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CHINA ELECTRIC POWER EQUIPMENT AND TECHNOLOGY CO., LTD.

DC transmission foundation and commutation theory

CET

Chang Yong

2020. 4

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Personal Profile

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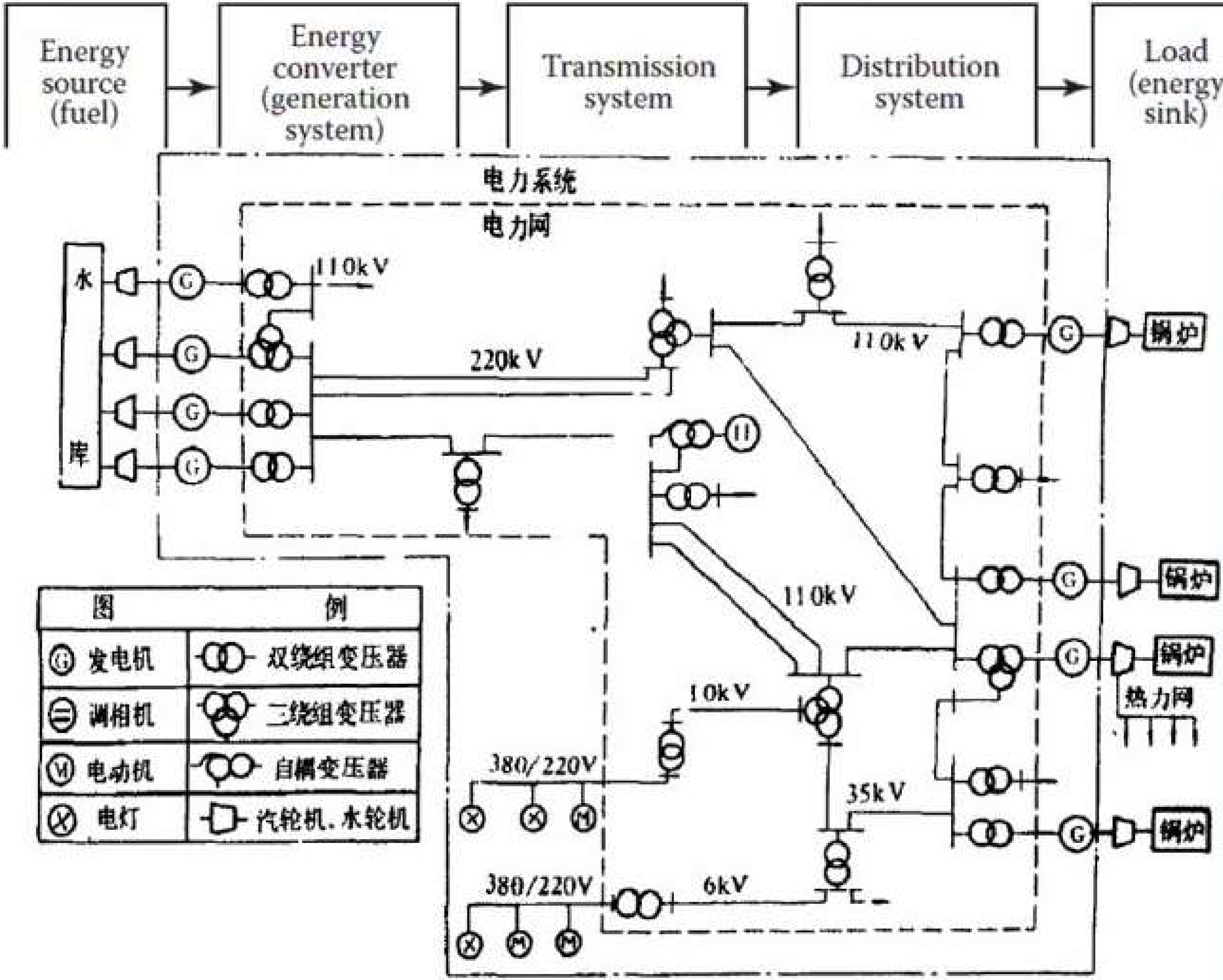
HVDC operation and maintenance

Power system and automation (Docter)

Summary

1. DC transmission history
2. Basic concept of HVDC
3. Commutation theory
4. HVDC control
5. Development prospect of HVDC technology

What is Power system



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特高压复龙站概况

NTDC Grid

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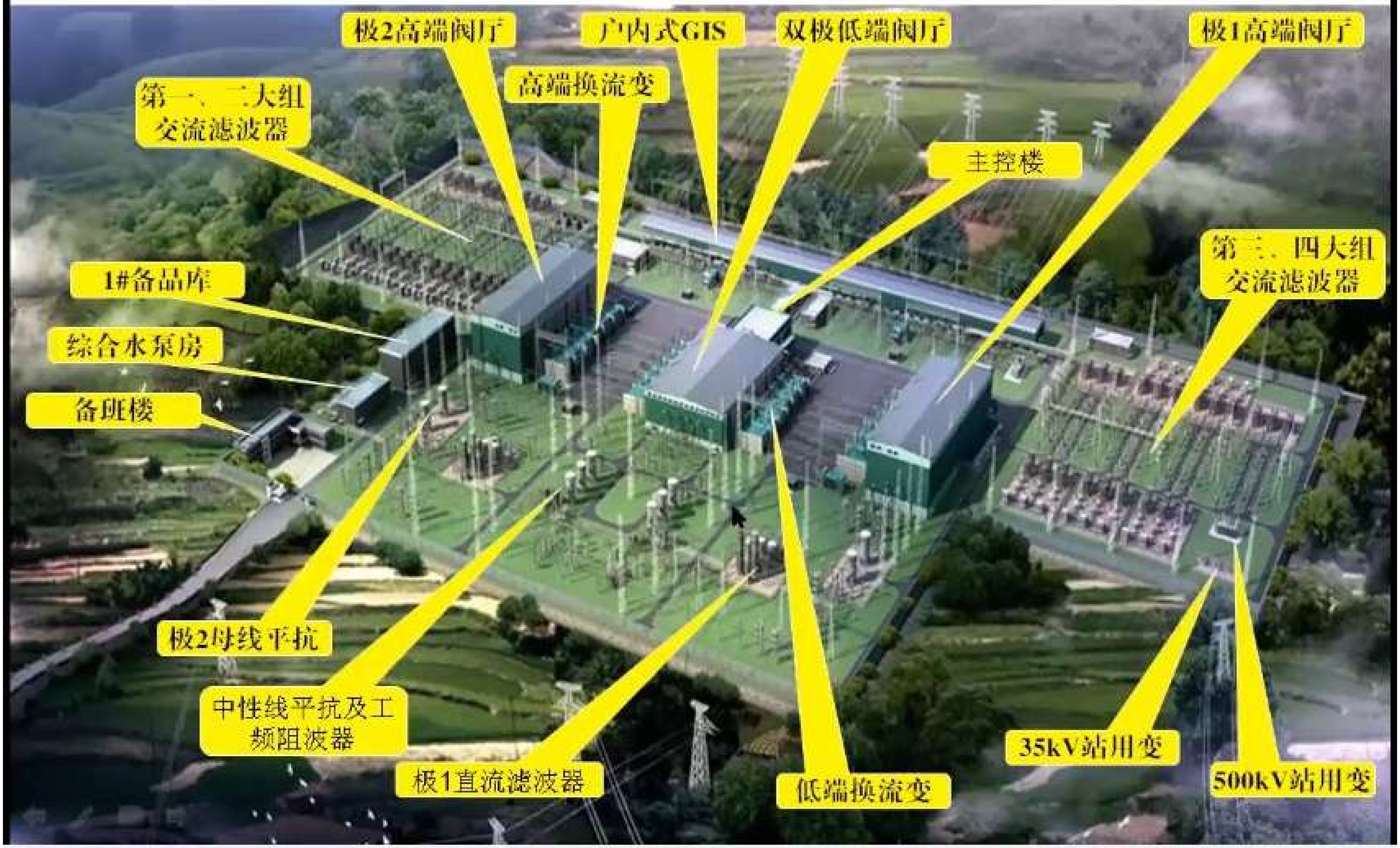
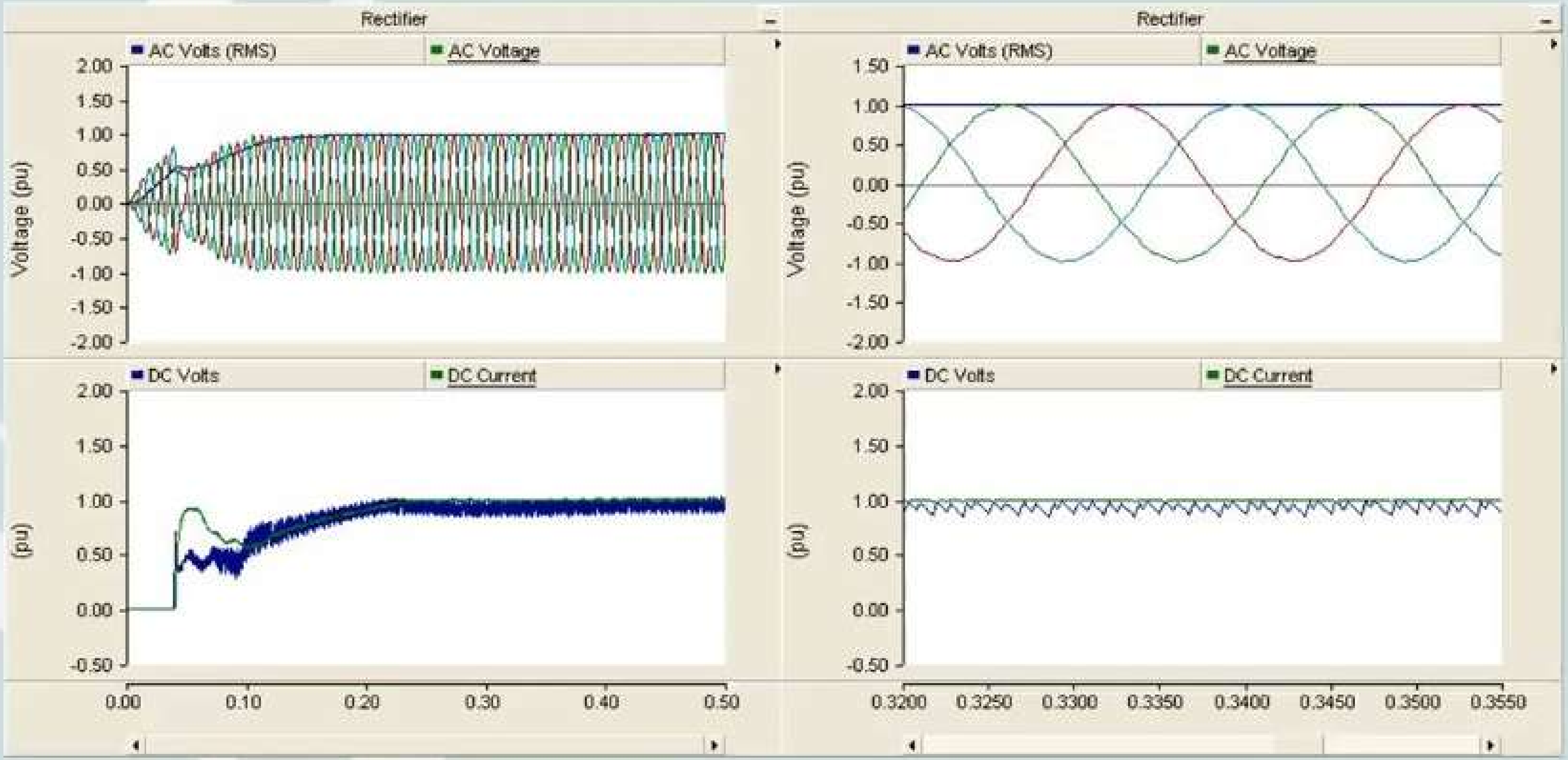
特高压复龙站概况

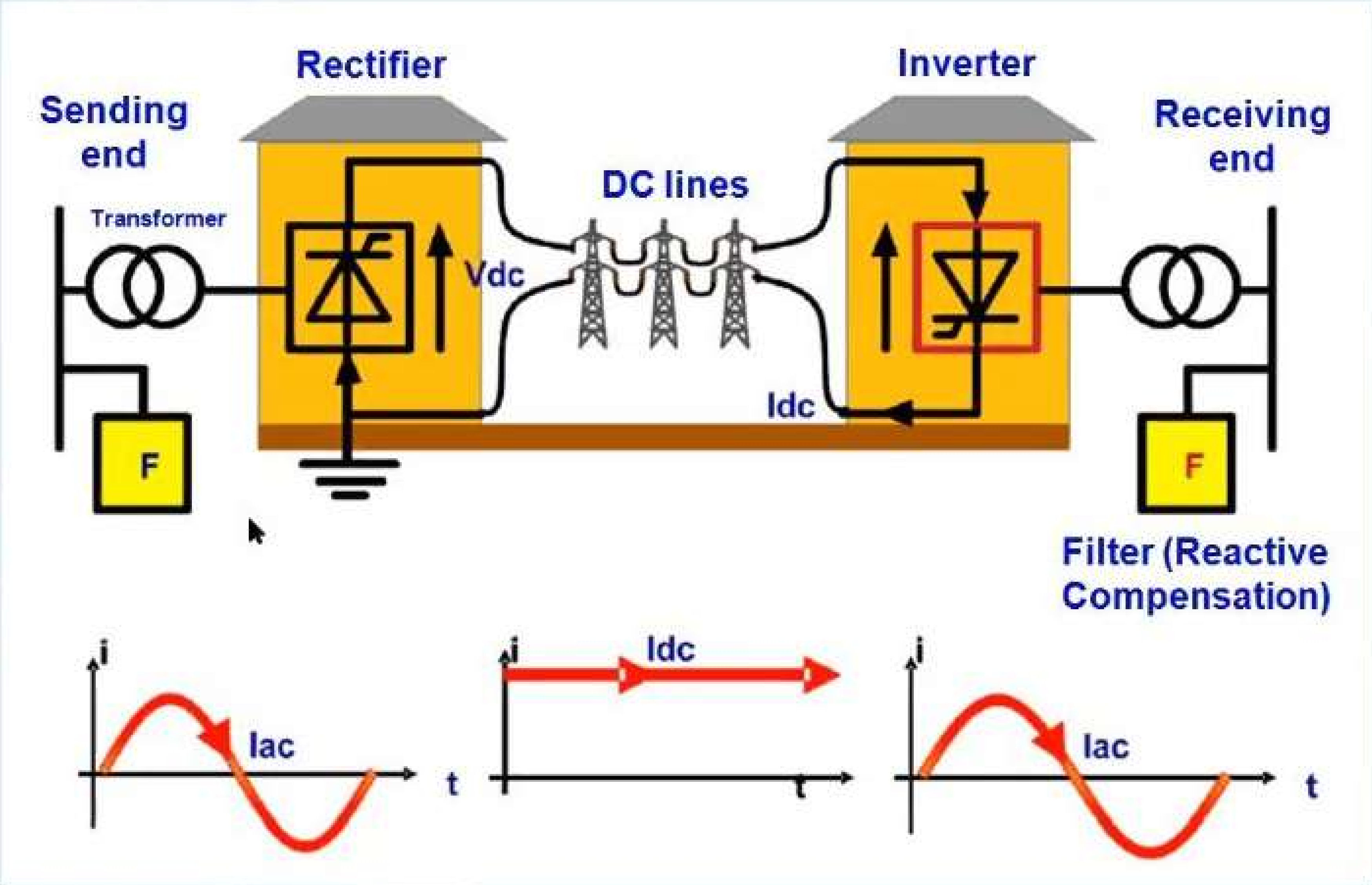


极2高端阀厅
户内式GIS
双极低端阀厅
极1高端阀厅
高端换流变
第一、二大组交流滤波器
主控楼
第三、四大组交流滤波器
1#备品库
综合水泵房
备班楼
极2母线平抗
中性线平抗及工频阻波器
极1直流滤波器
低端换流变
35kV站用变
500kV站用变

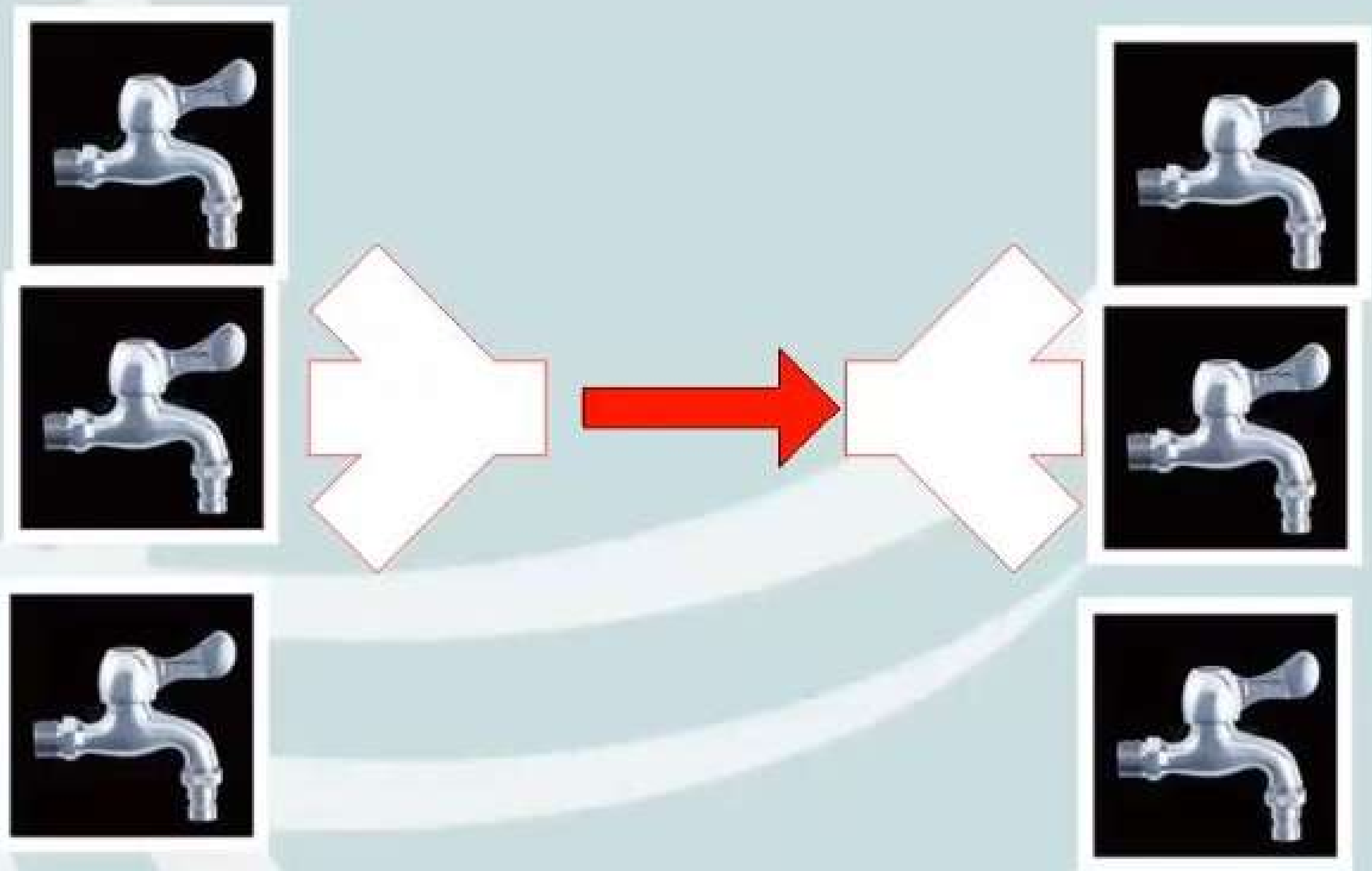
AC-DC


Rectifier
AC Volts (RMS)
AC Voltage
Voltage (pu)
DC Volts
DC Current
(pu)
0.00
0.10
0.20
0.30
0.40
0.50
0.3200
0.3250
0.3300
0.3350
0.3400
0.3450
0.3500
0.3550

AC-DC

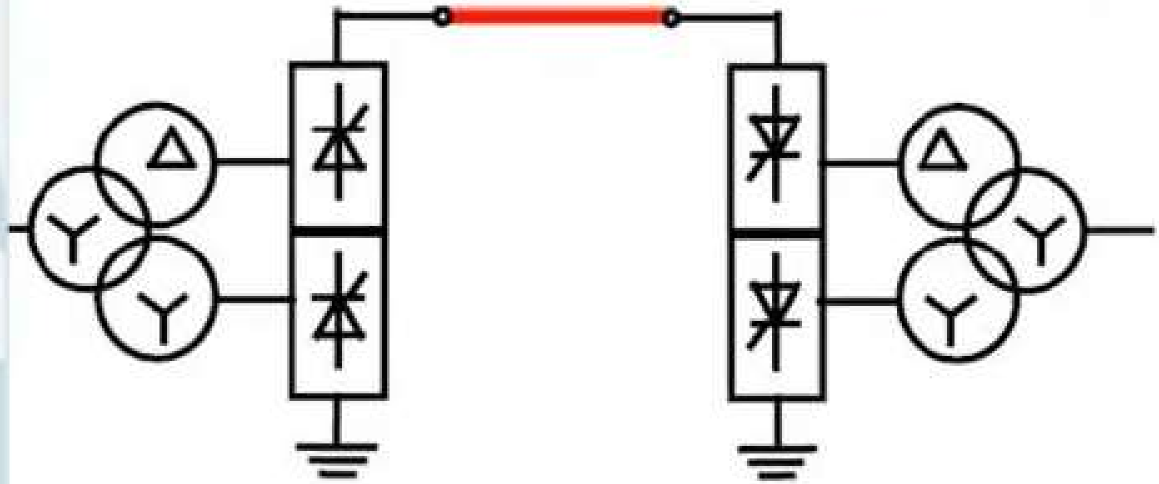

Rectifier
Inverter
Sending end
Receiving end
DC lines
Transformer
Vdc
Idc
F
F
Filter (Reactive Compensation)
i
Iac
t
i
Idc
t
i
Iac
t

AC-DC



Monopole DC system

Many cable DC transmission systems use single pole system structure. In this case, only one metal conductor is needed, and the earth or sea water is used as the circuit.



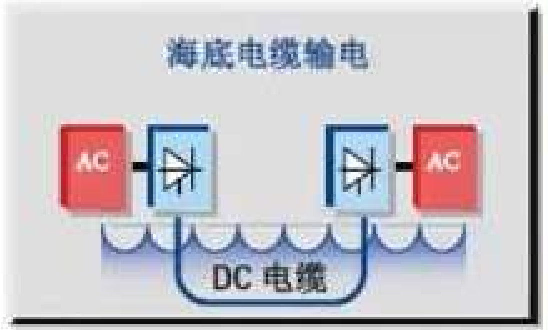
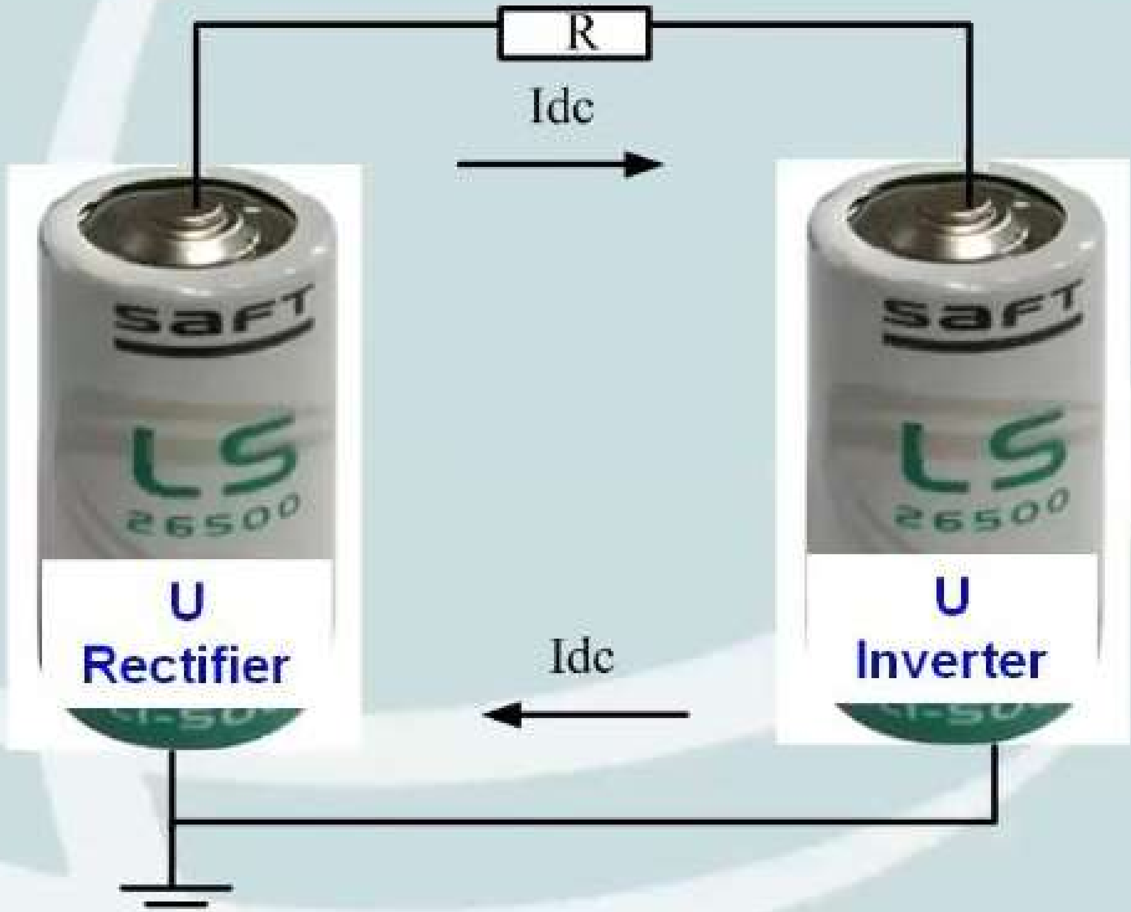


Image metaphor of HVDC



Single pole DC transmission

Bipolar DC system

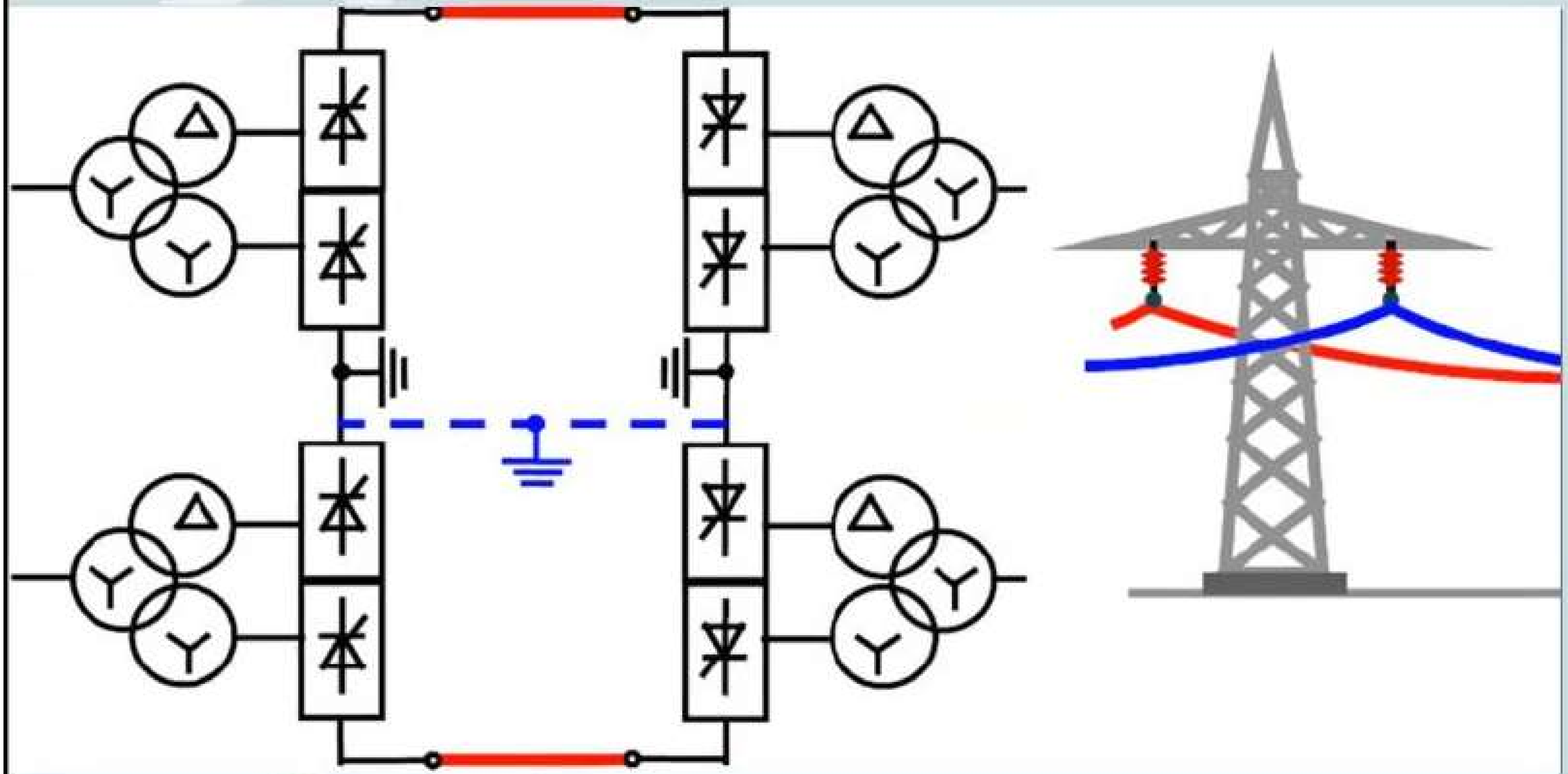


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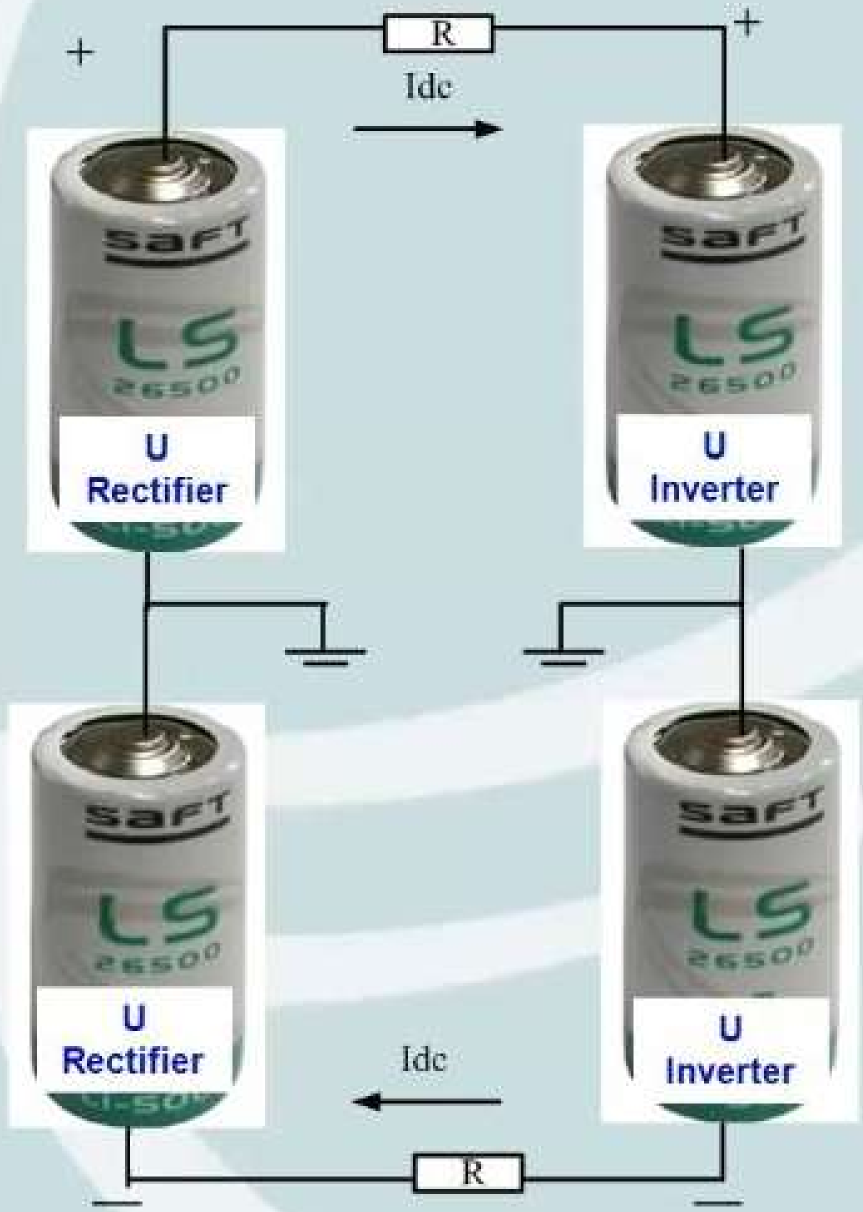
Image metaphor of HVDC



Bipolar DC transmission

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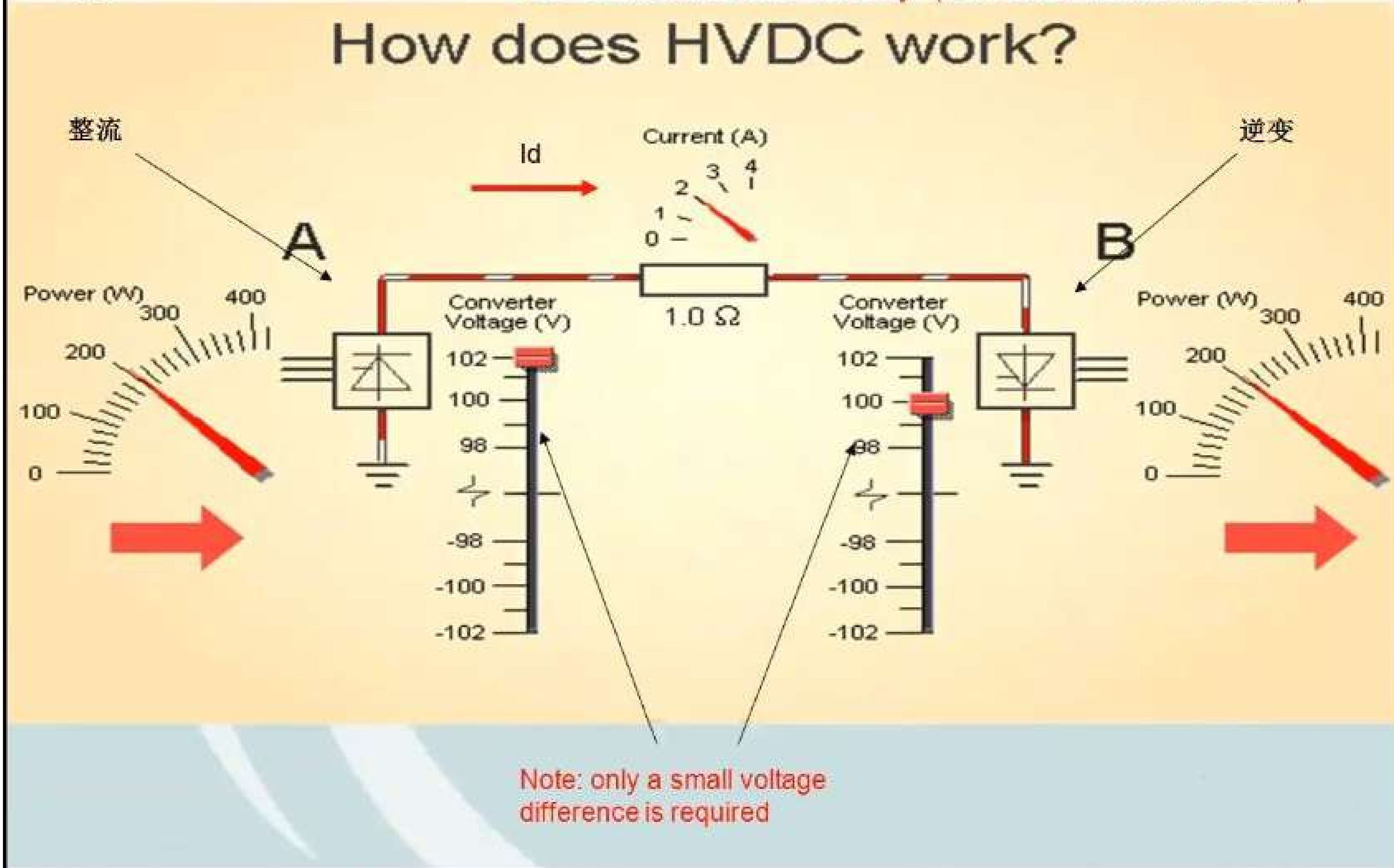
How does HVDC work?

DC transmission theory (forward transmission)



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How does HVDC work?

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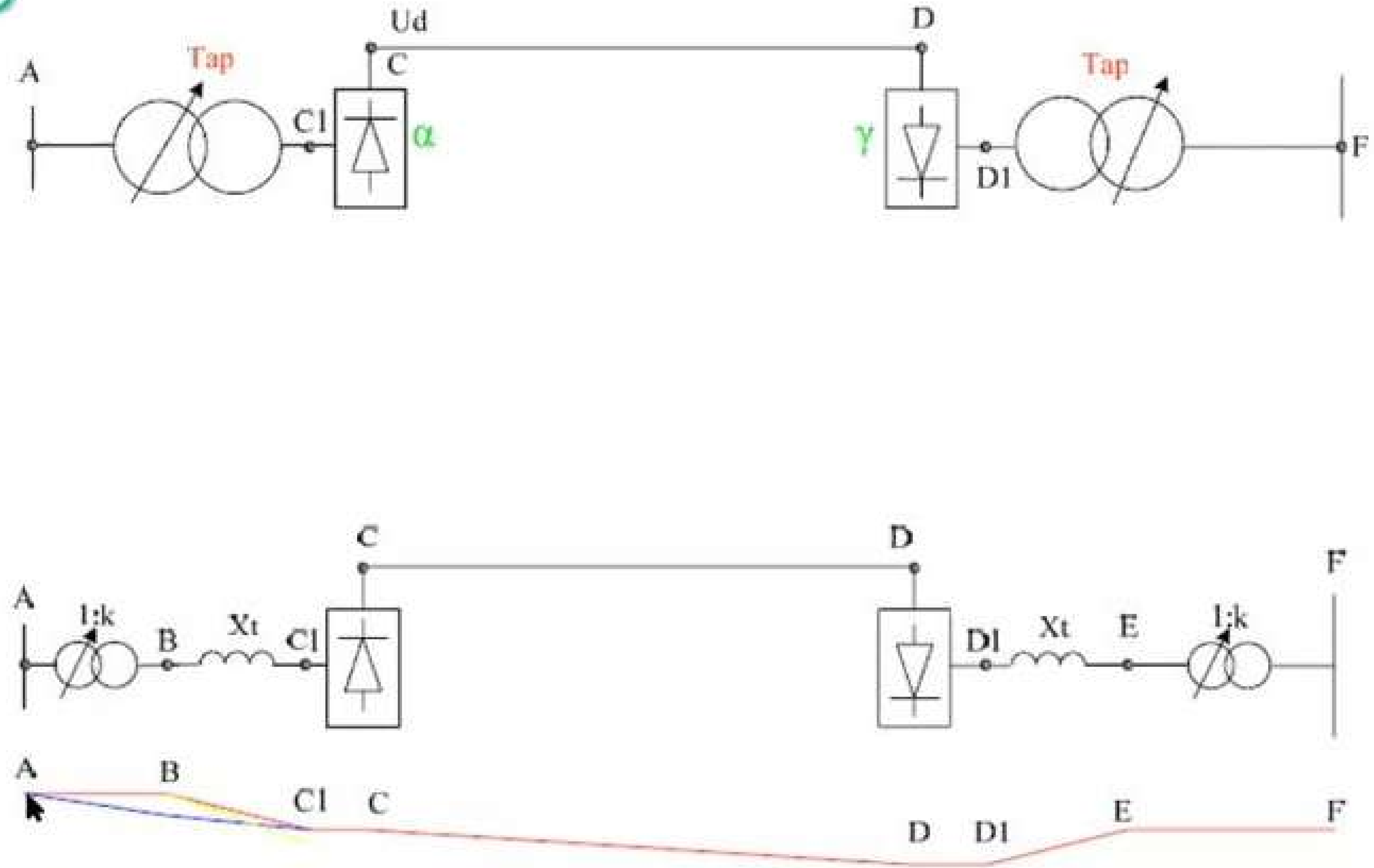

The history of HVDC

- In the 1980s and 1990s, people gradually mastered the principle of multiphase AC circuit, and created alternator, transformer and induction motor. Because AC power generation, transformation, transmission, distribution and use are very convenient, and economic, safe and reliable. As a result, alternating current has almost completely replaced direct current and developed into a huge power system in recent years.

Marcel Deprez

- In 882, the French physicist Deprez used a 2000V DC generator to deliver DC power to users through a 58km DC transmission line, realizing the first DC transmission in the world. Since then, the voltage, power and distance of DC transmission have reached 125kV, 20MW and 225km respectively.
- At that time, DC motor was used in series, with complex operation and low reliability. However, the development of high-voltage and large capacity DC motor had technical problems such as difficult commutation, so the development of DC transmission was limited.

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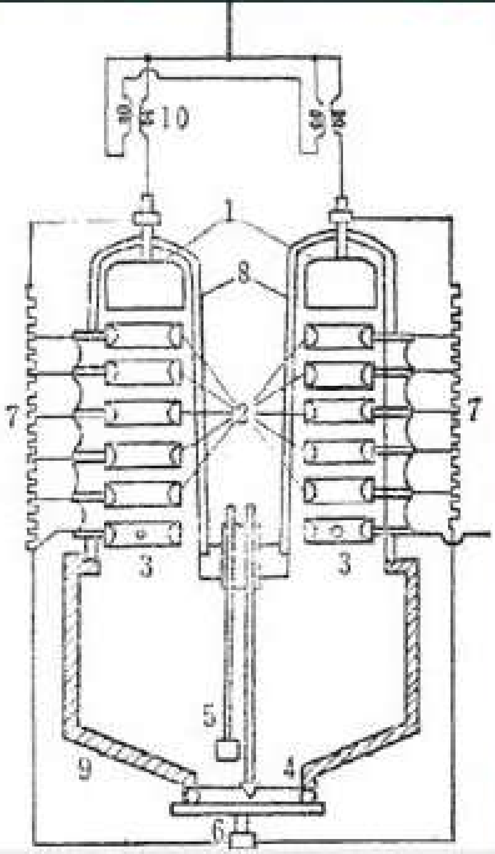
The history of HVDC

- From 1920 to 1940, mercury arc valve was developed and applied to AC-DC converter. Germany has built the first modern DC transmission project to transmit electricity to Berlin. The project is a symmetrical bipolar power transmission system with a voltage of ± 200 kV, a transmission capacity of 60 MW and two aluminum underground cables as conductors. It starts at Elbe of Dessauand and ends at Berlin-Marienfeld. The construction manufacturers are AEG and Siemens.
- After the defeat of Germany in 1945, all equipment of the project was transported to the Soviet Union and installed for operation, connecting Mosco and Kashira. It ceased operation in 1951.

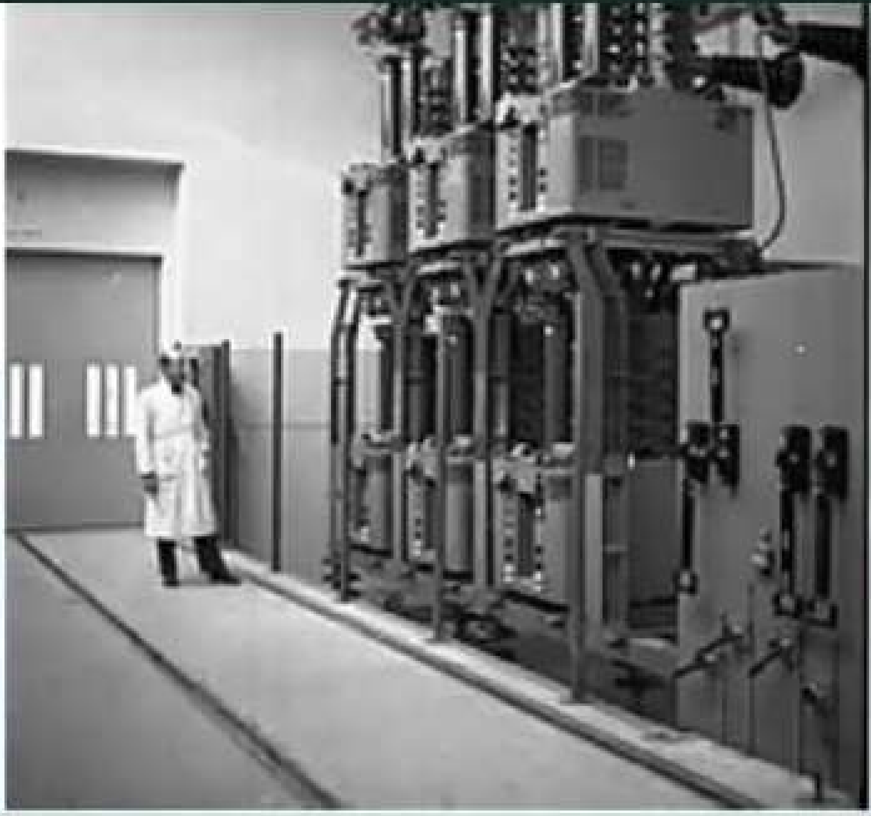
The history of HVDC

Since the 1950s, the demand for power has grown faster, the scale of power system has grown larger, and the limitation of AC transmission is more obvious in production practice. So the HVDC technology has been paid more attention. In this period, people explore the use of various components of the converter as a DC high-voltage power supply to replace the DC generator. Therefore, a mercury controlled arc valve converter is developed, which opens up a way for the development of high voltage and high power DC transmission in the future.



1-anode, 2-intermediate electrode, 3-control grid, 4-pilot anode, 5-excitation anode, 6-cathode, 7-voltage divider, 8-porcelain insulating sleeve, 9-box, 10 anode current equalizer

A six pulse mercury arc valve group with capacity of 20MW in Gotland project



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The history of HVDC

The history of HVDC

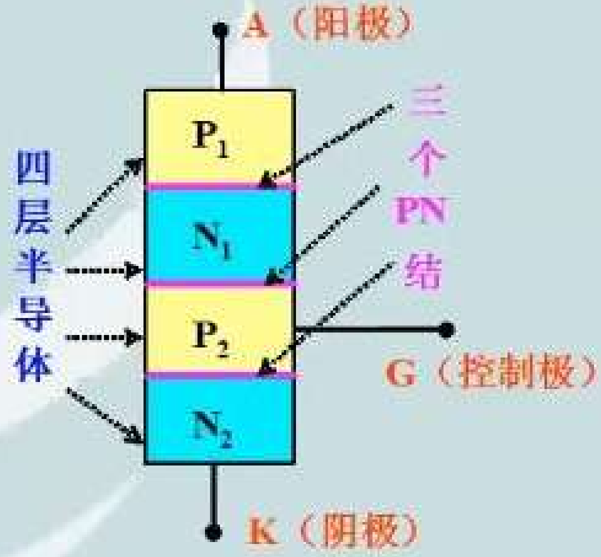
The most important stroke in the history of DC transmission

- In 1954, Sweden put in a 100kV, 20MW, 95km long submarine cable DC transmission line, which is the first industrial DC transmission line using mercury arc valve in the world, to transmit power from the local area to Gotland. Since then, many countries have also actively carried out the research and construction of HVDC, and built some HVDC projects one after another. In the 1960s, DC transmission projects were almost all transmission projects with submarine cables. Because across a wide sea area, the advantages of DC cable transmission are more prominent.

The history of HVDC

Thyristor DC transmission

- The manufacturing technology of mercury arc valve is complex, the price is expensive, the fault rate of reverse arc is high, the reliability is low, and the operation and maintenance are inconvenient.



- In 1969, a new generation of HVDC transmission system based on thyristor valve was used in the back-to-back DC project in the basin of Eel River in Canada, which became the first application project of using thyristor valve in HVDC transmission system;

The history of HVDC

- In 1975, Skagerrak link, the first 12 pulse converter project, was completed by ABB

- In 1979, the first HVDC transmission system based on microprocessor control technology was put into operation;

- In 1984, the highest voltage level HVDC transmission project in the 20th century (± 600kV, 6300 MW) was built in Itaipu, Brazil.

- In 1999, the first commercial flexible DC transmission, Gotland, 50MW.

- In 2000, the first capacitor commutated converter (CCC) was built in garabi, Brazil

The history of HVDC

DC transmission project with the highest voltage level and the largest transmission capacity in the world

- Xiangjiaba-Shanghai project: put into operation on July 8, 2010, with independent R & D, design and construction of State Grid Corporation of China. In the world, the transmission capacity is the largest, the transmission distance is the farthest, and the voltage level is the highest. For the first time in the world, it has realized the double promotion of UHVDC transmission voltage and current, the double breakthrough of transmission capacity and transmission distance. It is a new milestone in the history of power development in the world. It marks that China has conquered the worldwide problems in the two frontier fields of UHVDC in all aspects, including theoretical research and engineering The program construction, operation management, test capacity, standard setting and other aspects are in the forefront of the world.

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- Voltage: ± 800kV current: 4000A capacity: 6400mw (double pole)

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2 The basic concept of DC transmission

Disadvantages of HVDC

- Converter station equipment is expensive.
- The converter needs to consume a lot of reactive power.
- A large number of harmonics are produced in the operation of converter, which affects the operation of the system. Therefore, a large number of filter devices must be added.
- The converter has little overload capacity.
- At present, the technology of high voltage DC circuit breaker is not mature enough, which limits the development of multi terminal DC system.
- When the earth or sea water is used as the loop, it will corrode the metal components and pipes along the route and affect the navigation instruments.

Calculation method of converter station loss

Generally, the loss of converter station is not measured directly, but the loss of each equipment in the converter station under the typical load level is calculated respectively, and the total loss of converter station is obtaine请移开这个窗口。ion.

Loss items	Percentage of loss in total loss of converter station	Loss items	Percentage of loss in total loss of converter station
Converter transformer Among them:	39% — 53%	Thyristor converter valve	32% — 35%
No load loss	12% — 14%	Smoothing reactor	4% — 6%
Load loss	27% — 39%	AC filter	7% — 11%
		Other losses	4% — 9%

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Characteristics of HVDC

When the same power is transmitted, the cost of the line is low.

Active power loss of line small $P=UI, U\nearrow$, $\triangle P=I^2R\searrow$

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Suitable for underwater power transmission (no large problem of AC to ground capacitive current)

No system stability issues

Be able to limit the short-circuit current of system

Fast adjustment speed and reliable opera

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Loss of HVDC system

1）Conduction Losses of Valve W_1:The loss caused by the current flowing through the thyristor when conducting is considered in the calculation.

2）Loss of current diffusion when thyristor is opened W_2: Additional on state loss during current diffusion on silicon wafer when thyristor is opened.

3）Other Conduction Losses of Valve W_3:Loss caused by other components outside the thyristor in the main circuit of the valve.

4）Losses related to DC voltage W_4:It refers to the loss caused by the voltage applied to both ends of the valve on the parallel impedance of the valve when the valve is not conductive.

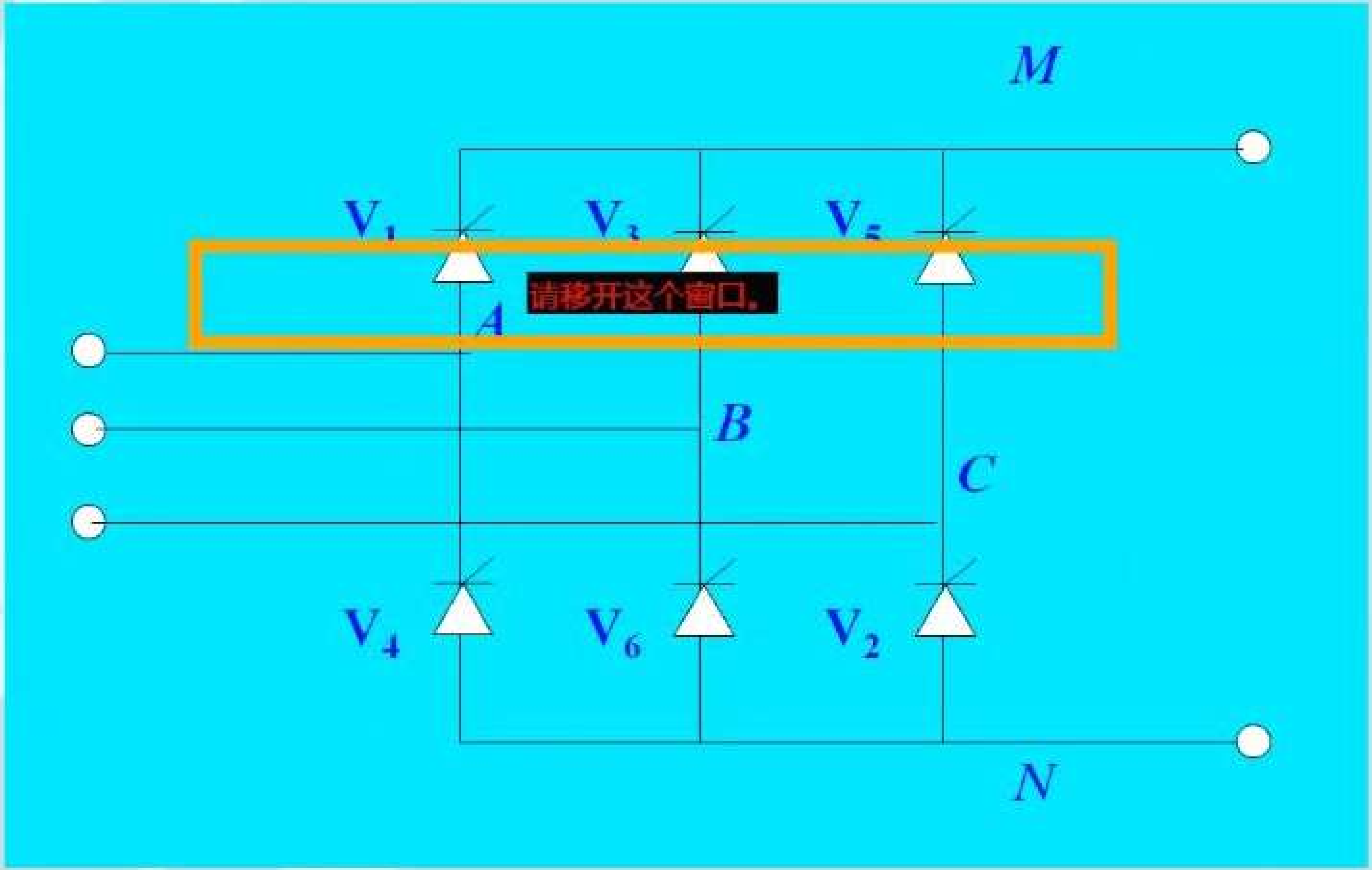
5）Damping resistance loss W_5:It refers to the loss caused by the AC voltage applied to both ends of the valve coupled to the damping resistance through the damping capacitance during the valve shutdown.

6）Capacitor charge discharge loss W_6:Loss due to step change of voltage applied to valve.

7）Valve off loss W_7:The loss of the reverse current flowing through the thyristor on the thyristor and the damping resistance during the closing process of the valve.

8）Hysteresis loss of valve reactor W_8

Schematic wiring diagram of three-phase bridge converter



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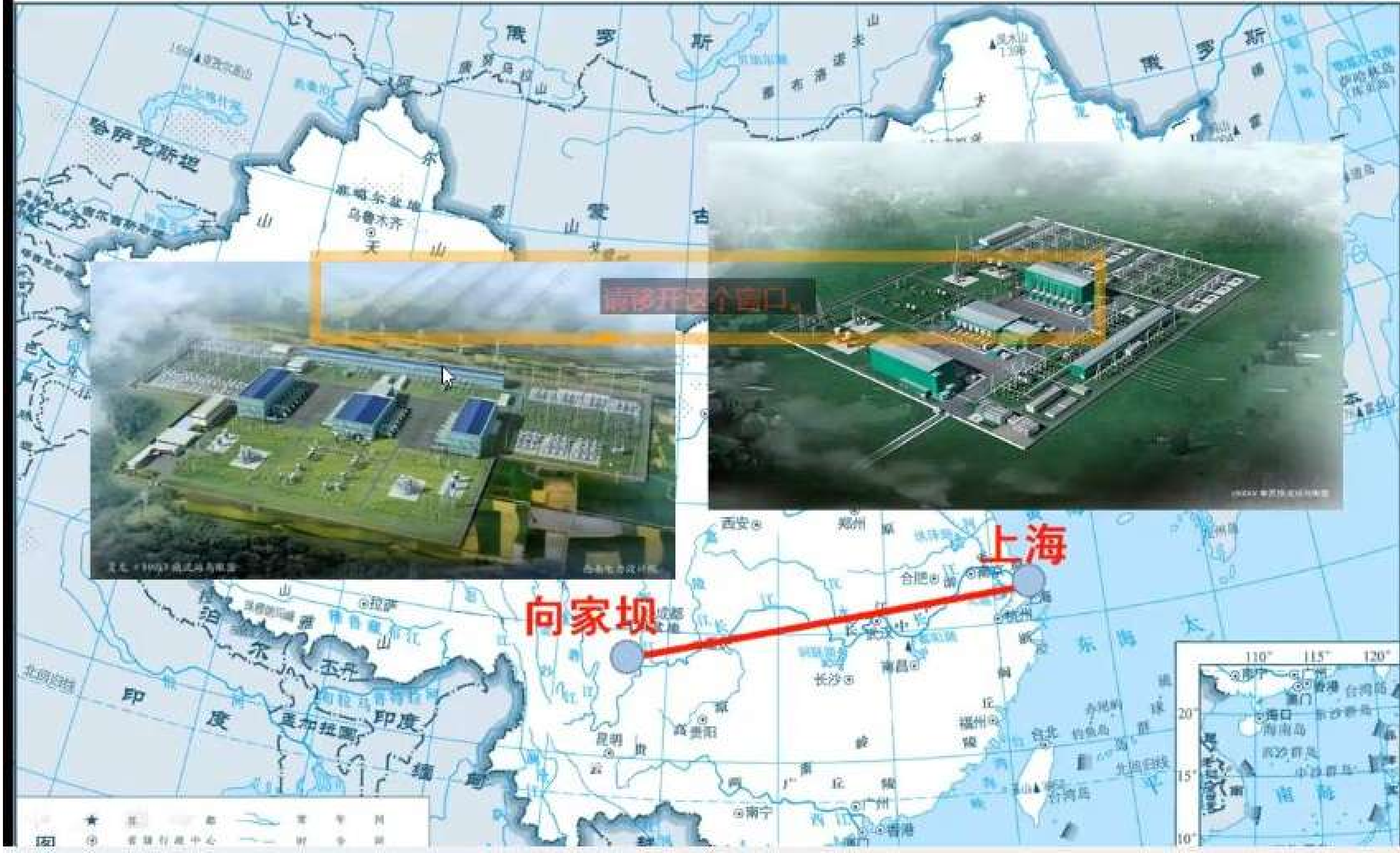
General Situation of Xiangjiaba-Shanghai Project




±800 kV Converter transformer


±800 kV DC line

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±800 kV DC converter station


±800 kV DC line

UHVDC transmission project in China's planning

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"12th Five Year Plan" DC transmission project

No.	Project	Voltage level (kV)	Conveying capacity (MW)	Commencement time	Production time
1	Jinping~South of Jiangsu	±800	7200	2008. 11	2012年12月
2	South of Hami~Zhengzhou	±800	8000	2012. 5	2014年9月
3	Xiluodu~West of Zhejiang	±800	8000	2012. 7	2014年12月
4	Ningdong~Shaoxing, Zhejiang	±800	8000	2013. 4	2015年10月
5	North of Hami~Chongqing	±800	8000	2014. 4	2016年10月
6	Hulun Buir~Qingzhou,Shandong	±800	8000	2015. 4	2017年10月
7	Xilin Gol~Taizhou, Jiangsu	±800	8000	2013. 6	2015年12月
8	West of Inner Mongolia~Wuhan, Hubei	±800	8000	2013. 6	2015年12月
9	Jiuquan~Hengyang, Hunan	±800	8000	2015. 1	2017年6月
10	Huai Dong~Chengdu, Sichuan	±1100	10000	2014. 4	2017年4月
11	Xilin Gol~Zhumadian, Henan	±800	8000	2015. 1	2017年12月
12	North of Shanxi~Xiangtan, Hunan	±800	8000	2014. 12	2017年12月

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UHVDC transmission project in China's planning

According to the development plan of State Grid Corporation of China, by the end of the 12th Five Year Plan, there will be 26 UHV converter stations and 54 UHV converter stations by the end of the 13th five year plan

Application of HVDC

- Long distance and large capacity transmission
- Asynchronous connection between AC power systems
- As a measure to limit the short circuit current when the AC power system is interconnected or the distribution network is increased
- Power supply to power intensive big cities
- Flexible (light) DC transmission

Power comparison between bipolar DC and three-phase AC

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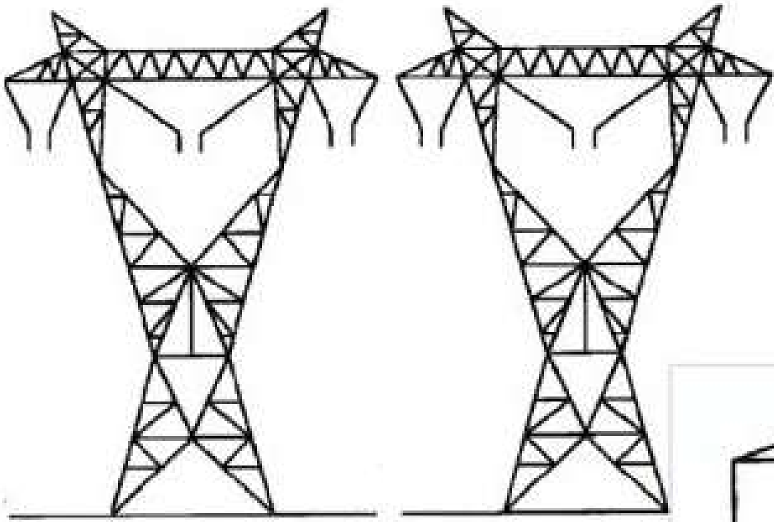
The power delivered by each conductor of DC line is $P_d=V_dI_d$
The power delivered by each conductor of AC line is $P_a=V_aI_a\cos\varphi$
When both of them adopt the same current density and have the same insulation level $P_d=1.5P_a$

It can be seen that the total power that can be delivered by the DC line with only two conductors is equivalent to that of the AC line with three conductors.

Therefore, DC transmission can save a lot of non-ferrous metals, steels, insulators and line fittings. In addition, DC transmission is superior to AC transmission in terms of line corridor, tower height and floor area.

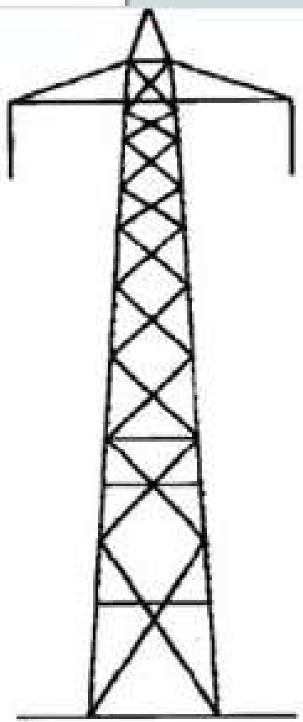
Save line corridor

Tower structure and line corridor corresponding to different transmission schemes with 2000 MW capacity



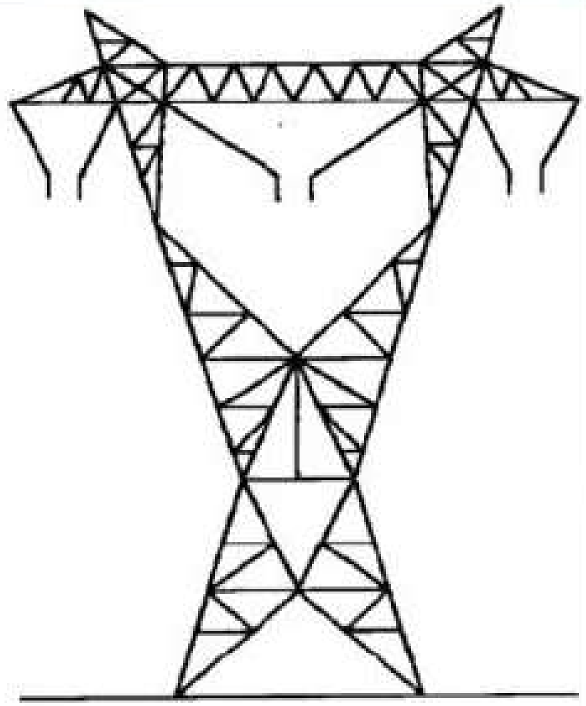
2 × 500 kV AC

100m



±500 kV DC

50m



800 kV AC

85m

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Disadvantages of HVDC

- Converter station equipment is expensive.
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- A large number of harmonics are produced in the operation of converter, which affects the operation of the system. Therefore, a large number of filter devices must be added.
- The converter has little overload capacity.
- At present, the technology of high voltage DC circuit breaker is not mature enough, which limits the development of multi terminal DC system.
- When the earth or sea water is used as the loop, it will corrode the metal components and pipes along the route and affect the navigation instruments.

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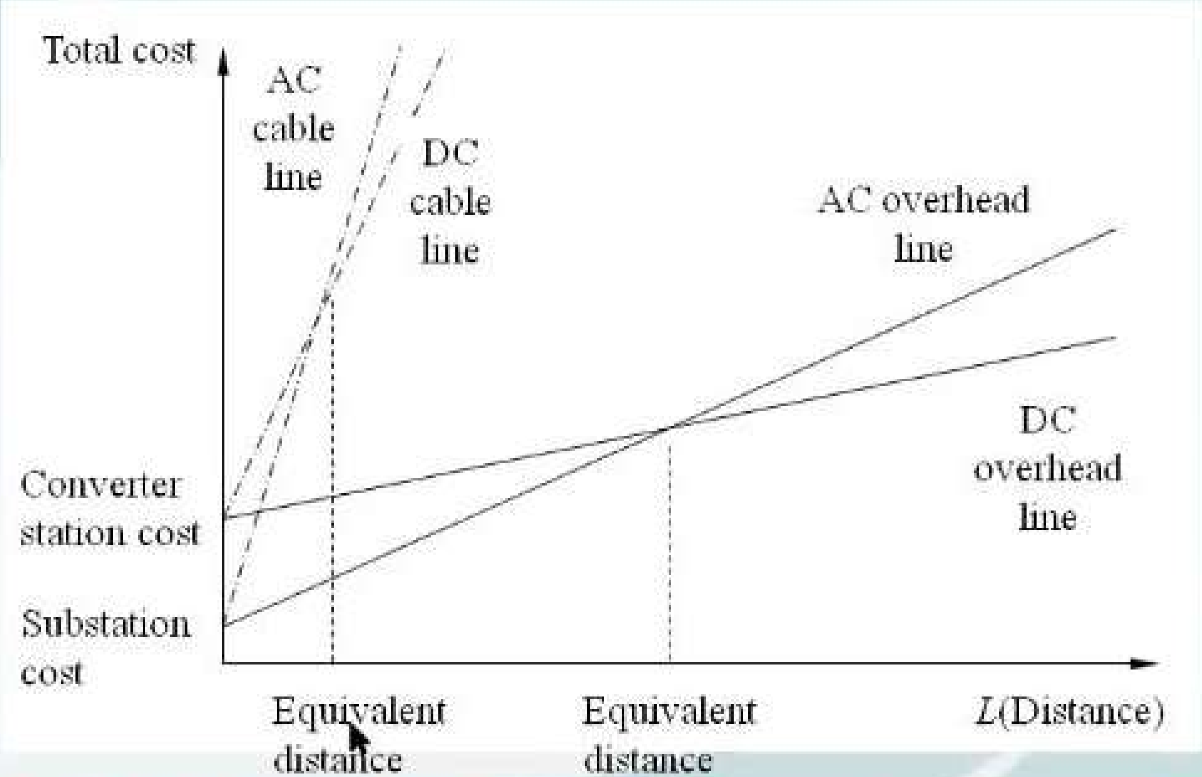
Equivalent transmission distance

- Under the comparable conditions of the same transmission power and comparable reliability indexes, the investment of converter stations is much larger than that of substations compared to DC, but the cost per unit length of DC transmission lines is lower than that of AC lines.
- When the transmission distance increases to a certain value, the investment (including the total cost of the line and the equipment at both ends) of the two will be equal. This distance is called the equivalent distance of AC / DC transmission.

Equivalent transmission distance



Equivalent distance between DC transmission and AC transmission

Equivalent distance of overhead line is about 640-960km
Equivalent distance of underground cable line is 56-90km
The equivalent distance of submarine cable line is 24-48km

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Loss of HVDC system

The engineering losses of DC transmission system include:

The losses of converter stations at both ends, DC transmission lines and grounding electrodes.

The loss of DC line depends on the length and cross-section of the transmission line. For long-distance DC transmission line, it accounts for 5% - 7% of the rated transmission capacity, which is the main part of the loss of DC transmission.

The equipment of converter station is various and the loss mechanism is different, so it is difficult to calculate accurately. The current method is to test and calculate the losses of the main equipment in the converter station, and then add these losses to get the total loss, which is generally 0.5% - 1% of the transmission capacity.

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Loss of HVDC system

Characteristics of converter station loss:

1) There are many kinds of equipment, the loss mechanism is different, and the loss of the same equipment is different under different operating conditions.

2) Normal operation will produce harmonics, harmonic current will produce additional loss.

3) Considering different load levels, the input of equipment is different, so the loss is also different.

4) Generally, the loss is divided into hot standby (also known as no-load loss or fixed loss) and total operation loss (hot standby loss and load loss, the latter also known as variable loss). Select several load points between no-load and full load to calculate the loss of converter station.

Loss of HVDC system

Calculation method of converter station loss

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Load loss	27% – 39%	AC filter	7% – 11%
		Other losses	4% – 9%

Loss of HVDC system

Loss of main equipment in converter station

Loss of thyristor converter valve
Loss of converter transformer
Loss of smoothing reactor
Loss of shunt capacitor
Loss of shunt reactor
Loss of AC filter
Loss of DC filter
Station power loss
Other losses

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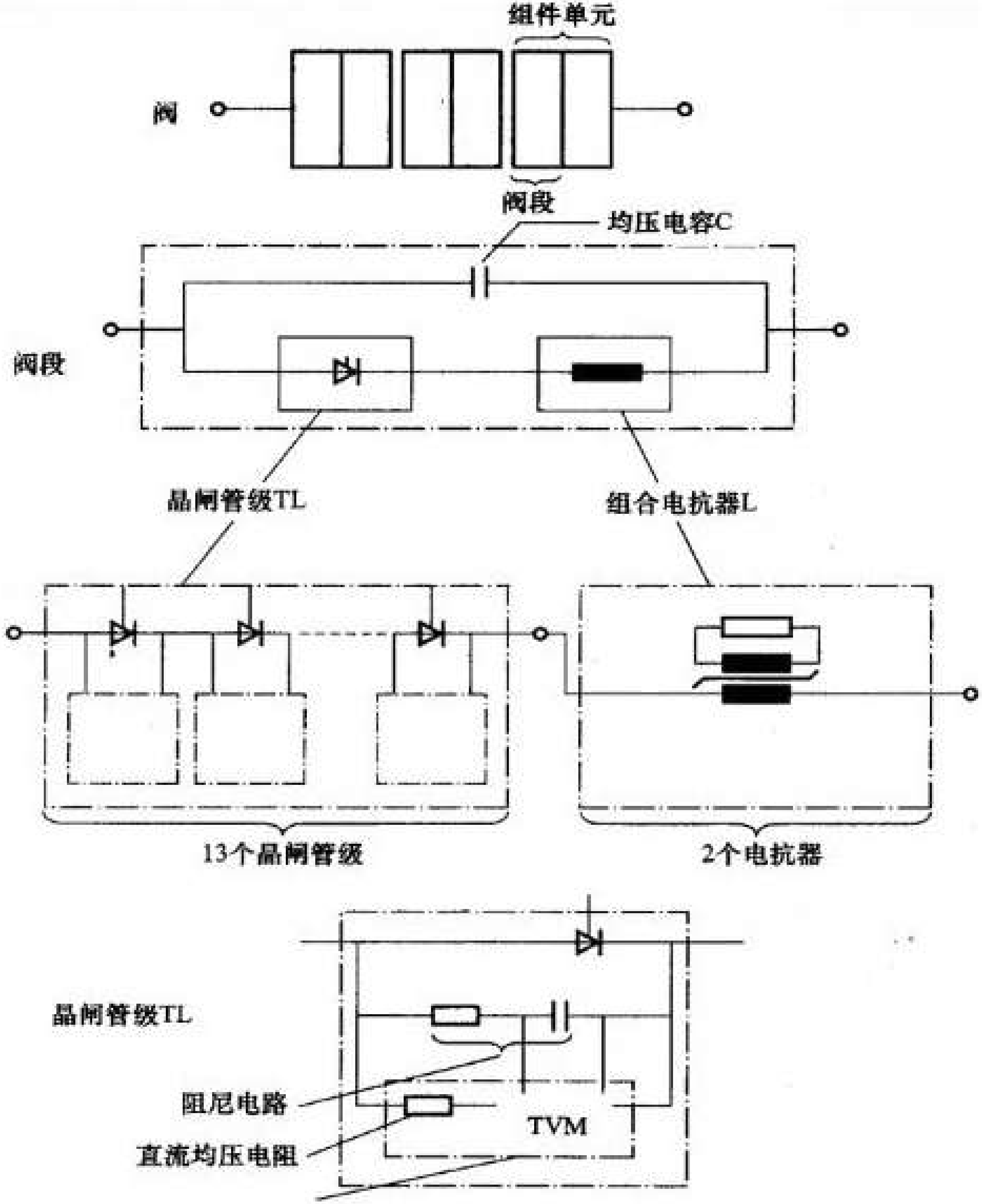
1) Loss of thyristor converter valve

The thyristor converter valve is mainly composed of thyristor, valve reactor, DC equalizing resistance, damping capacitance and resistance, steep wave equalizing capacitance, thyristor triggering and monitoring system, etc. 85% - 95% of the loss of the converter valve is caused by the thyristor and damping resistance.



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Loss of HVDC system

1）Conduction Losses of Valve W_1:The loss caused by the current flowing through the thyristor when conducting is considered in the calculation.

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7）Valve off loss W_7:The loss of the reverse current flowing through the thyristor on the thyristor and the damping resistance during the closing process of the valve.

8）Hysteresis loss of valve reactor W_8

Loss of HVDC system

2) Loss of converter transformer:

Including no-load loss and load loss. Because the converter will produce a lot of harmonics, the load loss of converter is larger than that of common power transformer.

1 Loss of hot standby:under hot standby = no load

2 Operation loss:excitation loss (core loss) + current related load loss, mainly considering the relationship between copper loss and frequency under harmonic frequency.

Loss of HVDC system

3) Loss of other main equipment

① Loss of smoothing reactor

Consider the loss caused by DC loss and harmonic

② Loss of shunt capacitor

The loss of harmonic current is very small and can be ignored. The power frequency loss is given at the time of delivery.

③ Loss of shunt reactor

Factory test for measurement

④ AC filter and DC filter

Including: loss of reactance, capacitance and resistance

⑤ Station power loss

Loss varies with the state of operation.

⑥ Other: refers to the loss caused by other auxiliary measurement, lightning arrester and other equipment.

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Loss of HVDC system

Loss of DC line

DC line losses include voltage related losses and current related losses.

1. The loss related to voltage mainly refers to the corona loss and insulator leakage loss of the line, the latter value is small and ignored.

The two pole voltage and corona current of the line are measured respectively by the measured statistical method

$$\Delta P_C = U_{d1} \cdot I_1 + U_{d2} \cdot I_2$$

2. Current related loss refers to the loss generated on the line resistance.

$$\Delta P_d = R_d \cdot I_d^{\,2}$$

Rd is related to the operation mode of DC system.

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Loss of HVDC system

Loss of earth electrode system

The grounding electrode system includes grounding electrode and grounding electrode lead. The loss of the grounding electrode system is closely related to the operation mode.

Single pole or double wire parallel earth loop mode: DC load current will all pass through the grounding electrode system, and its loss will be calculated according to DC load current;

Single pole metal circuit mode: no current passing through the grounding electrode system, no loss;

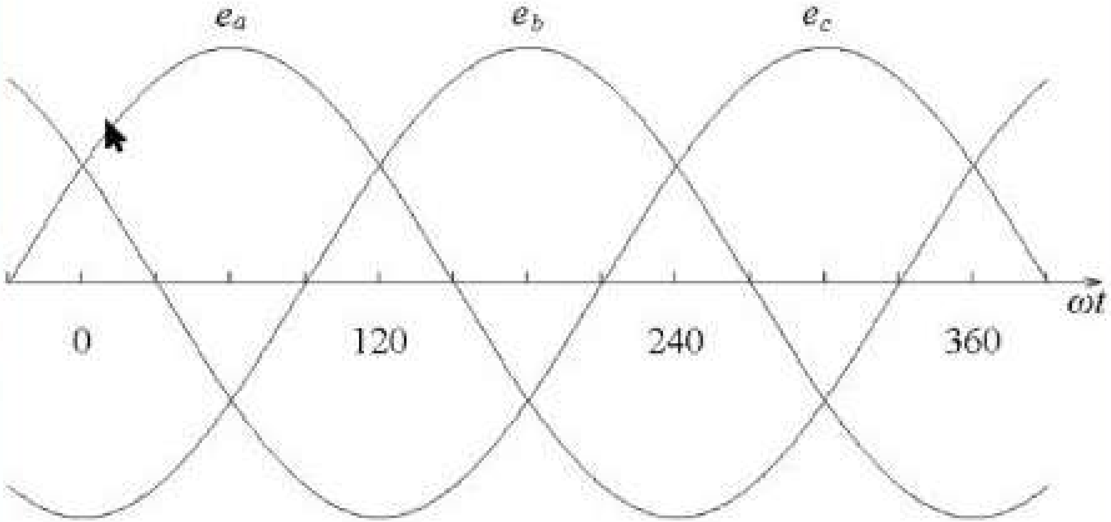
Bipolar current symmetry mode: the current flowing through the grounding electrode system is less than 1% of the rated DC current, resulting in negligible loss;

Bipolar current asymmetry mode: the current flowing through the grounding electrode system is the difference between the two poles, then the loss of the grounding electrode system is calculated according to the difference between the two poles.

The loss of grounding electrode line and grounding electrode is calculated according to the current.

Three phase power supply at AC side

$$e_a = \sqrt{2}E\sin(\omega t + 30°)/\sqrt{3}$$
$$e_b = \sqrt{2}E\sin(\omega t - 90°)/\sqrt{3}$$
$$e_c = \sqrt{2}E\sin(\omega t + 150°)/\sqrt{3}$$



- The vector of e_{ac} is the reference.
- E is the effective value of EMF of AC power line

$$e_{ac} = e_{co} + e_{oa} = e_a - e_c = \sqrt{2}E\sin\omega t$$
$$e_{ba} = e_{ao} + e_{ob} = e_b - e_a = \sqrt{2}E\sin(\omega t - 120°)$$
$$e_{cb} = e_{bo} + e_{oc} = e_c - e_b = \sqrt{2}E\sin(\omega t + 120°)$$

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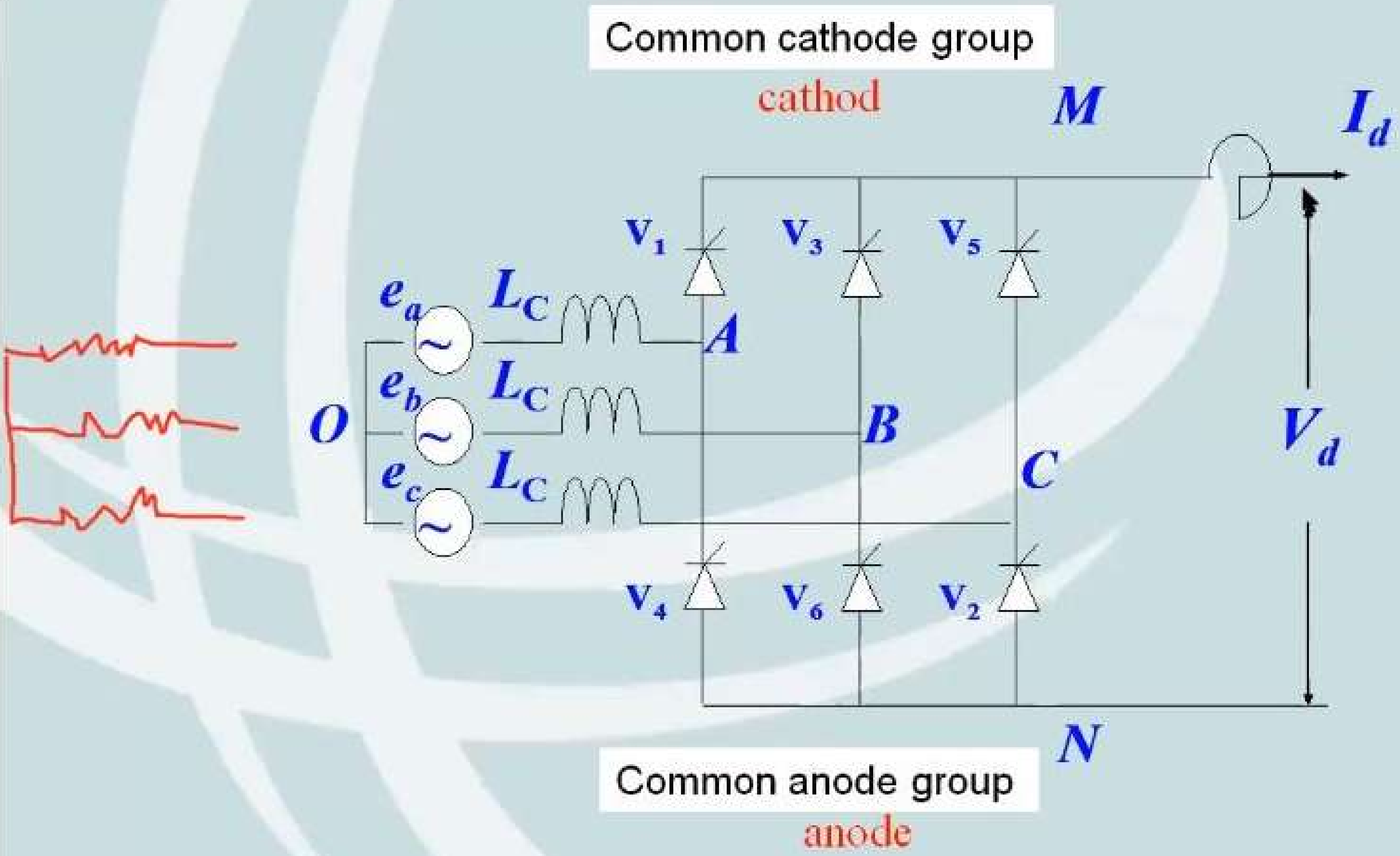
6 working principle wiring diagram of pulse rectifier



3 Commutation theory

4.1 Main Circuit and Main Equipment

Rated Value of HVDC system is a continuous operation mode, and when the power be transmited from the Matiari C/S to Lahore C/S , in the dc line side of smoothing reactor of converter station, continuous operation with the following ratings:

Rated Power: Bipole 4000MW, Monopole 2000MW
Rated Voltage: ±660kV
Rated Current: 3030kA

Bird's Eye View of ±660kV Matiari Converter Station

Bird's Eye View of ±660kV Lahore Converter Station

4.1 Main Circuit and Main Equipment

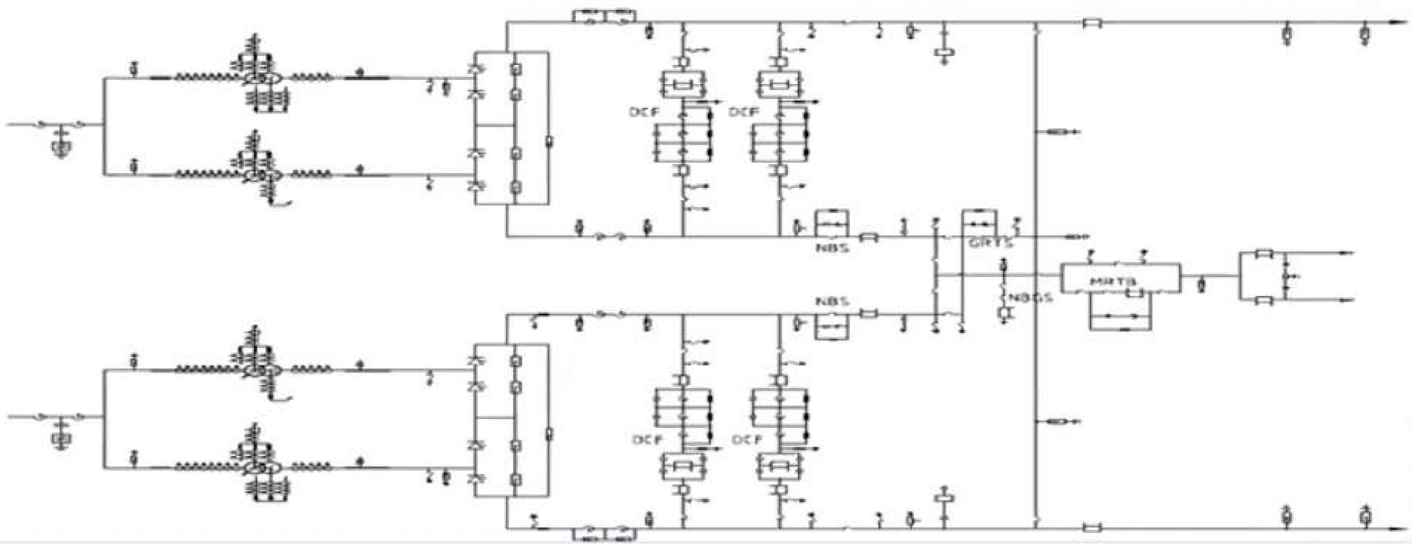


Fig . Single Line diagram of M C/S
One 12-pulse valve group for each pole
Transformer（6+1）units for each pole

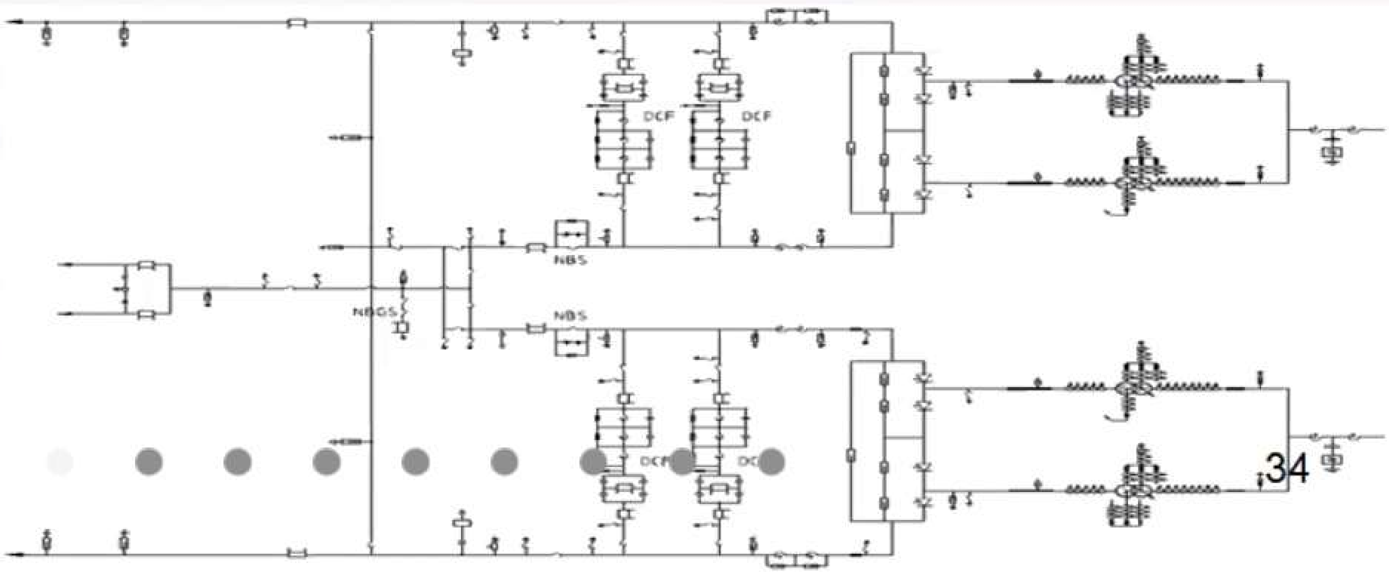
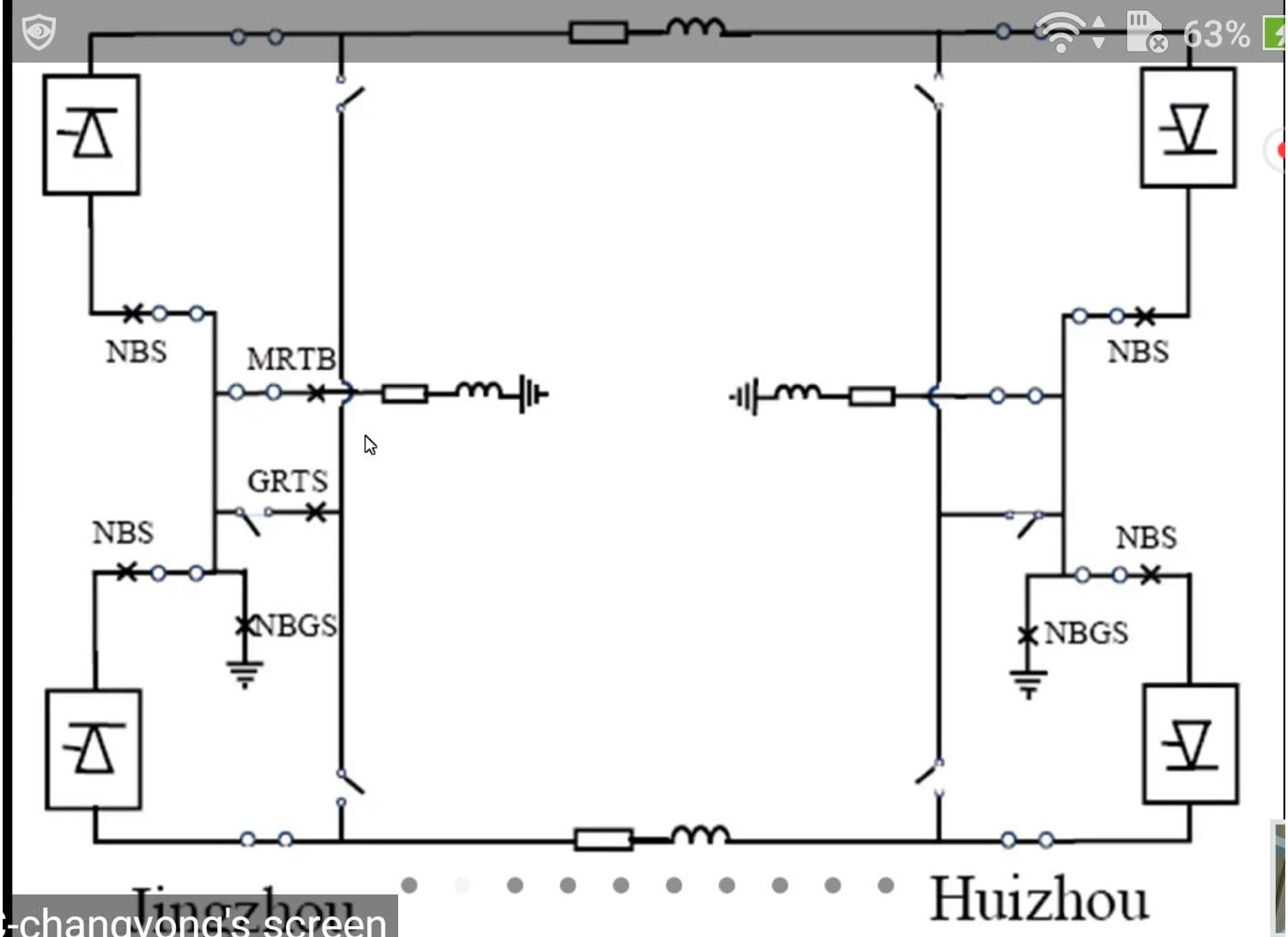


Fig . Single Line diagram of L C/S
One 12-pulse valve group of each pole
Transformer（6+1）units for each pole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