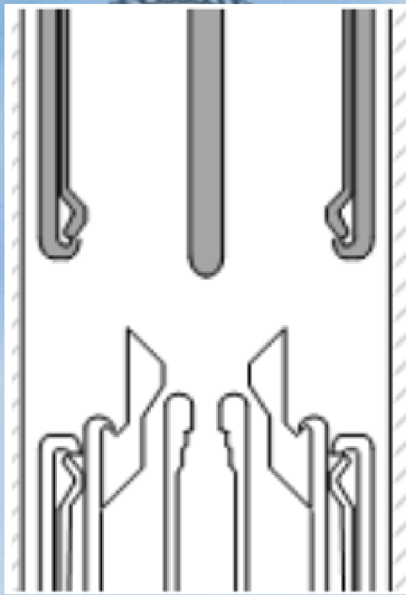
The arc extinguishing ability of circuit breakers is very important! Currently, the maximum is 63kA



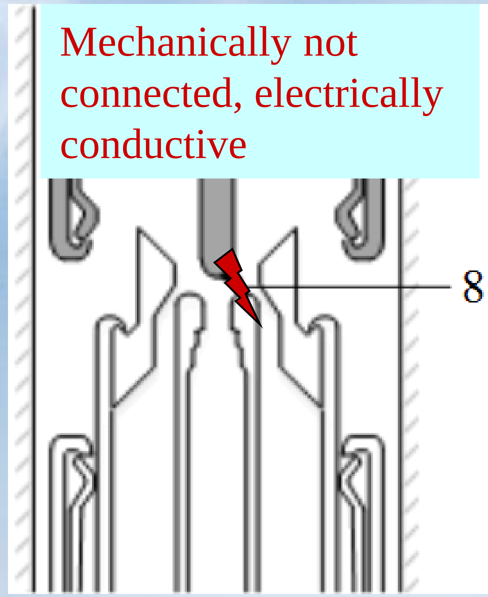
Opening position,
circuit disconnected

Arc ignition and extinguishing process of circuit breaker closing

- During closing process, contacts are first in a separate state and bear a higher voltage between them;



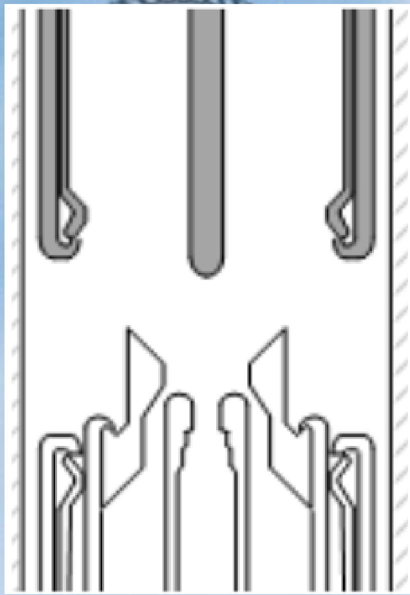
Opening position circuit disconnected



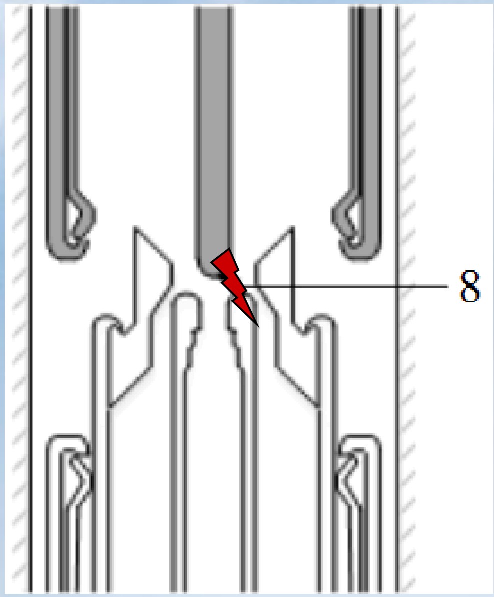
Arc ignition between arc contacts

Arc ignition and extinguishing process of circuit breaker closing

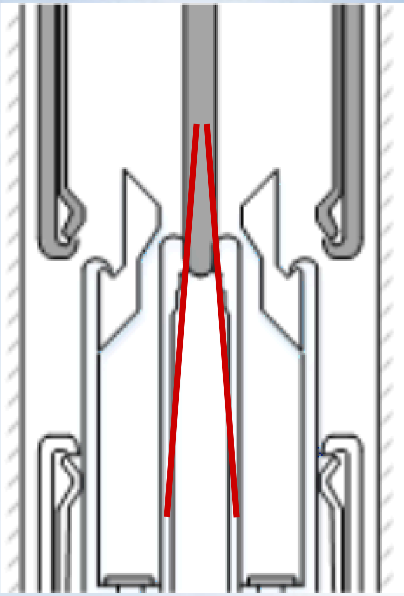
- During closing process, contacts are first in a separate state and bear a higher voltage between them;
- Once receiving closing signal, the moving contact moves upwards, insulation strength between the contacts decreases gradually. And there is always an alternating potential difference between the two contacts. The gap is breakdown when this potential difference is around a peak. Arc 8 ignition. This phenomenon is called pre breakdown;



Opening position circuit disconnected



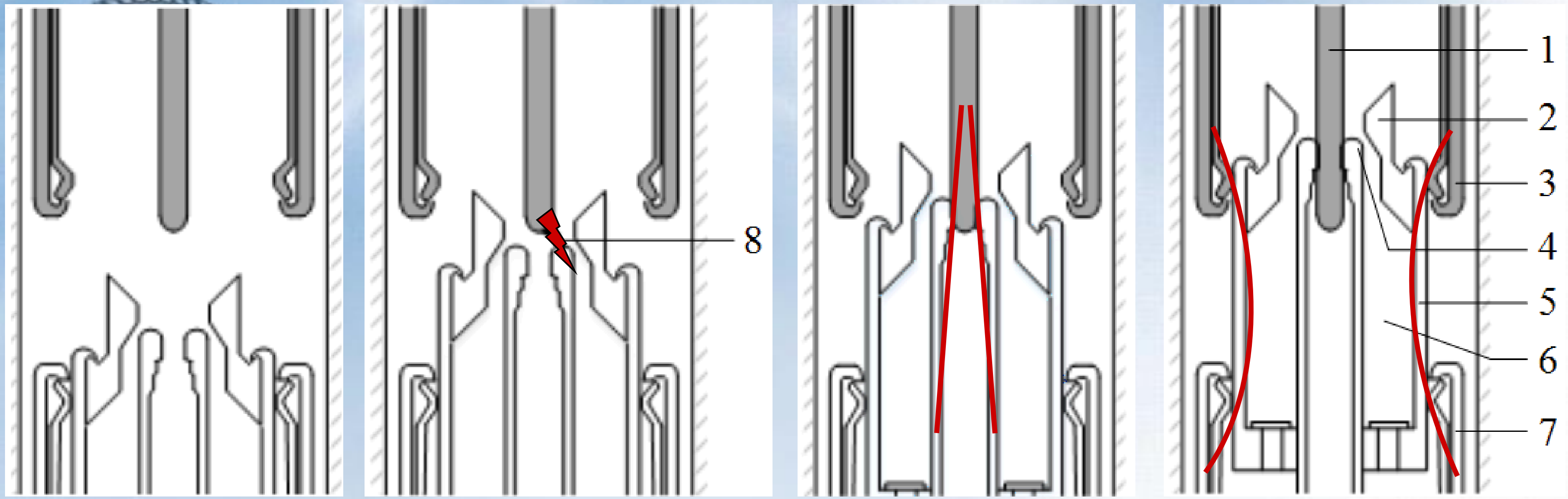
Arc ignition between arc contacts



Contacts connected,
arc is extinguished, current flows through the arc contacts

Arc ignition and extinguishing process of circuit breaker closing

- During closing process, contacts are first in a separate state and bear a higher voltage between them;
- Once receiving closing signal, the moving contact moves upwards, insulation strength between the contacts decreases gradually. And there is always an alternating potential difference between the two contacts. The gap is breakdown when this potential difference is around a peak. Arc 8 ignition. This phenomenon is called pre breakdown;
- The moving contact continues to move upwards, and the two contacts come into connection. The arc extinguishes and the circuit is completely connected;



Opening position circuit disconnected

Arc generated between arc contacts

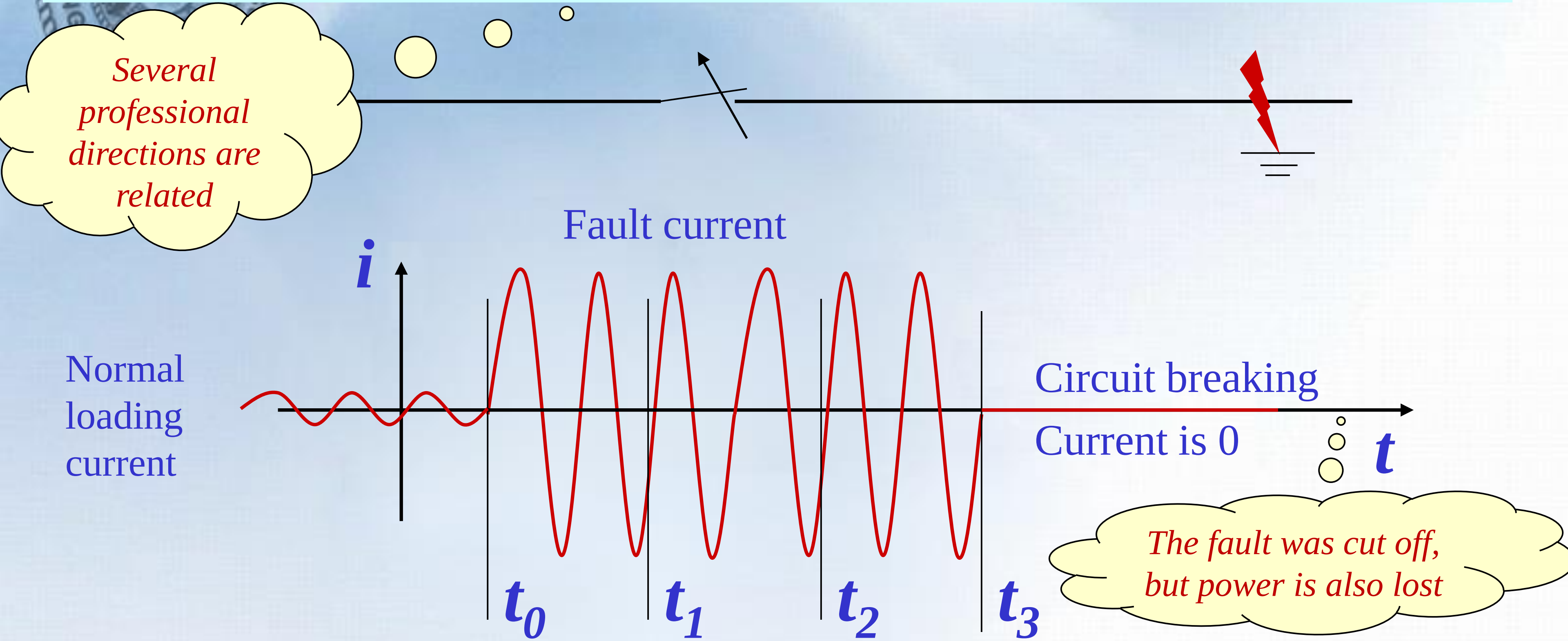
Contacts connected, arc is extinguished, current flows through the arc contacts

Main contact connected, and current flows normally through the main contact

Arc ignition and extinguishing process of circuit breaker closing

- During closing process, contacts are first in a separate state and bear a higher voltage between them;
- Once receiving closing signal, the moving contact moves upwards, insulation strength between the contacts decreases gradually. And there is always an alternating potential difference between the two contacts. The gap is breakdown when this potential difference is around a peak. Arc 8 ignition. This phenomenon is called pre breakdown;
- The moving contact continues to move upwards, and the two contacts come into connection. The arc extinguishes and the circuit is completely connected;
- The moving contact continues to move upwards, and the current flows between 5 and 1, ending the closing process.

The basic process of circuit breaker breaking the short circuit fault



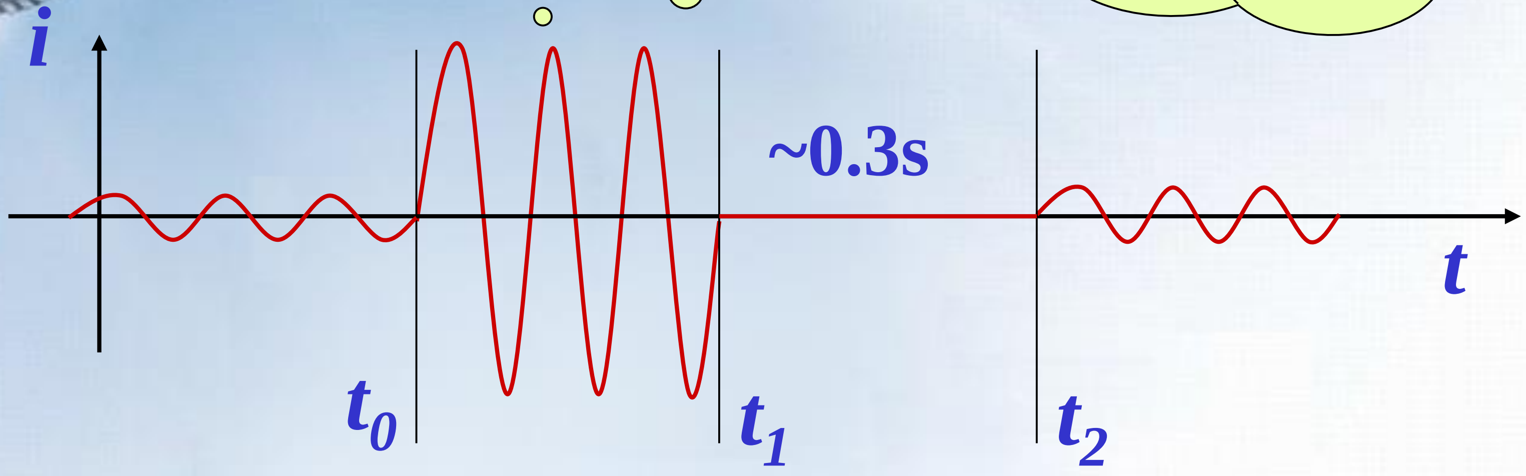
t_0 experiences a short circuit fault; t_1 circuit breaker receives an opening command;

t_2 contact begins to separate; t_3 when the current between the contacts crosses 0, the arc is extinguished and the opening is successful.

The arc extinguishing ability of circuit breakers is very important! Currently, the maximum is 63kA

Automatic reclosing of circuit breaker (successful reclosing)

Imagine: Surge arrester is required quickly cut off the power-flow current……



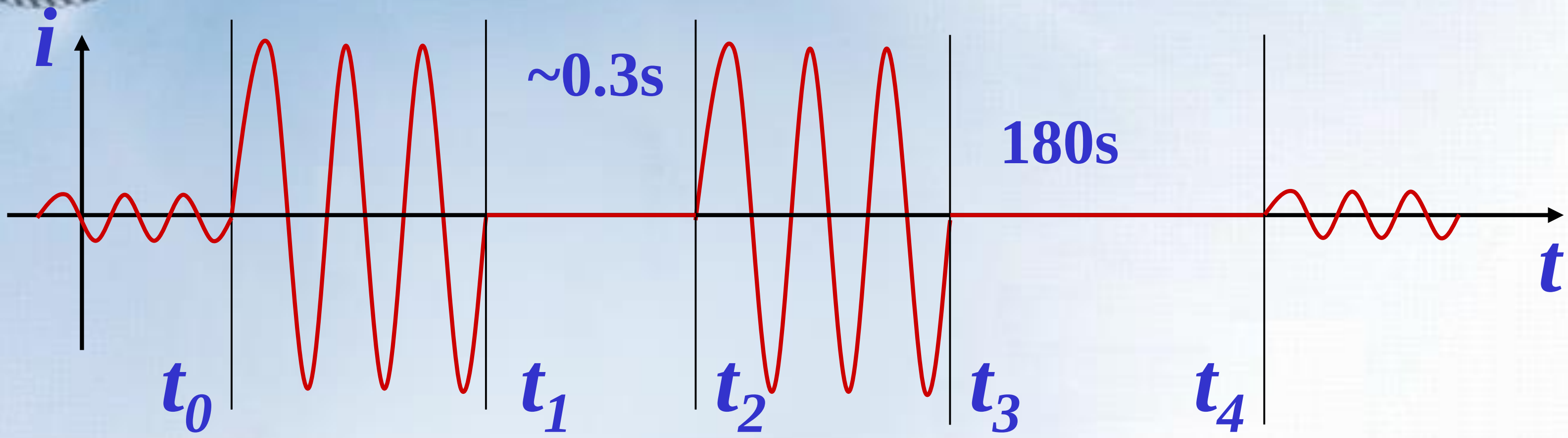
t_0 experiences a short circuit fault; t_1 circuit breaker extinguishing arc;

After about **0.3s dead time**, t_2 will automatically reclose.

If the fault disappears, normal loading current will be restored and reclosing is successful.

To avoid power outages caused by various momentary faults, automatic reclosing is necessary

Automatic reclosing of circuit breaker
(reclosing fail, but successful forced power delivery)



t_0 experiences a short circuit fault; t_1 circuit breaker extinguishing arc; About 0.3s later, t_2 automatically reclose. If the fault still persists and reclosing fail, it can only be re-opened; t_3 opens again to extinguish the arc. After 180 seconds, t_4 is forcibly transmitted. If the fault disappears, the forced transmission is successful and the circuit returns to normal.

- If there is still a fault during forced transmission, it must be opened again immediatly and will no longer reclose. Diagnosed as a permanent fault, immediately identify the fault point and conduct maintenance as soon as possible.

The core of switching overvoltage generation is the oscillation of electromagnetic energy between capacitive and inductive elements in the circuit caused by sudden changes in the circuit parameters.

From the perspective of HV switchgear (circuit breaker), there are several situations where circuit parameters undergo sudden changes, including:

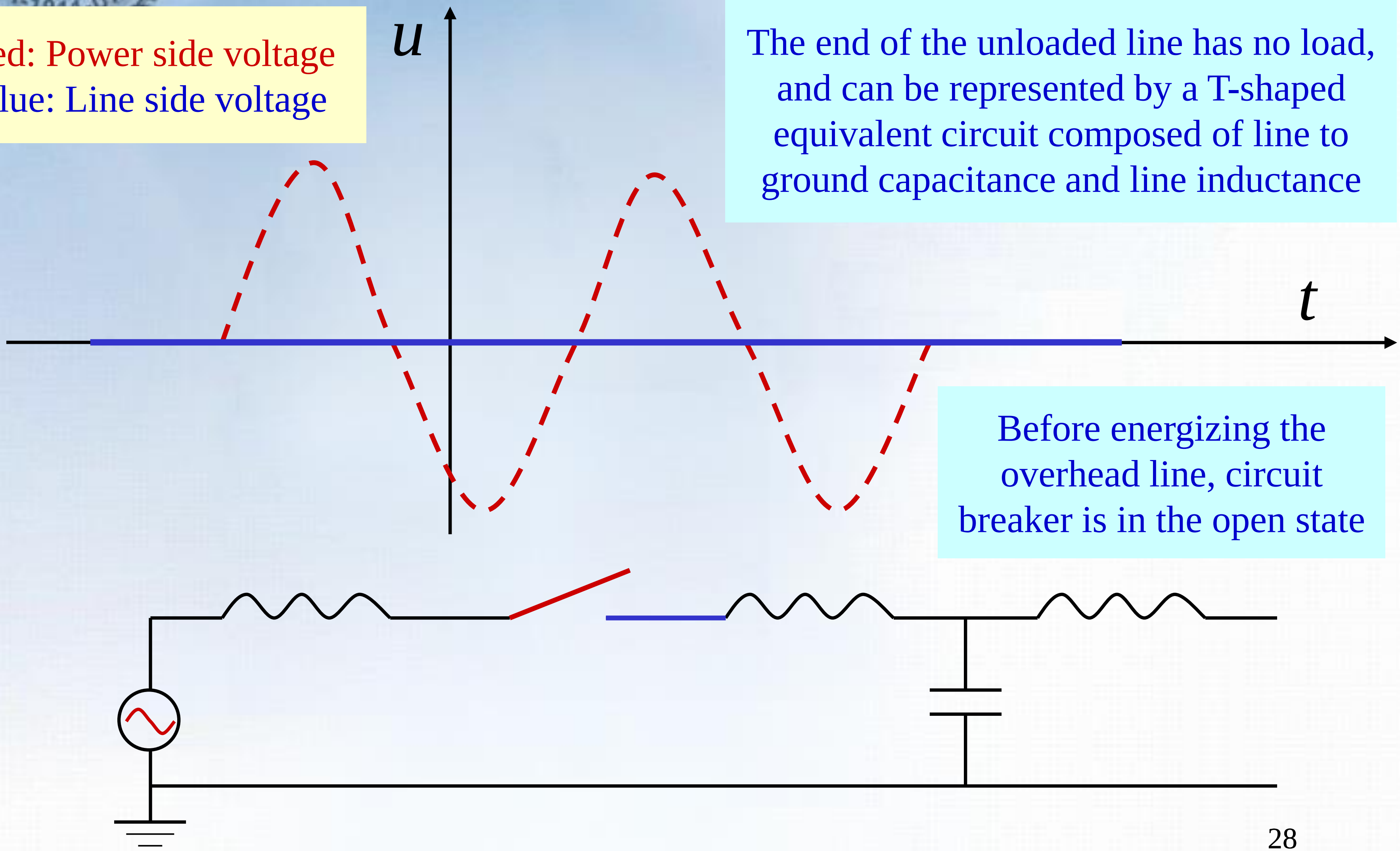
	Capacitive load		Inductive load	
Breaking (opening)	Capacitive low current (cut off no-load line)	Capacitive high current	Inductive low current	Inductive high current
Making (closing)	Capacitive low current (close no-load line)	Capacitive high current	Inductive low current	Inductive high current
Example	no-load line	capacitor banks	no-load transformer and no-load motor	the fault current

How does overvoltage occur when there is a low capacitive current in the opening/closing process? What is the relation between overvoltage and the opening/closing of circuit breaker?

10.2 Overvoltage by energizing an unloaded line

Red: Power side voltage
Blue: Line side voltage

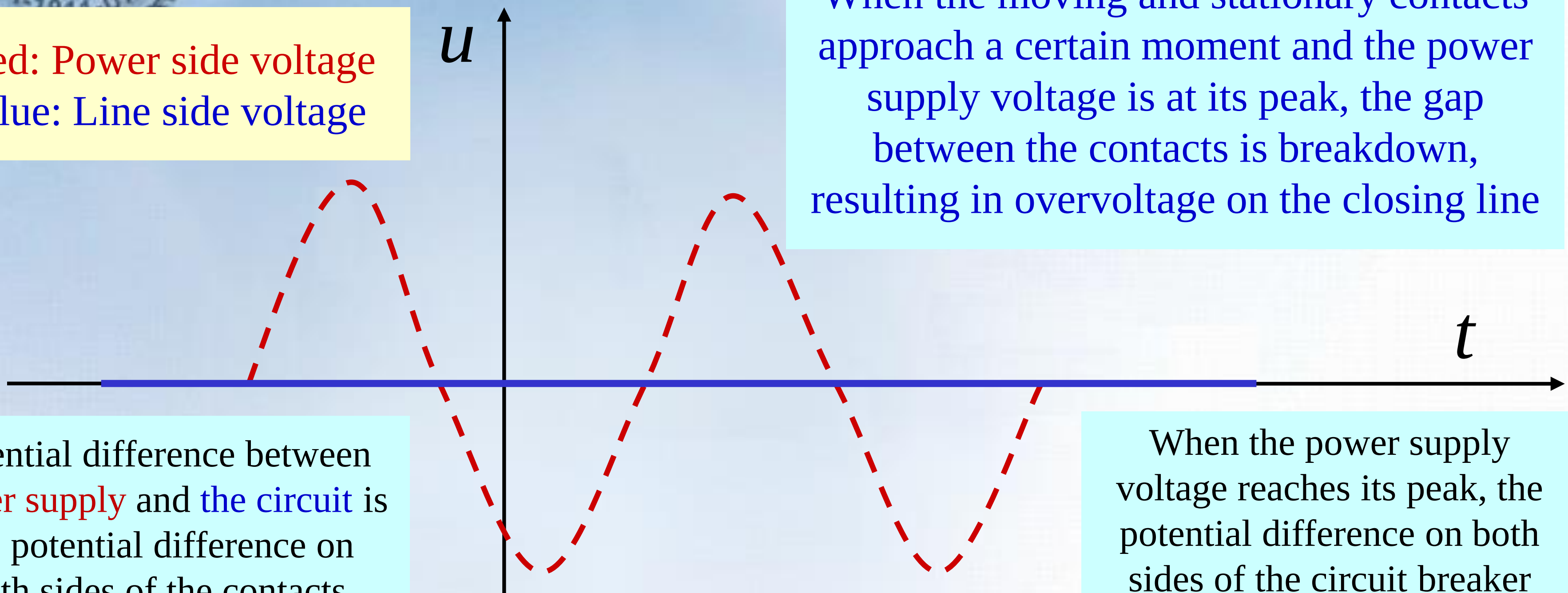
The end of the unloaded line has no load, and can be represented by a T-shaped equivalent circuit composed of line to ground capacitance and line inductance



Before energizing the overhead line, circuit breaker is in the open state

10.2 Overvoltage by energizing an unloaded line

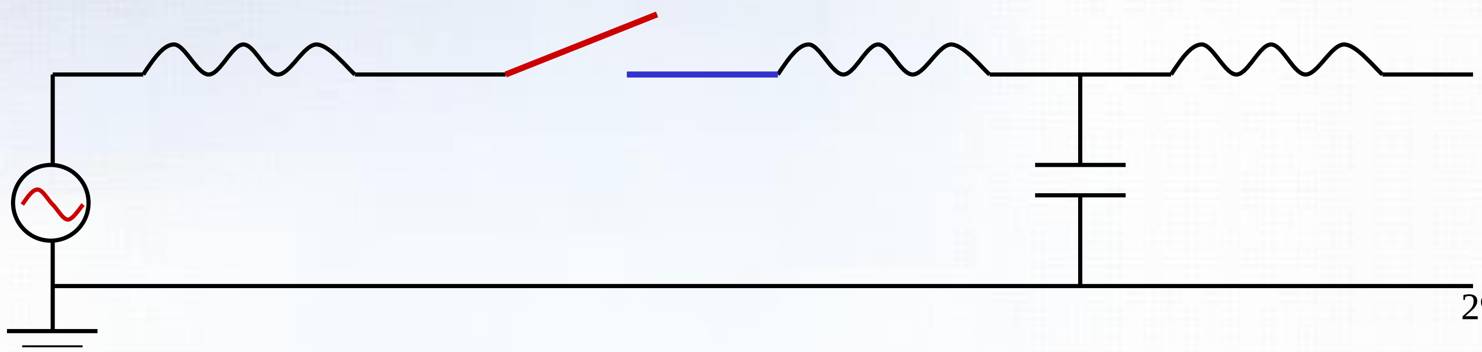
Red: Power side voltage
Blue: Line side voltage



When the moving and stationary contacts approach a certain moment and the power supply voltage is at its peak, the gap between the contacts is breakdown, resulting in overvoltage on the closing line

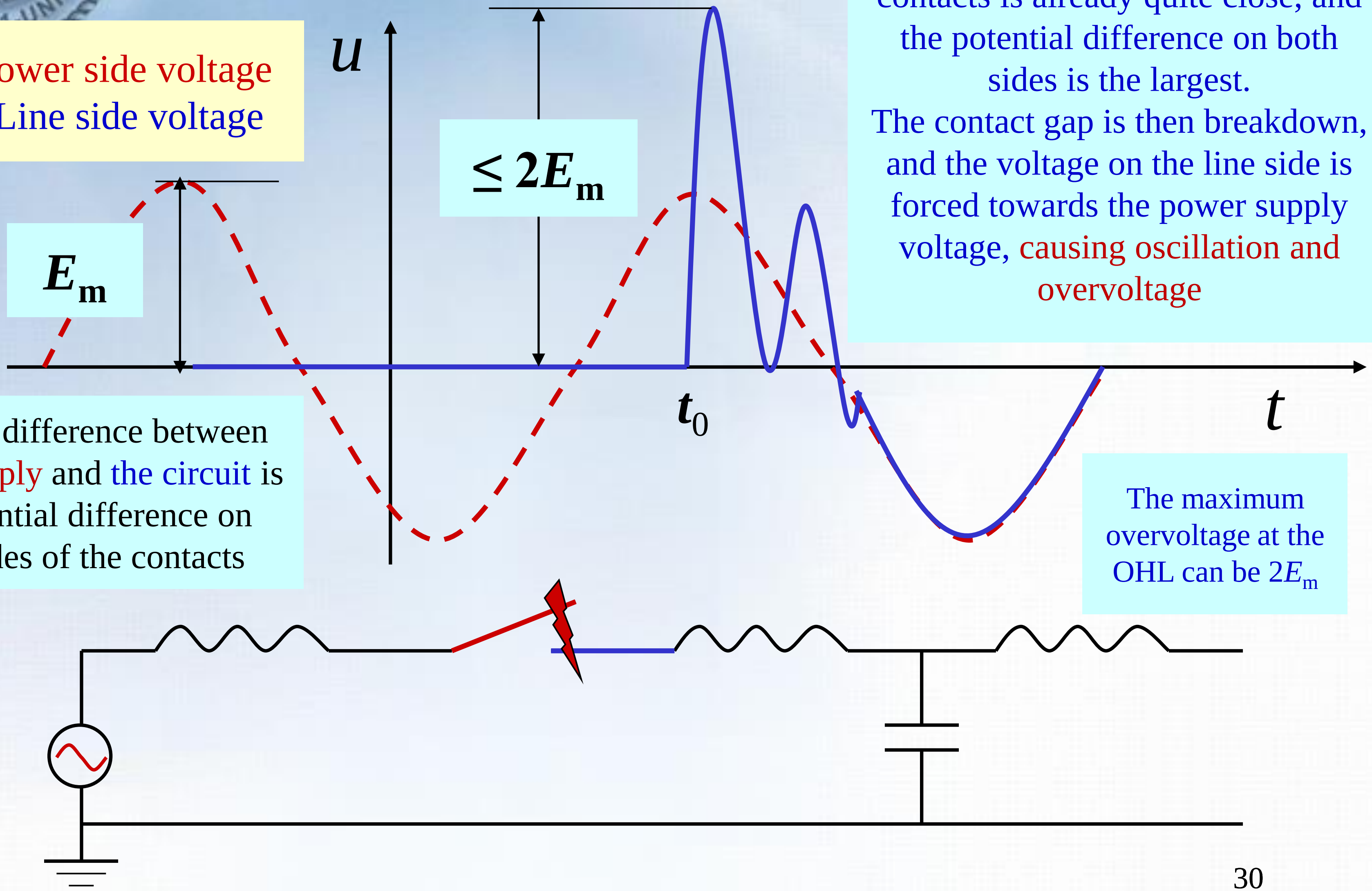
Potential difference between power supply and the circuit is the potential difference on both sides of the contacts

When the power supply voltage reaches its peak, the potential difference on both sides of the circuit breaker contact reaches the maximum



Will the overvoltage of energizing a loaded line be higher or lower?

Red: Power side voltage
Blue: Line side voltage



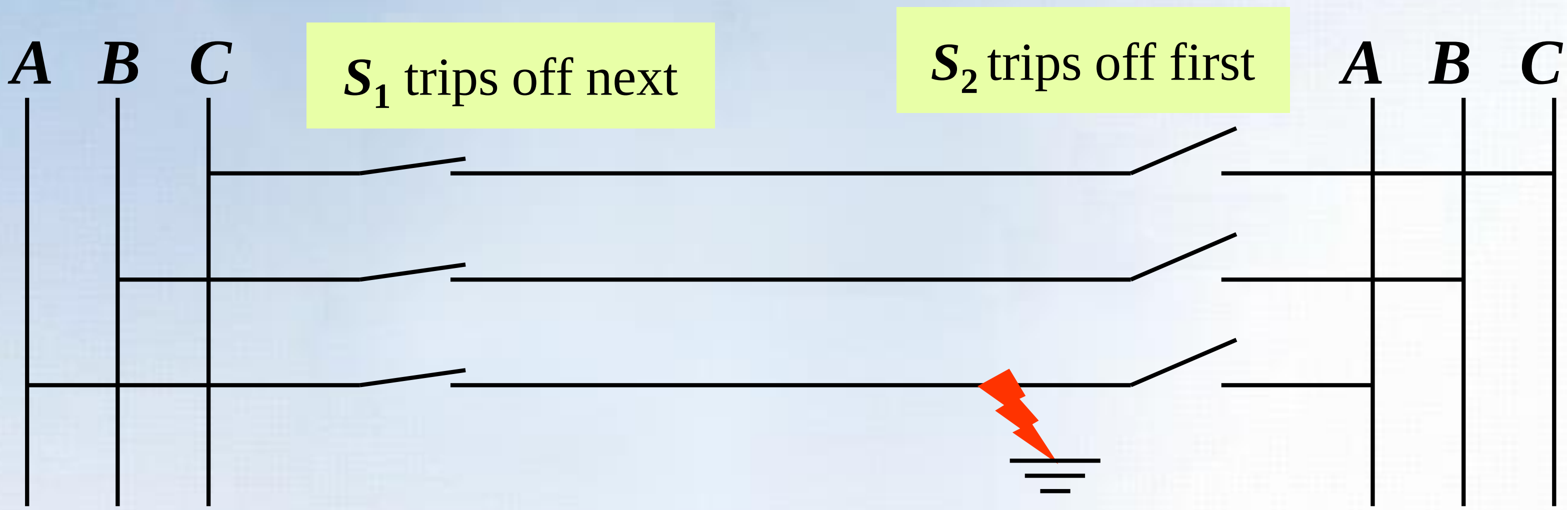
At time t_0, the distance between the contacts is already quite close, and the potential difference on both sides is the largest.
The contact gap is then breakdown, and the voltage on the line side is forced towards the power supply voltage, causing oscillation and overvoltage

Potential difference between power supply and the circuit is the potential difference on both sides of the contacts

The maximum overvoltage at the OHL can be $2E_m$

Reclosing overvoltage by three-phase automatic reclosing

Basic situation: Phase A flashover to ground, requires both sides of circuits trip off and cut-off the power supply on both sides, in order to extinguish the fault arc at the grounding point.
After the fault disappears, circuit breakers at both sides will automatically reclose to supply the power (many grounding faults in OHLs are instantaneous faults such as lightning strikes).

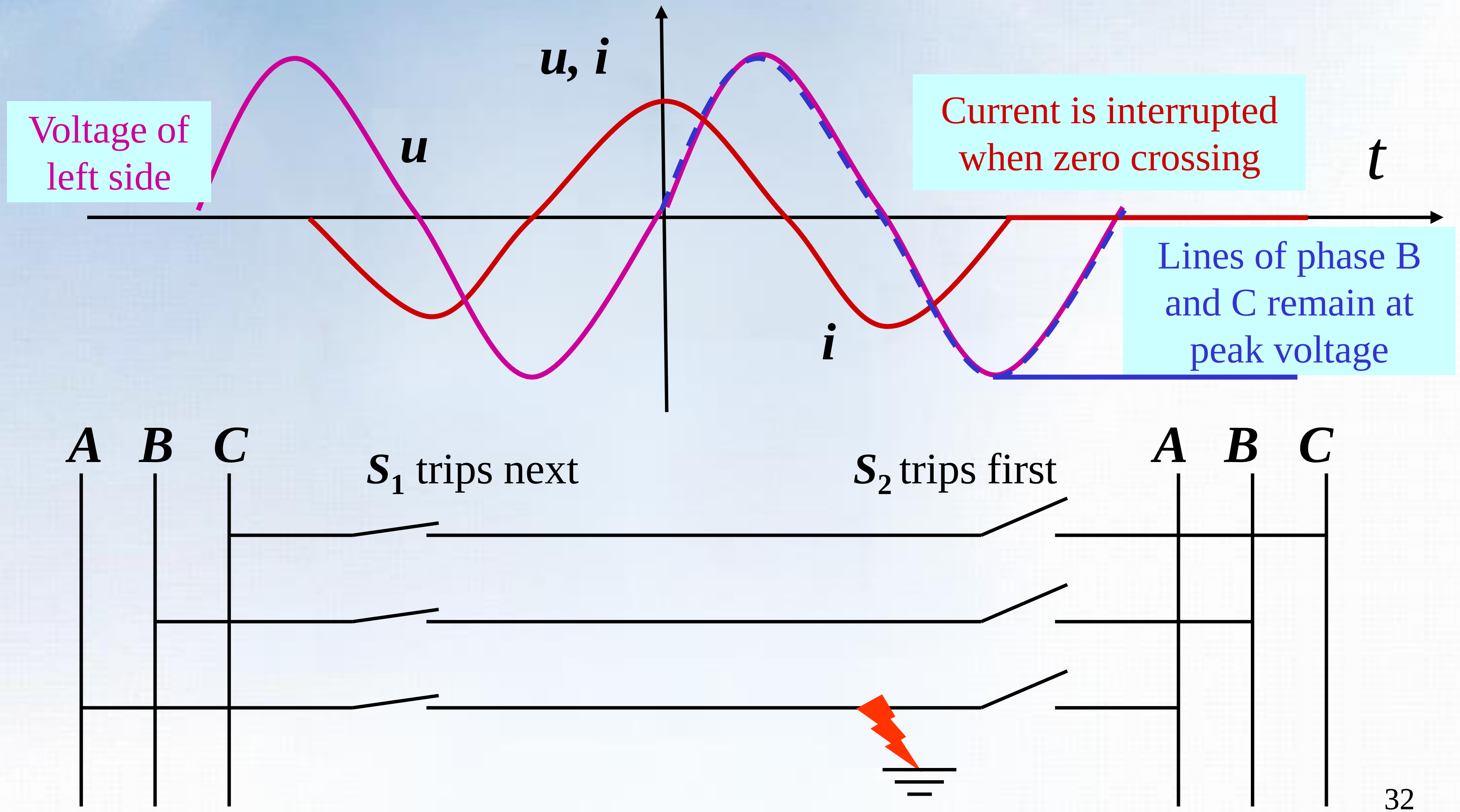


Process: Phase A flashover to the ground, the proximal circuit breaker S_2 detects a fault signal first and trips off three phase first;

When the remote S_1 trips off, the normal phases B and C (without grounding fault) cut off the no-load line, that means interrupt a small capacitive current.

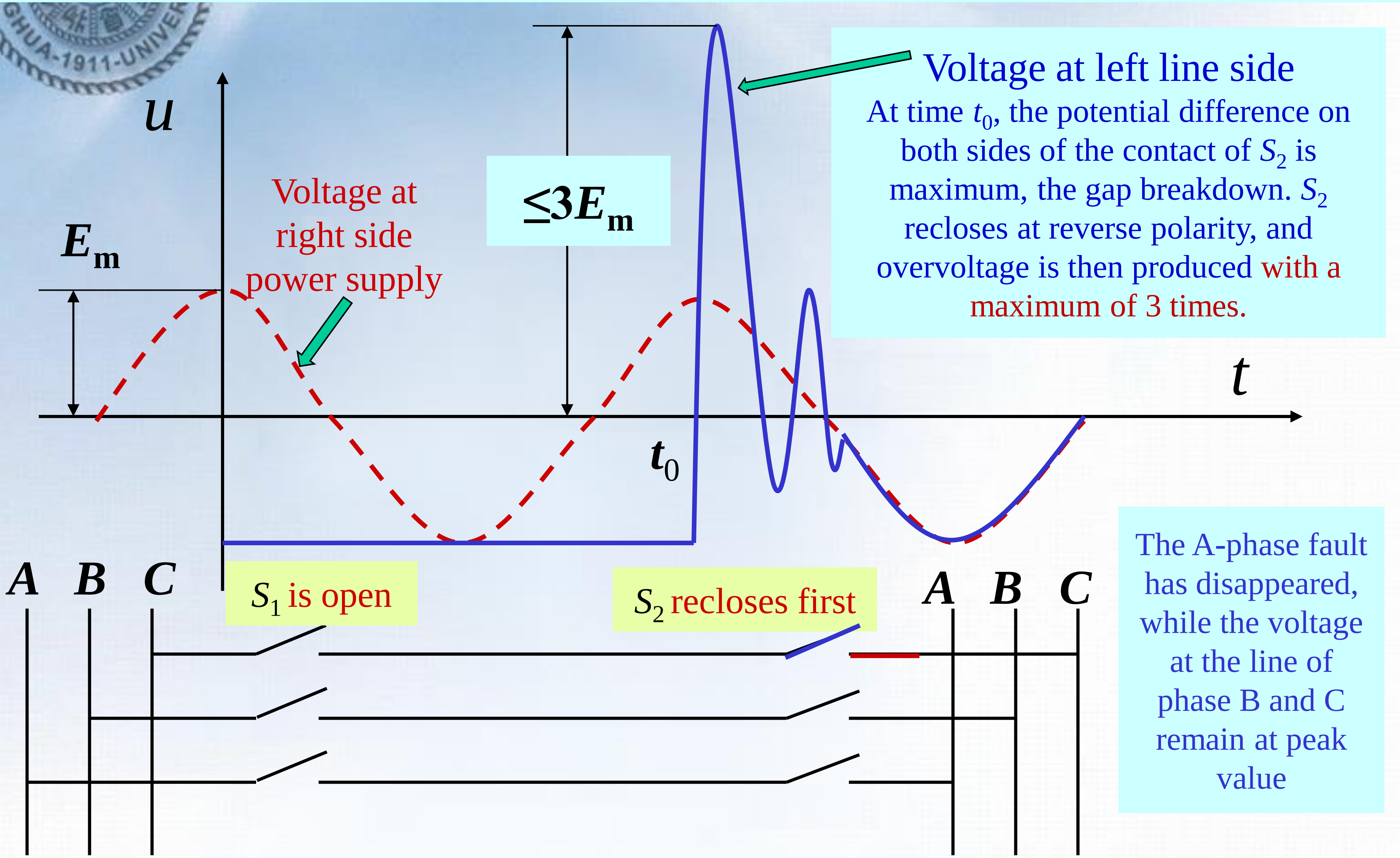
When the remote S_1 trips off next, the arc of S_1 extinguished when current of phase B and C passed zero, but the capacitive voltage lagged behind the current by 90° .

Therefore, after S_1 trips off, the line of phase B and C remained at peak voltage. When S_2 automatically recloses, there will be a reclosing overvoltage at phase B and C.



Reclosing overvoltage by three-phase automatic reclosing

If phase A flashover to the ground, S_2 trips off first and S_1 trips off next. There is residual peak voltage in the line of phase B and C. when S_2 recloses first, S_2 recloses as reverse polarity closing

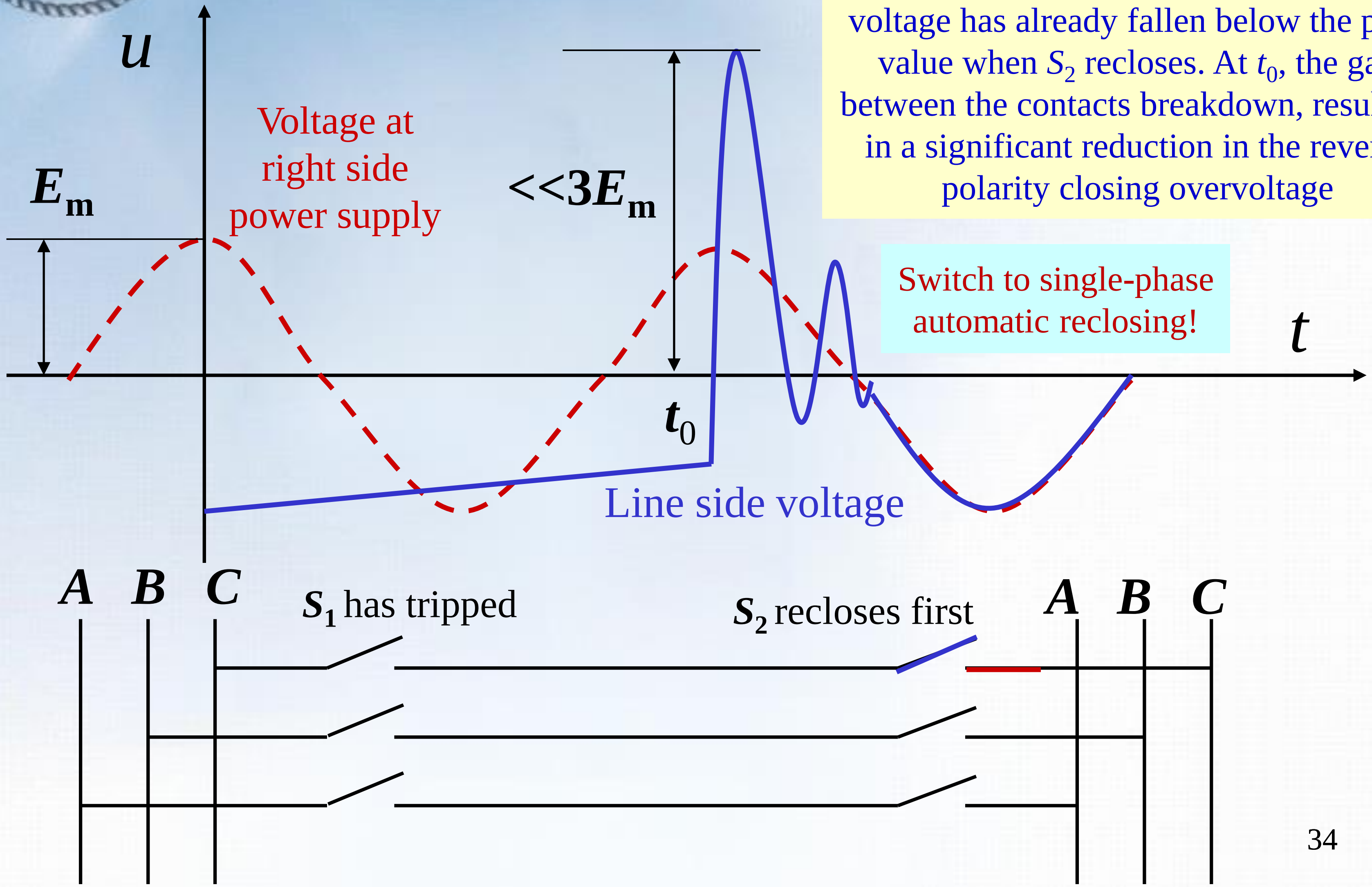


Reclosing overvoltage by three-phase automatic reclosing

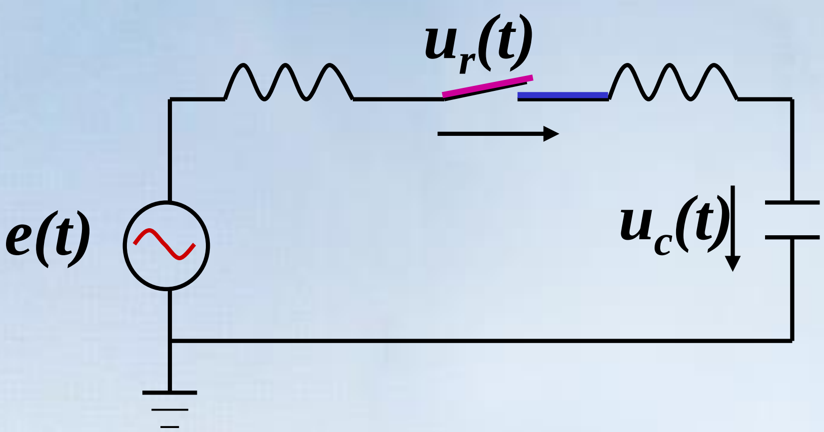
If phase A flashover to the ground, S_2 trips off first and S_1 trips off next. There is residual peak voltage in the line of phase B and C. when S_2 recloses first, S_2 recloses as reverse polarity closing

If there is a leakage in the line, the line voltage has already fallen below the peak value when S_2 recloses. At t_0, the gap between the contacts breakdown, resulting in a significant reduction in the reverse polarity closing overvoltage

Switch to single-phase automatic reclosing!



10.3 Overvoltage by de-energizing an unloaded line



The unloaded line can be represented by a T-shaped equivalent circuit composed of line to ground capacitance and line inductance (omitting the inductance on the right side)

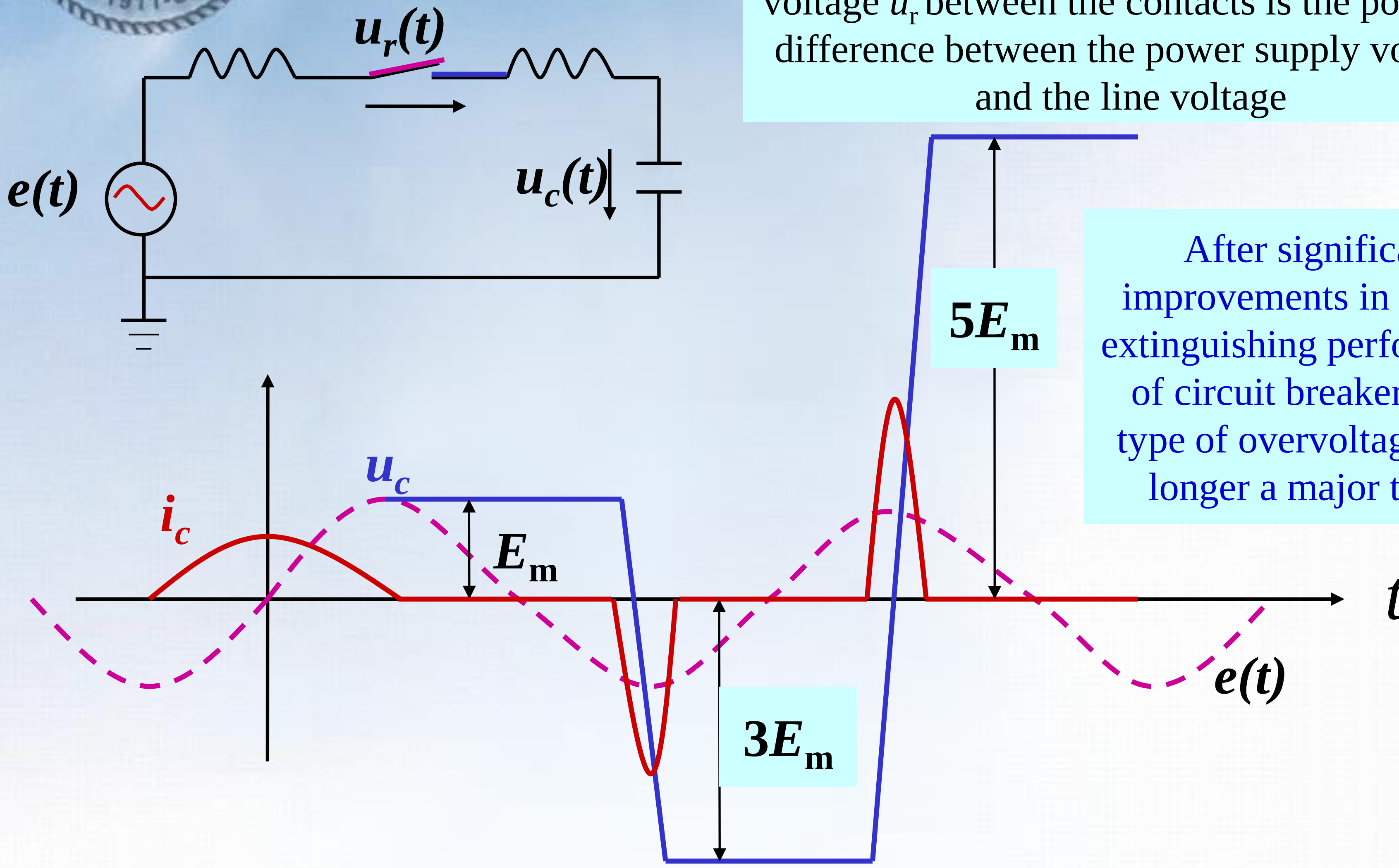
The current of the unloaded line is a small capacitive current, with the current leading the voltage by 90°

Red: Power source side voltage
Blue: Line side voltage

Before switch-off (de-energizing) the unloaded line, the circuit breaker is in a closed state.
Once the contacts are opened, the recovery voltage u_r between the contacts is the potential difference between the power supply voltage and the line voltage

10.3 Overvoltage by de-energizing an unloaded line

Once the contacts are opened, the recovery voltage u_r between the contacts is the potential difference between the power supply voltage and the line voltage



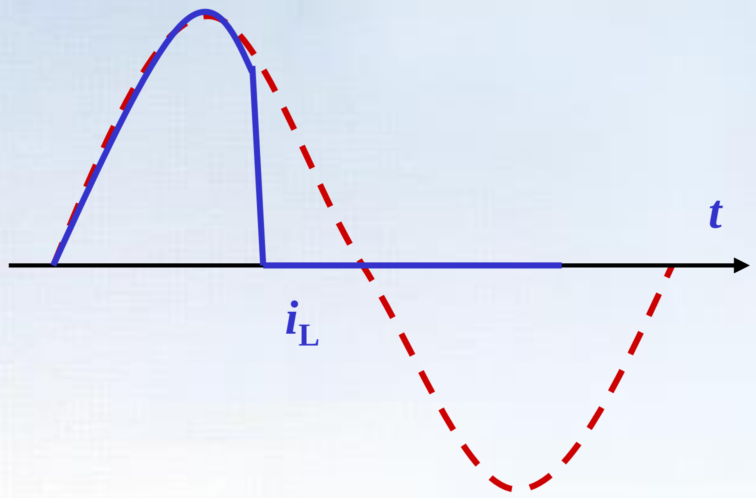
After significant improvements in the arc extinguishing performance of circuit breakers, this type of overvoltage is no longer a major threat

The above energizing and de-energizing unloaded line are making or breaking a capacitive small currents, produced a switching overvoltage

When investing the capacitor banks, there is also a problem of closing inrush current with high capacitive current, produced an overcurrent

When cutting off the no-load transformer, it also interrupts the inductive small current, which produced a switching overvoltage

When using a vacuum circuit breaker to cut off an induction motor, it cuts off the inductive small current, produced a current chopping overvoltage

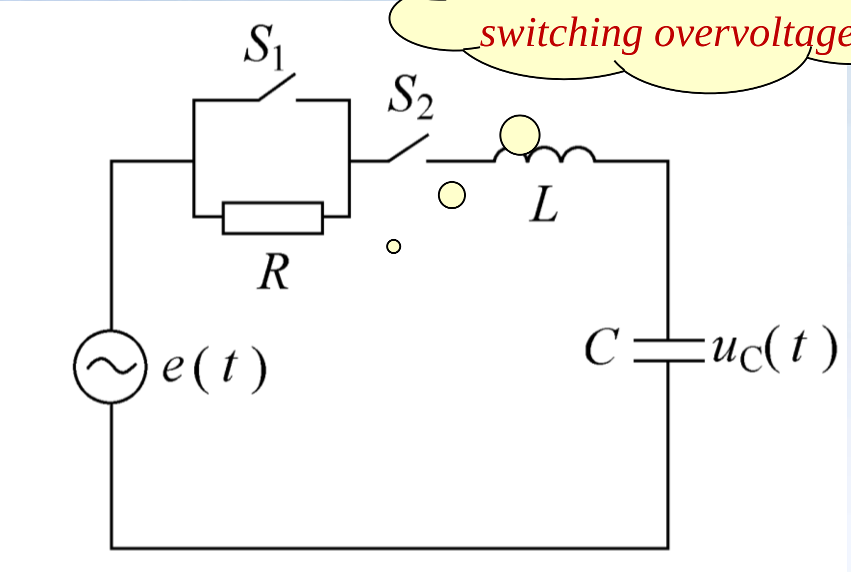


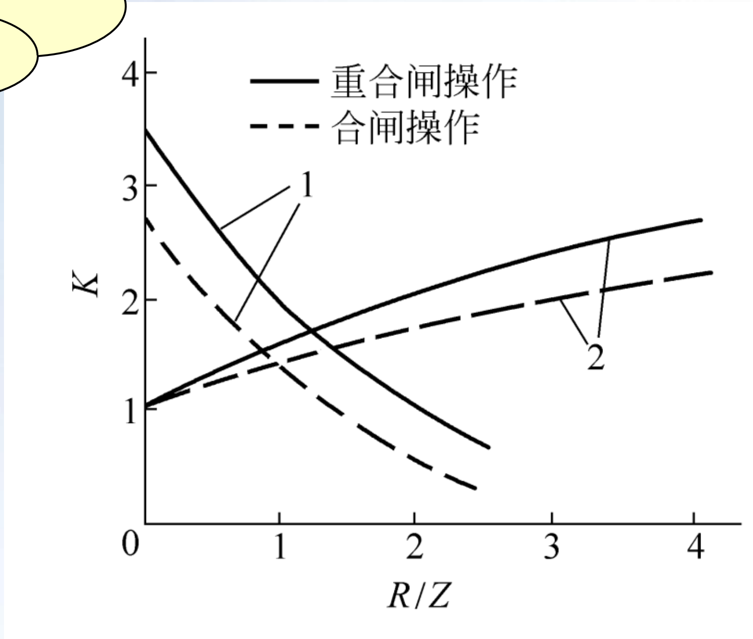
The vacuum circuit breaker has a strong ability to extinguish arc.
When cutting off the inductive small current, the arc is forcibly extinguished before the current passes zero, and the di_L/dt is too high, resulting in a current chopping overvoltage on the inductive equipment such as motor

10.5 Measures to limit switching overvoltage

- Firstly, use shunt reactors to limit temporary power frequency overvoltage.
- Utilize parallel resistors to limit switching overvoltage, with lightning arresters as backup.
- Use lightning arresters to limit the overvoltage of cut-off unloaded transformer.

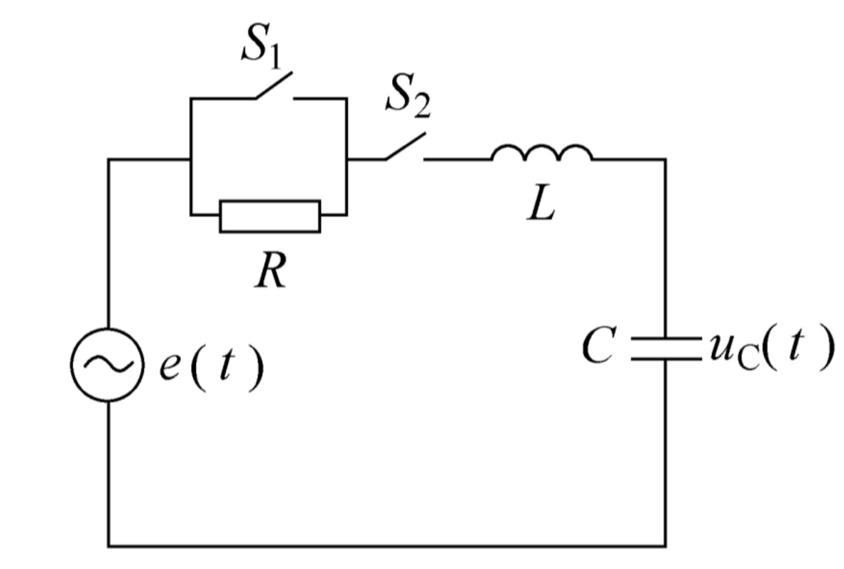
How can parallel resistors limit switching overvoltage?

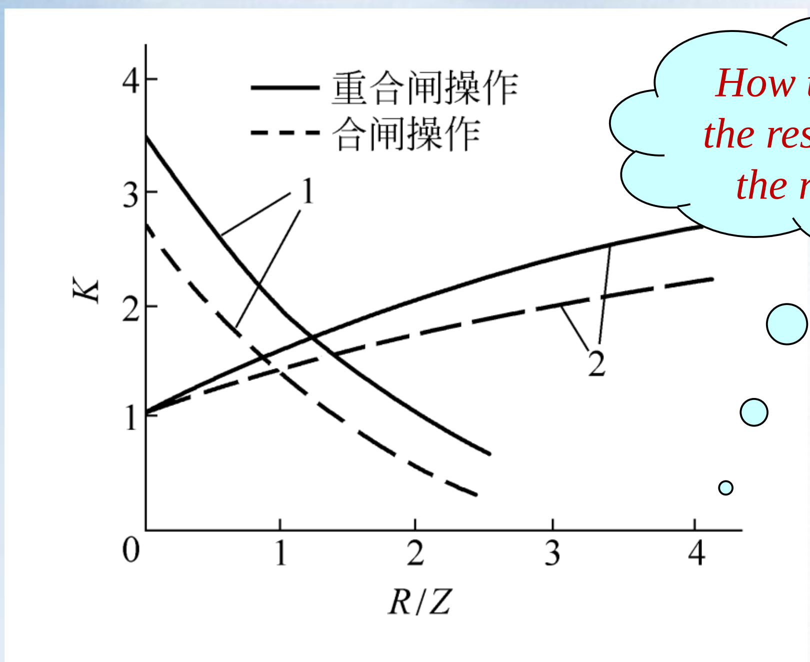




Using parallel resistors to limit switching

Using parallel resistors to limit switching overvoltage





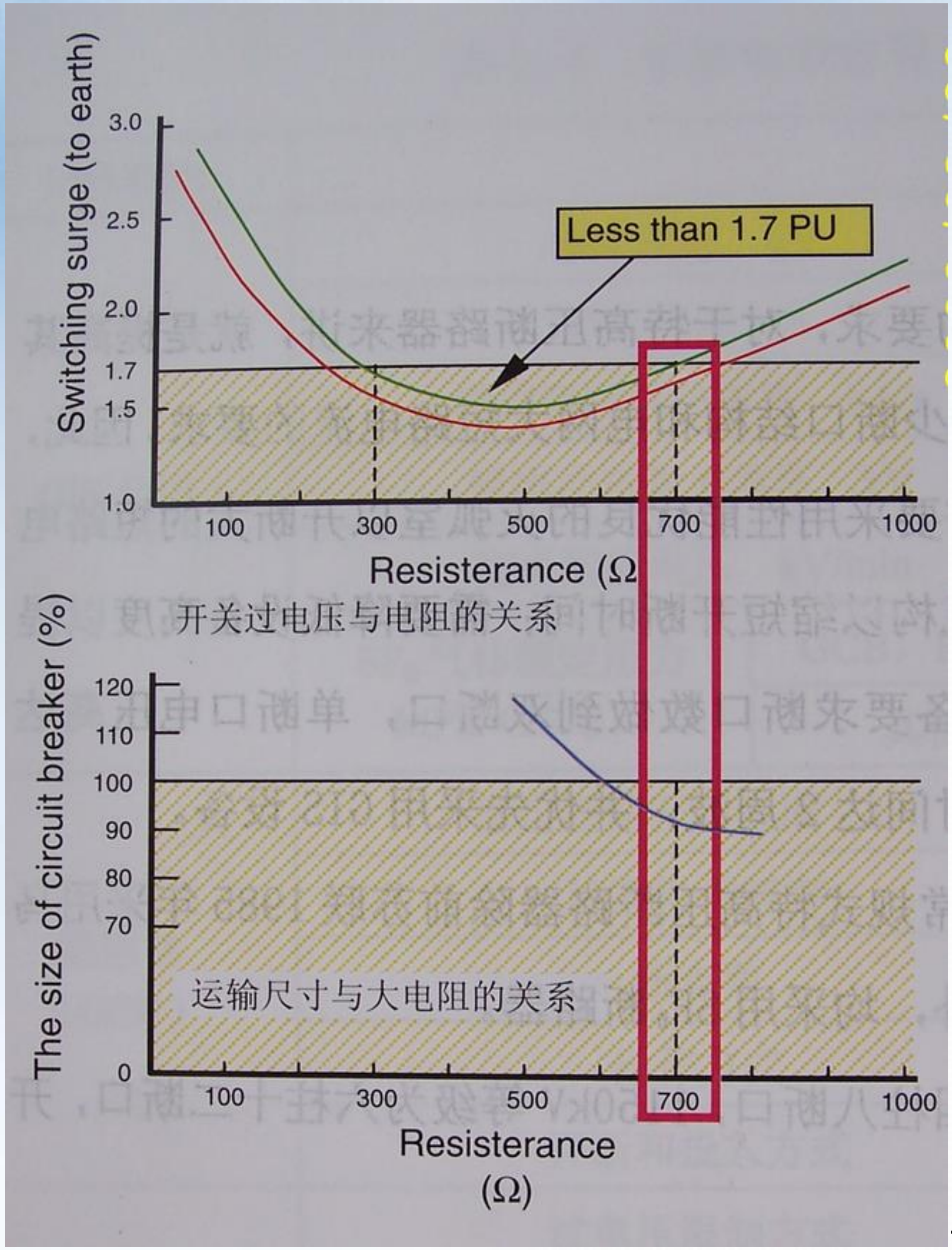
How to choose the resistance of the resistor?

When closing, close the S_2 first, connect the parallel resistor R into the series circuit, and then close S_1 after 1.5-2 cycles;

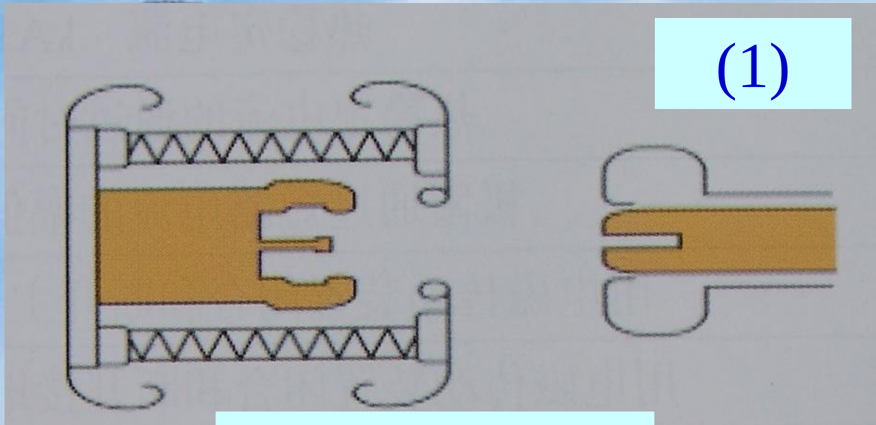
When opening, open the S_1 first, connect the parallel resistor R into the series circuit, and then open S_2 after 1.5-2 cycles;

The connection time for parallel resistors of 500kV circuit breakers in China is generally 10-15ms.

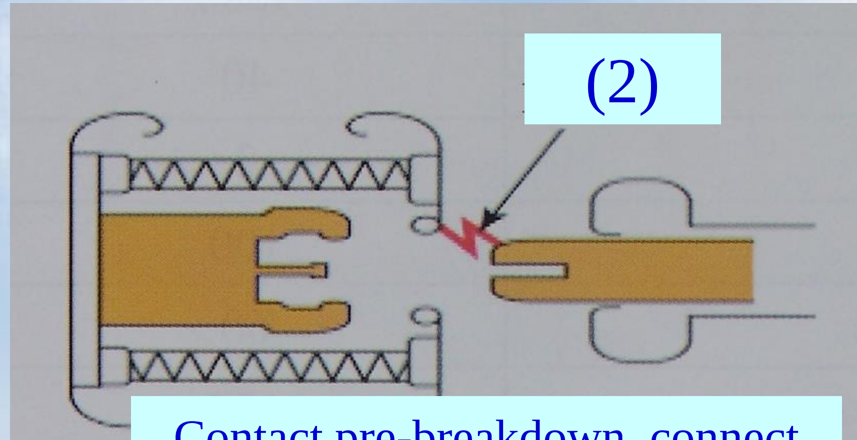
Using parallel resistors to limit switching overvoltage



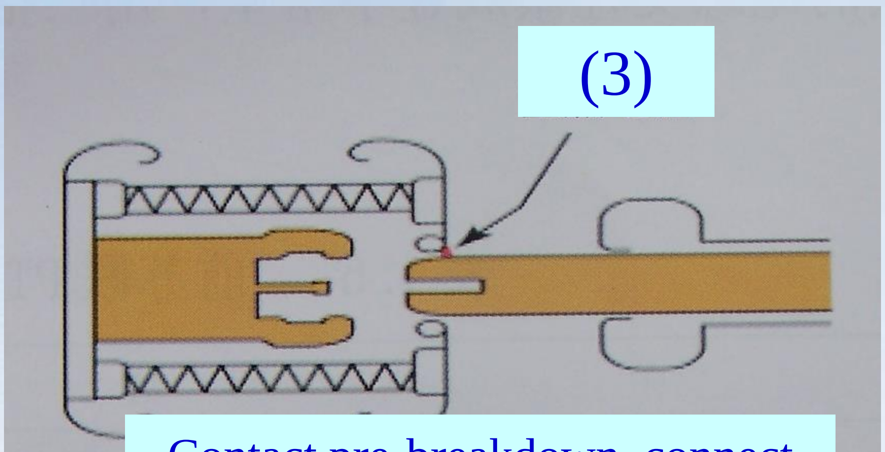
Selecting the parallel resistance values in Japan UHV circuit breaker



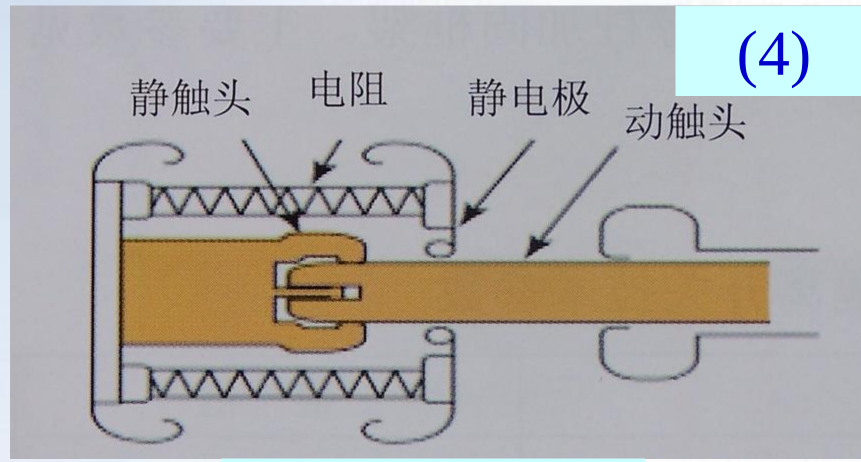
Before closing



Contact pre-breakdown, connect the resistor in series



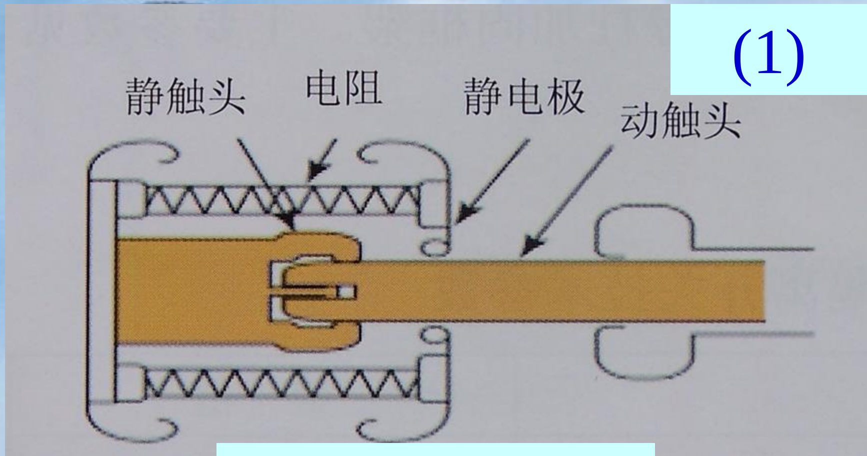
Contact pre-breakdown, connect the resistor in series



Closing completed

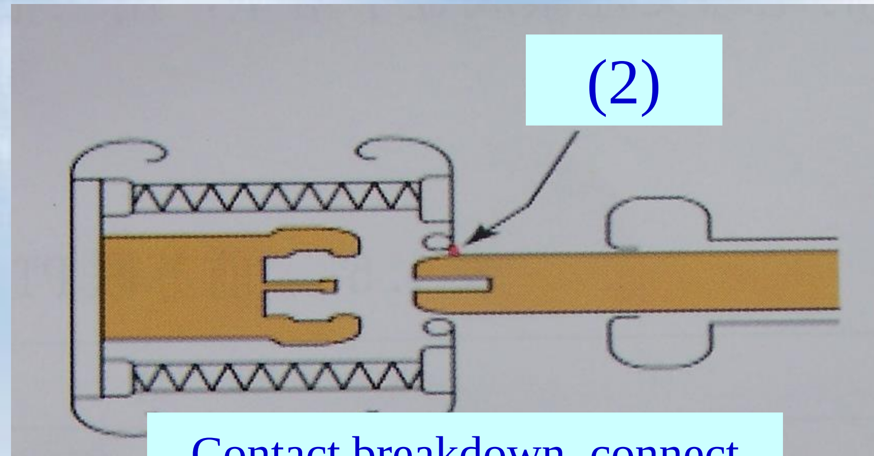
Series connection of the parallel resistor in the closing process of circuit breaker

In one motion of the movable contact, the connection and exit of parallel resistors is completed in sequence!



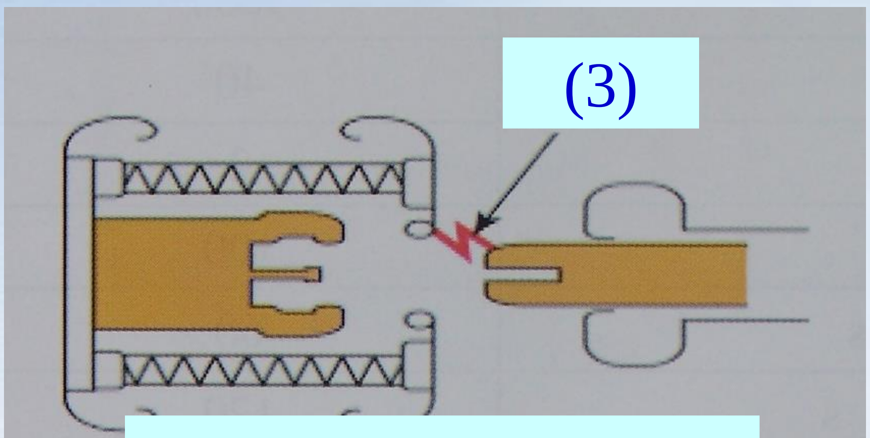
(1)

Before opening



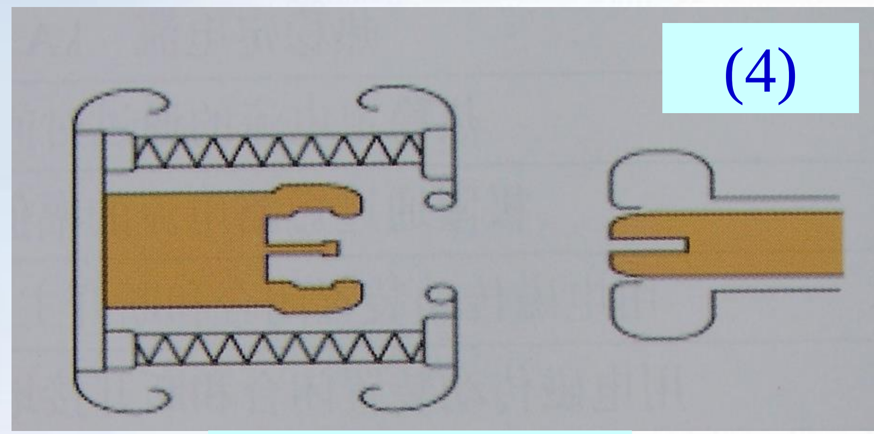
(2)

Contact breakdown, connect the resistor in series



(3)

Contact breakdown, connect the resistor in series



(4)

Opening completed

Series connection of the parallel resistor in the opening process of circuit breaker

In one motion of the movable contact, the connection and exit of parallel resistors is completed in sequence!

10.4 Very Fast Transient Overvoltage (VFTO)

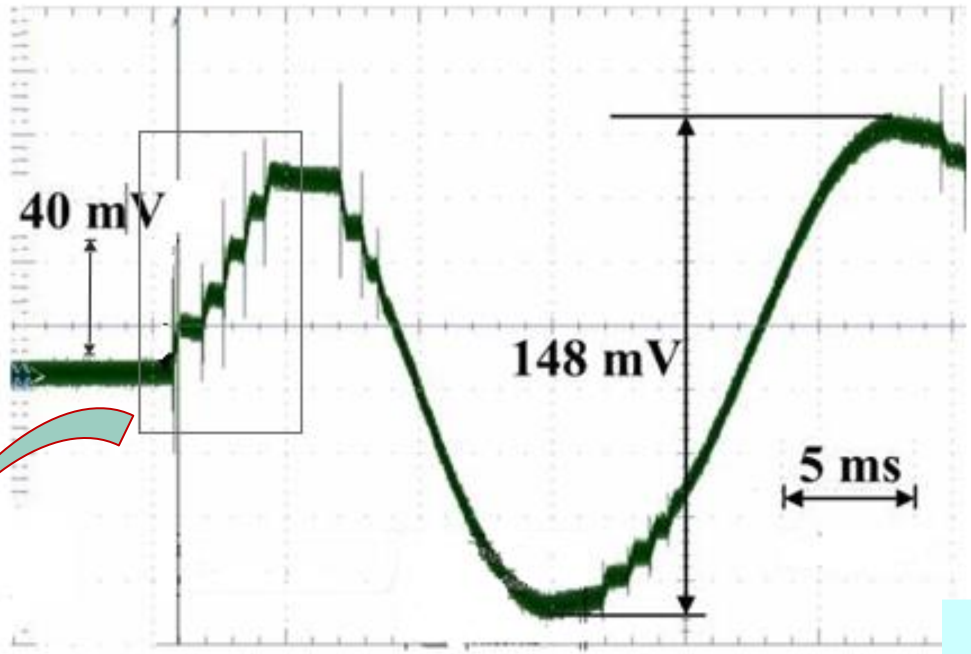
In GIS, when operating the isolating switch for an unloaded short busbar, due to the relatively slow movement of the contacts, the gap between the isolating switch and the circuit breaker is repeatedly breakdown, resulting in a traveling wave with sharp steepness.
The traveling wave undergoes multiple refractions, reflections and superposition at the node where the GIS wave impedance changes, forming the VFTO.

Characteristics of VFTO: high amplitude, steep wavefront, high frequency, and multiple continuous pulses. The amplitude range is about 1.5-2.8pu, with a rise time of several ns.

The internal VFTO generated between HV conductor (pole) and enclosure has a significant impact on the insulation of GIS and its connected equipment with windings.

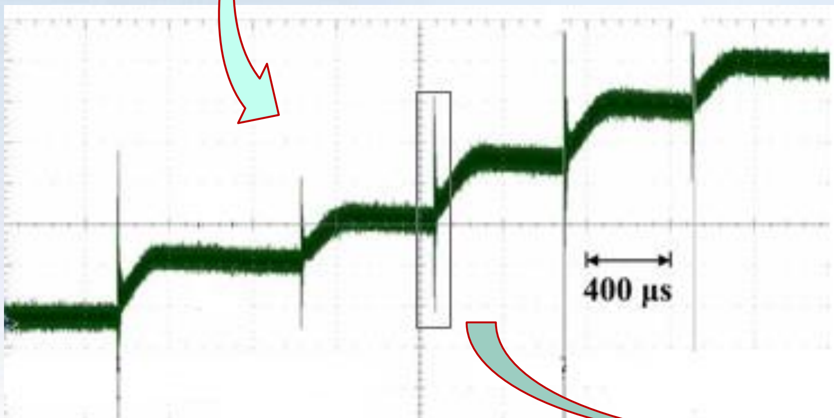
External VFTO can harm the insulation of the secondary equipment connected to the enclosure, or cause electromagnetic interference to the measurement and control equipment, resulting in mis-operation of the secondary equipment.

Suppress of VFTO: Parallel resistors can be installed on the isolating switch of GIS, or ferrite magnetic rings can be installed on the conductive rod of GIS.

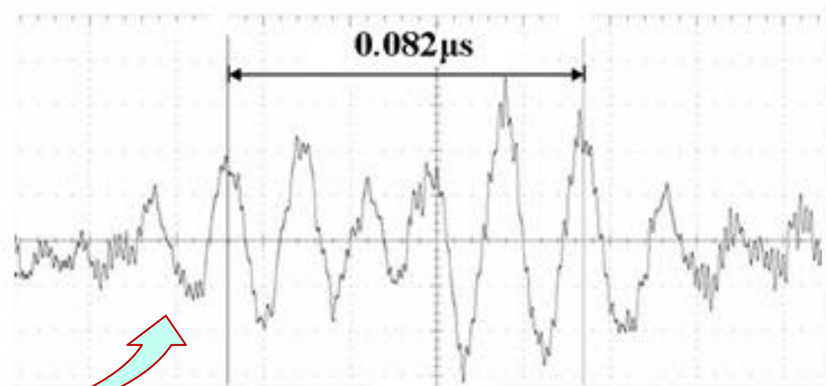


(a) VFTO波形

measured waveform of VFTO



(b) 波形局部展开



(c) 单次振荡展开

10.6 Basic concepts and methods of insulation coordination

How to choose ***appropriate insulation level***

Basic concepts of insulation coordination

Based on the various subjected voltages of equipment in the system (normal working voltage and overvoltage), and the characteristics of the voltage limiting device and the insulation characteristics of the equipment **to determine the necessary insulation withstand level** of the equipment, **to reduce the probability** of insulation damage and non-continuous operation caused by various voltages acting on the equipment **to an** economically and operationally **acceptable level**.

Technically handle the coordination relationship between various voltages, voltage limiting measures, and equipment insulation withstand level;

Economically coordinate the relationship between equipment investment costs, operation and maintenance costs, and the cost of accident losses (reliability).

Other factors that affect insulation coordination: neutral point treatment of grounding, power frequency overvoltage, different grid structures at different stages, etc.

Basic methods of insulation coordination

Deterministic method (often be used):

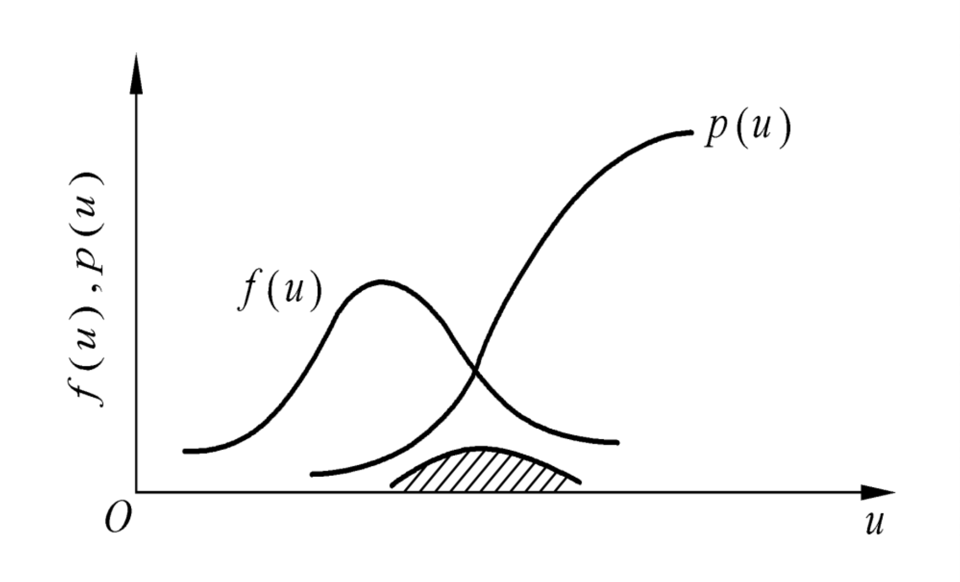
Make sure the minimum insulation withstand level of equipment higher than the maximum overvoltage that occurs on the equipment, and maintain a certain margin.

Statistical method:

With the known probability distribution of overvoltage amplitude and flashover voltage, to calculate the probability of insulation failure and tripping rate of the line, and determine the insulation level based on technical and economic comparison.

The main difficulty: A large number of random factors, and sometimes the probability distribution of various statistical data, is unknown.

In fact, simplified statistical method is more commonly used after making assumptions on certain probabilities



The total shaded area in the figure, which is the probability of insulation breakdown caused by a certain overvoltage, i.e., the failure rate

Insulation coordination

Reliability (number and lasting time of power outages) vs. **Economy** (initial investment, operation and maintenance, power outage losses)

Insulation coordination issue: Adopting appropriate voltage controlling and protective measures, without increasing equipment investment, not only to limit the possible high amplitude overvoltage, ensuring the security and reliability of equipment and system operation, but also to reduce the requirements for insulation level of various transmission and distribution equipment, reducing investment costs of main equipment, operation and maintenance, and accident losses.

Rated voltage level / kV	Neutral isolated grounding system		Neutral solidly grounding system				
	≤30 ~ 65	**110~ 145**	**110~ 220**	**330**	**500**	**750**	**1000**
Permitted phase to ground switching overvoltage multiple	**4.0**	**3.5**	**3.0**	**2.75**	**2.0**	**1.8**	**1.7**
The permitted phase to phase switching overvoltage is a multiple of the phase to ground switching overvoltage	**1.3 ~ 1.4**			**1.4 ~ 1.45**	**1.5**		

Rated voltage level / kV	Neutral isolated grounding system		Neutral solidly grounding system				
	≤30 ~ 65	**110~ 145**	**110~ 220**	**330**	**500**	**750**	**1000**
Permitted phase to ground switching overvoltage multiple	**4.0**	**3.5**	**3.0**	**2.75**	**2.0**	**1.8**	**1.7**
The permitted phase to phase switching overvoltage is a multiple of the phase to ground switching overvoltage	**1.3 ~ 1.4**			**1.4 ~ 1.45**	**1.5**		

External overvoltage (lightning overvoltage)	Internal overvoltage			
	Power frequency voltage increase (temporary overvoltage)	Resonance overvoltage	Arc grounding overvoltage	Switching overvoltage
Lightning strikes the the tower top Lightning strikes phase conductors Lightning strikes ground wire in mid of span Lightning strike the ground close to line	Caused by the capacitance rise effect of no-load long lines, Asymmetric short circuit, Sudden load shedding (load rejection), etc. *It is the basis for switching overvoltage oscillations, must be considered for insulation coordination*	Ferromagnetic resonance overvoltage and parameter resonance overvoltage (often found in distribution systems)	Caused by single-phase grounding faults in neutral isolated grounding systems	Energizing an unloaded line (including reclosing), De-energizing an unloaded line, De-energizing an unloaded transformer, Current chopping, System splitting overvoltage VFTO

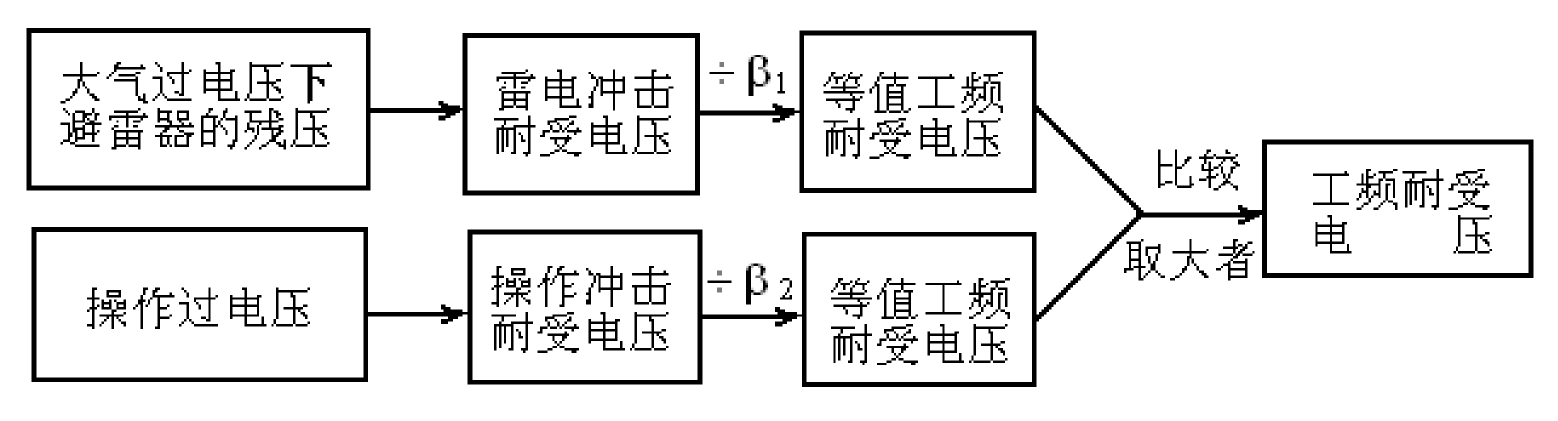
Insulation level of electrical equipment:

The insulation level **expressed in kV** by the test voltage that the equipment can withstand (without flashover, discharge, or other damages).

Corresponding to the various working voltages that the equipment insulation may subjected to, it can be divided into full wave basic impulse level (BIL), basic switching impulse level (BSL), and power frequency withstand level.

The test corresponds to lightning impulse test, switching impulse test, short-term (1min) power frequency test and slightly longer power frequency tests under special circumstances.

When the voltage level is not high, for the convenience of testing, the power frequency withstand voltage is commonly used as a substitute, as shown in the following figure



When the voltage level is high, lightning impulse and switching impulse should be tested separately, and cannot be replaced by power frequency test.

Equipment with higher voltage level can choose different insulation levels if needed.

(See Appendix Tables A-1, A-2, A-3)

Insulation level of electrical equipment:

The insulation level **expressed in kV** by the test voltage that the equipment can withstand (without flashover, discharge, or other damages).

BIL, BSL, and power frequency insulation levels correspond to lightning impulse test, switching impulse test, short-term (1min) power frequency test, and slightly longer power frequency test under special circumstances, respectively.

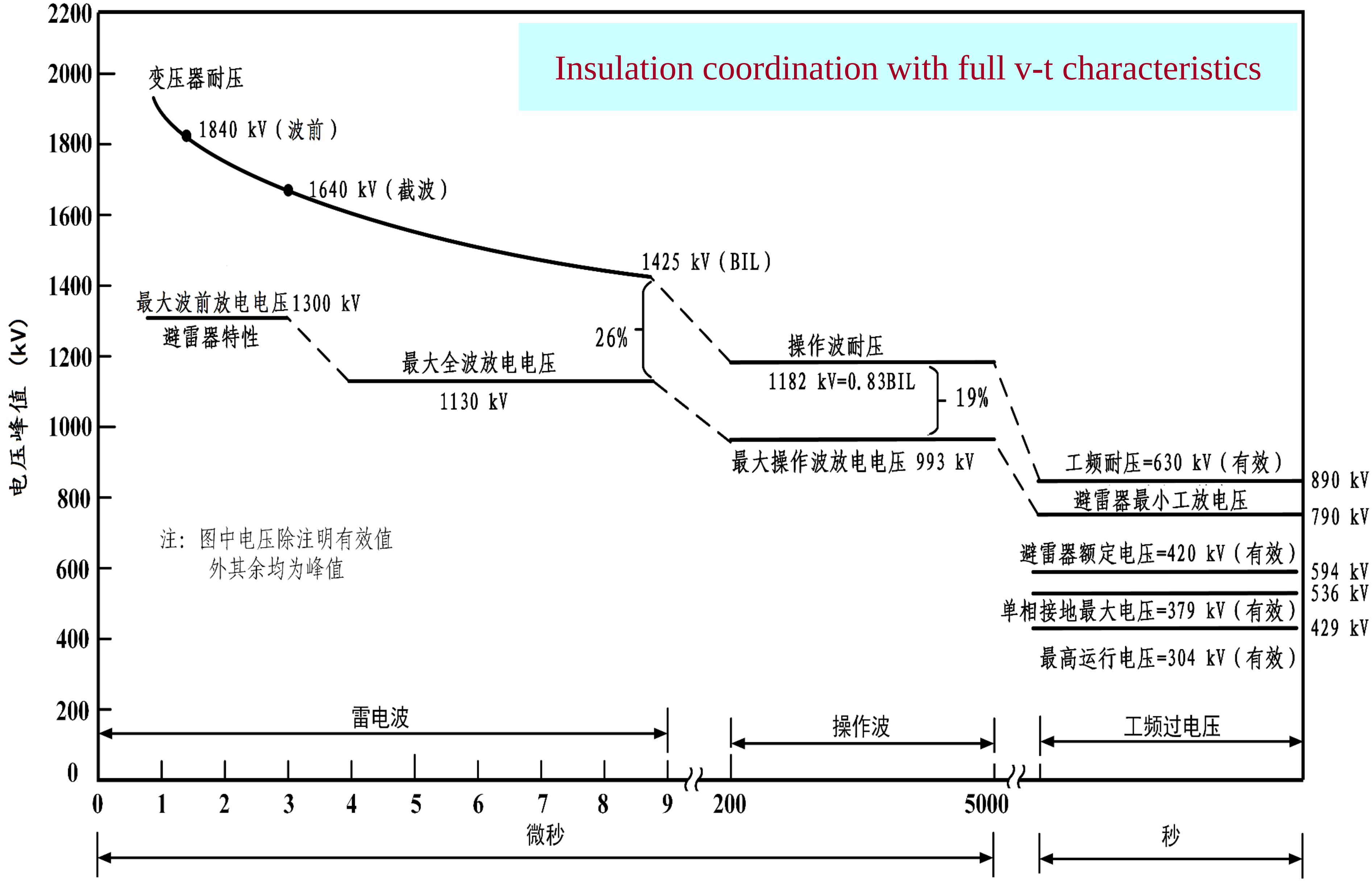
For example:

The coordination coefficient between the BIL of the transformer and the lightning impulse protection level (U_p) of the surge arrester is generally within between 1.2 and 1.4. According to IEC regulations, BIL$\geq 1.2U_p$

The BSL of the transformer is matched with the switching surge protection level (U_p') of the arrester, with BSL$\geq 1.15\ U_p'$

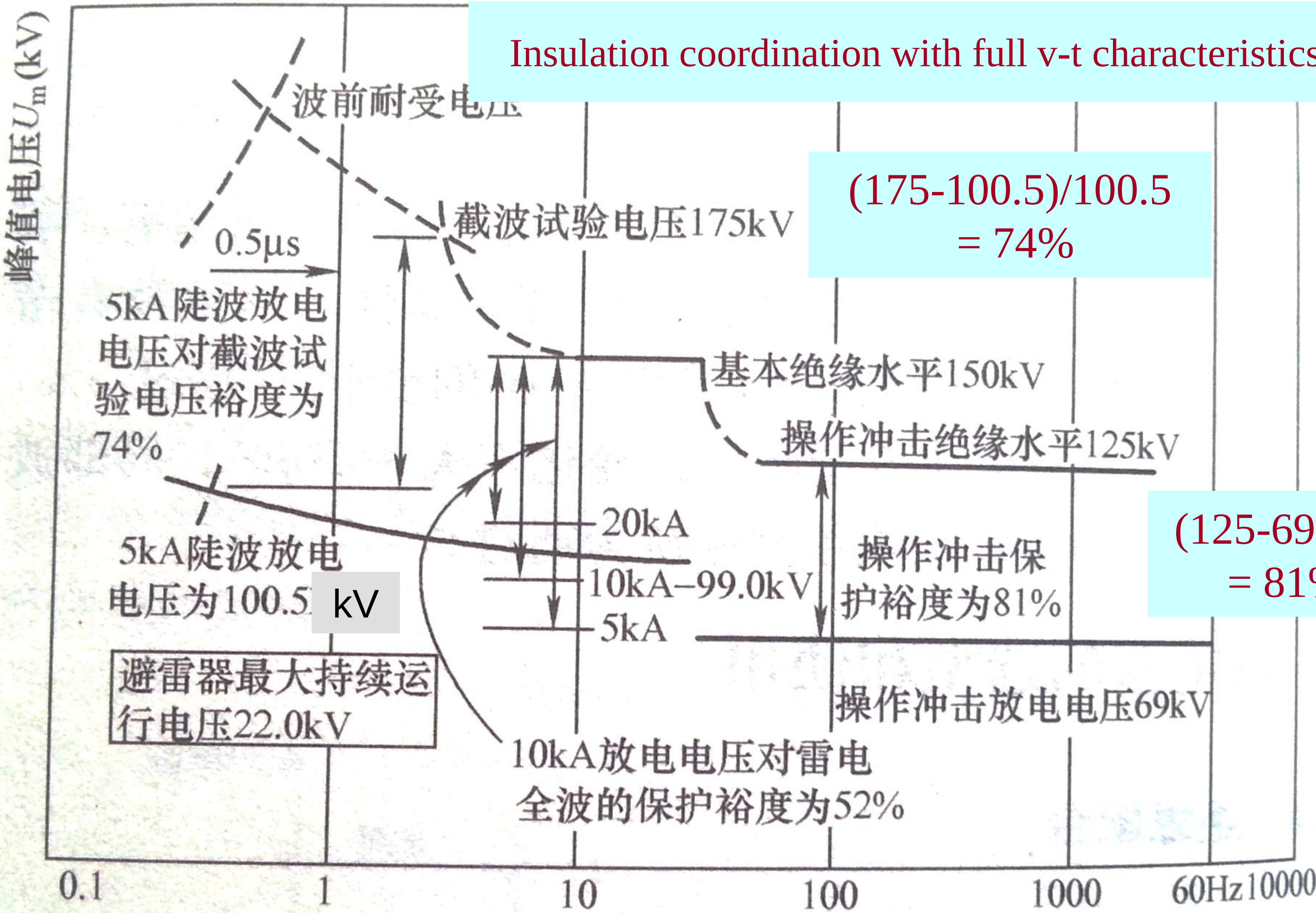
After selecting the protection level of the arrester, there are clear requirements for the insulation level (BIL, BSL) of the transformer.

Insulation coordination with full v-t characteristics



Insulation coordination for transformers and parallel reactors in the 500kV power grid of the Central Southern Power Company of the United States

Insulation coordination with full v-t characteristics



(175-100.5)/100.5
= 74%

(125-69)/69
= 81%

图 5.2-24 避雷器与油浸式变压器的绝缘配合

Insulation coordination in GIS substation

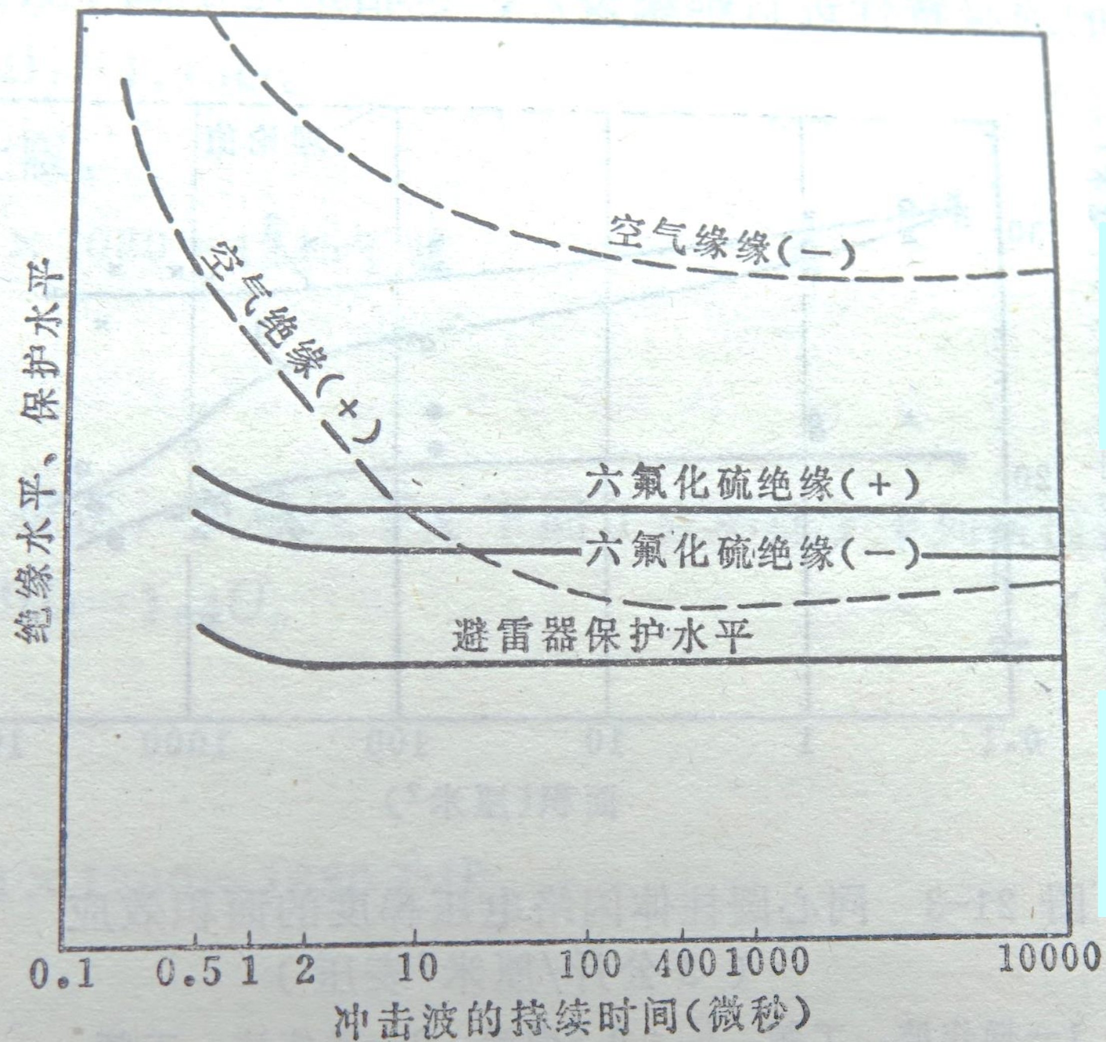


图 21-1 六氟化硫全封闭变电所的绝缘配合示意（虚线为常规变电所的外绝缘）

Attention: Polarity effects of extremely non-uniform fields and slightly non-uniform fields

Attention: The v-t characteristics of the protective device and the protected device

The basic principles of insulation coordination in substations in China:

For systems ≤ 220kV, the insulation level of electrical equipment is mainly determined by lightning overvoltage;

For EHV systems ≥ 330kV, switching overvoltage becomes the main contradiction.

Strategies for the determination of overvoltage protection :

- The first step is to use parallel reactors to limit the power frequency overvoltage to a certain range
- Second, control the switching overvoltage within a certain range through circuit breaker parallel resistance or improving circuit breaker performance.
- Then, lightning arresters are used as backup protection (lightning arresters do not need to act frequently under switching overvoltage).

So, the insulation level of substation equipment is determined by the residual voltage (protection level) of the surge arrester under lightning impulse.

The basic principles of insulation coordination for transmission lines in China:

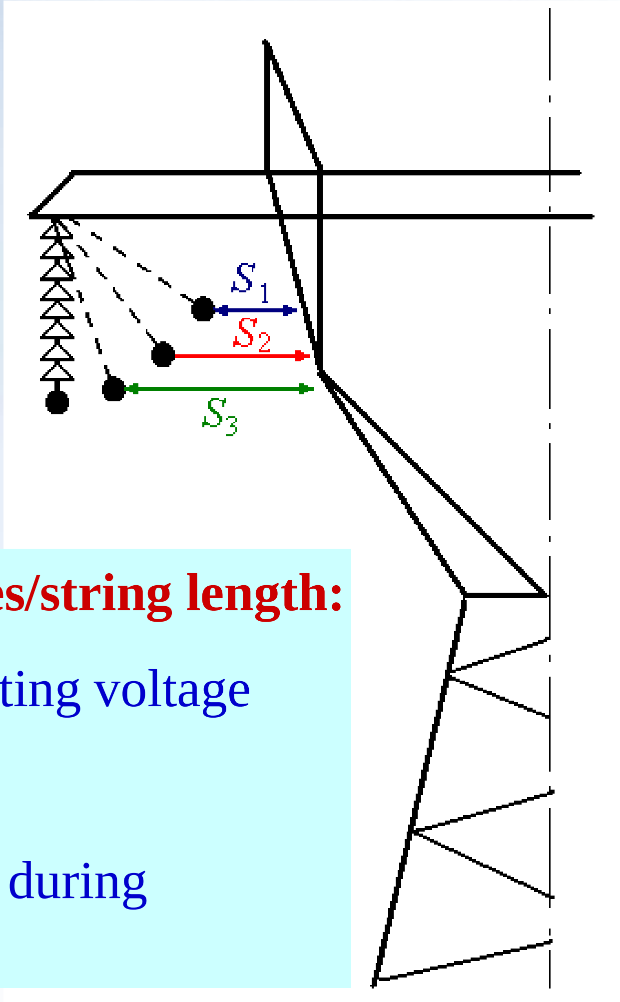
After integrating different voltage and wind speed combinations, maintaining a certain lightning withstand level and controlling a certain lightning trip rate; in polluted areas, the outdoor insulation level is determined by the highest operating voltage.

Determination of tower top clearance:

S_1: Power frequency overvoltage + maximum wind speed

S_2: Switching overvoltage + 50% maximum wind speed

S_3: Lightning overvoltage + 10m/s wind speed



Determination of the number of insulator pieces/string length:

No pollution flashover occurs at the highest operating voltage

No rain flash occurs under switching overvoltage

Ensure a certain level of lightning withstand level during lightning strikes

The special problems under high voltage and high stress
(transmission and distribution systems and their equipment)
cover three levels: materials, equipment, and systems

Gas, solid, liquid dielectric materials	⟺	Transmission and distribution equipment	⟺	Power transmission and distribution system

Integrating three levels of learning, is both a challenge and an advantage.

When study a chapter, it is important to associate it with other chapters if there are some relations

The special problems under high voltage and high stress
(transmission and distribution systems and their equipment)
cover three levels: materials, equipment, and systems

Gas, solid, liquid dielectric materials

Electric field structure (insulation structure)

↔

Transmission and distribution equipment
transformers, switchgears, CT, PT, OHL, insulators, surge arresters, etc

High voltage testing equipment
high voltage generation and measurement

↔

Power transmission and distribution system
voltage level, transmission capacity, overvoltage, insulation coordination, relay protection, etc

When study a chapter, it is important to associate it with other chapters if there are some relations

The special problems under high voltage and high stress

(transmission and distribution systems and their equipment)

cover three levels: materials, equipment, and systems

Operating environmental conditions
such as AC, DC, harmonics, lightning, switching, wind and rain, temperature and humidity, pollution, altitude, etc.

Manufacturing processes
such as winding, extrusion, molding, casting, impregnation, curing, etc.

Gas, solid, liquid dielectric materials

Electric field structure (insulation structure)

Transmission and distribution equipment
transformers, switchgears, CT, PT, OHL, insulators, surge arresters, etc

High voltage testing equipment
high voltage generation and measurement

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Power transmission and distribution system
voltage level, transmission capacity, overvoltage, insulation coordination, relay protection, etc

Gas, solid, liquid dielectric materials

Electric field structure
(insulation structure)

High voltage testing equipment
high voltage generation and measurement

Test methods
such as polarization, conductivity, loss, AC/DC, impulse, etc.

Operation and maintenance
such as insulation, dielectric loss, partial discharge, withstand voltage, etc

When study a chapter, it is important to associate it with other chapters if there are some relations

A course is organized into three levels, reflecting the main content of high voltage and insulation technology

The special problems under high voltage and high stress

(transmission and distribution systems and their equipment)

cover three levels: materials, equipment, and systems

The application of new materials brings about comprehensive improvement in equipment and system performance, and corresponding changes in testing and operation, such as SF_6, silicon rubber, XLPE and ZnO

The development of new equipment has also brought about changes in materials and structures, testing and operation methods, and system performance, such as SF_6 GIS/GIL, silicon rubber insulators, XLPE cables, ZnO arresters, various power electronic equipment, and various monitoring or sensing devices

The changes in system level also require improvements in equipment performance, materials and structures such as new voltage level, AC and DC, Bulk Power Transmission Project from West-to-East, and offshore wind power, next generation of power system based on clean and renewable energy, etc.

Back to the tips in the first class

- There may not always have standard answers in industry practice
- Different concerns in science, technology, and engineering.
- Pay attention to the method of research and study on "high voltage". It is often necessary to face physical phenomena directly, to find problems, to refine problems, and then to solve them

Master the principles of science
Know the technical measures
Understand industry specifications

Focus more on finding problems
Sorting out and refining problems
Can you foresee some problems

- Understand the industry background and the technology policy
- Combined with industry development, theory + practice

Objective: To cultivate high-quality talents
with primary "professional depth + industry width"

Wish all the students a happy study and a smooth exam!

上课讲过的都属于考试的范围
包括绪论、各章、附录、课件和专题

下述章节不在2025春期末考试范围

第2章：2.1.2
第5章：5.3.3、5.4.3、5.4.4、5.5、5.8
第6章：6.1.5、6.2.3、6.3.5、6.4
第7章：7.7、7.8、7.9、7.10、7.11、7.12
第8章：8.3.1
第9章：9.4.3
第10章：10.4、10.6.5

考试时间：6-10 (周二) 19:00-21:00，请提前到场

考试地点：六教6C 201

考试方式：开卷考试，可翻阅自备纸质复习资料

考试须独立完成！

可带无通讯功能的计算器

其他要求请学习清华大学考试规定

答疑：6.7(周六)上午，10:00-11:00，高压馆205

6.10(周二)上午，9:30 -11:30，高压馆205