Selected Topic:
Introduction to High Voltage Insulation
(Content and purpose of study and research)

I. Problems & developments of Insulation technologies

II. Main contents of high voltage insulation research

III. Dielectrics for study of high voltage insulation

IV. Purposes of high voltage insulation research

I. Problems and developments of insulation technology

1. Basic concepts of insulation and the main causes of problems

- **Electrical insulation:** Using dielectrics to isolate different potentials
- **Insulation problems mainly come from three aspects:**
  - ✓ The first, the worldwide demand for electricity is growing rapidly, and thus the continuous increase in high voltage and large capacity of power generation, transmission and transformation equipment
  - ✓ The second, the application fields of electrical equipment are continuous to be expanded, and thus the operating environment becomes more and more complex and harsher
  - ✓ The third, the demand of higher reliability and more economics of electrical equipment

I. Problems and developments of insulation technology

2. Insulation problems caused by high voltage and large capacity transmission

- Major AC systems in chronological order of their installation (the first time of each AC voltage level transmission system occurs)

Voltage (kV)	10	50	110	220	287	380	525	735	1150
Year	1890	1907	1912	1926	1936	1952	1959	1965	1985

In 100 years, the world's transmission voltage level has increased by 100 times

- Voltage level of DC transmission system (kV):

Voltage (kV)	±100,	±160,	±200,	±320,	±400,	±500,	±660,	±800,	±1100
Year	1954							2010	2019

I. Problems and developments of insulation technology

Problems of insulation discharge of EHV equipment are still prominent

Discharge failure of 500 kV transformer (China)

Fire accident of 500 kV transformer Caused by insulation

Discharge failure of 500 kV reactor (Brazil)

Tsinghua University

I. Problems and developments of insulation technology

Deflagration simulation test of transformer

I. Problems and developments of insulation technology

Failures of 220 kV Zhanglian 1 power cable transmission line (Beijing)

By Beijing EPC

I. Problems and developments of insulation technology

Failure of the B-phase cable of 02 unit of Fuchunjiang Plant

By East China EPRI

I. Problems and developments of insulation technology

3. The insulation problem caused by the complexity of the environment and the expansion of the application field

(1) Application environment of dielectrics and energy technologies

(2) Application of dielectrics in information technologies and biotechnologies

(3) Electrical equipment and insulation technology

I. Problems and developments of insulation technology

3. The insulation problem caused by the complexity of the environment and the expansion of the application field

(1) Application environment of dielectric and energy technologies

- Application fields of electrical equipment has extended from conventional to extreme conditions
  - ✓ **Harsh atmospheric environment, high temperature, extremely high temperature, high vacuum, high pressure and high gas pressure:** power transmission from west to east, high altitude, dusty, hot and humid zone, deep oil exploration and aerospace
  - ✓ **Radiation field:** Nuclear energy and applications, electromagnetic ejection, frequency conversion, microwave, plasma and high power pulses
  - ✓ **Chemical atmosphere, ultra-low temperature:** immersed in water, immersed in oil, immersed in brine, low temperature superconductivity and other special operating environments

I. Problems and developments of insulation technology

Outdoor insulation problems

DC power transmission

AC compact power transmission

I. Problems and developments of insulation technology

Outdoor insulation problems

Hydrophobicity measurement after the first snow cover

Hydrophobicity measurement after the second snow cover

Bottom surface hydrophobicity of the insulator after the third snow cover in 2003

I. Problems and developments of insulation technology

Outdoor insulation problems

Halo phase | Arcing stage | Arc development | Lightning arc

Four stages of the arc development during icing flashover of the insulator

I. Problems and developments of insulation technology

Outdoor insulation problems

Damage to the insulator after icing flashover

I. Problems and developments of insulation technology

Outdoor insulation problems

Tracking and erosion

I. Problems and developments of insulation technology

Insulation problems of two-phase fluid

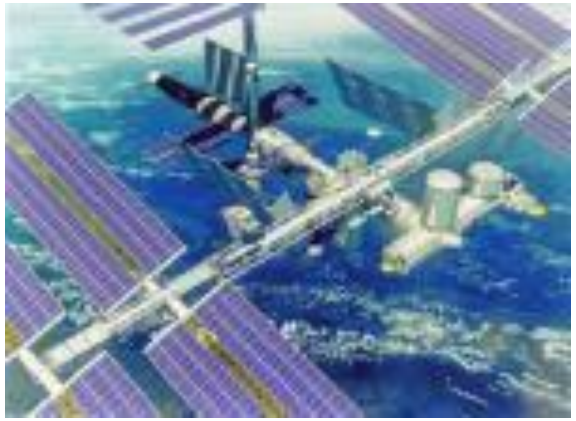
50 MW evaporative cooling turbine generator

Model of 200 MW evaporative cooling turbine generator

Evaporative Cooling Technology

I. Problems and developments of insulation technology

Insulation problems in space

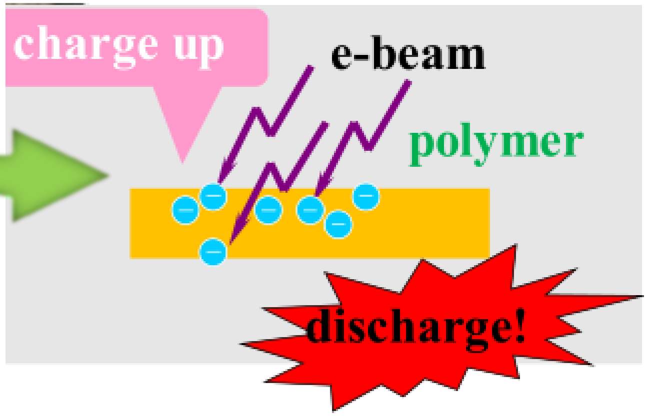


Cover of solar battery panel (glass)

Thermal blanket (Kapton)

Spacecraft

e-beam, proton
(charged particles)
UV, x-ray, γ-ray
(electro-magnetic waves)



In space environment,

high energy rays → bulk charge

Charging causes unexpected accidents
Heat flux pass through the blanket
Break the connection between battery cells

By T. Takada

清華大学
Tsinghua University

I. Problems and developments of insulation technology

Insulation problems at low temperature

August 2003: 10m/10.5kV/1.5kA HTS power cable system

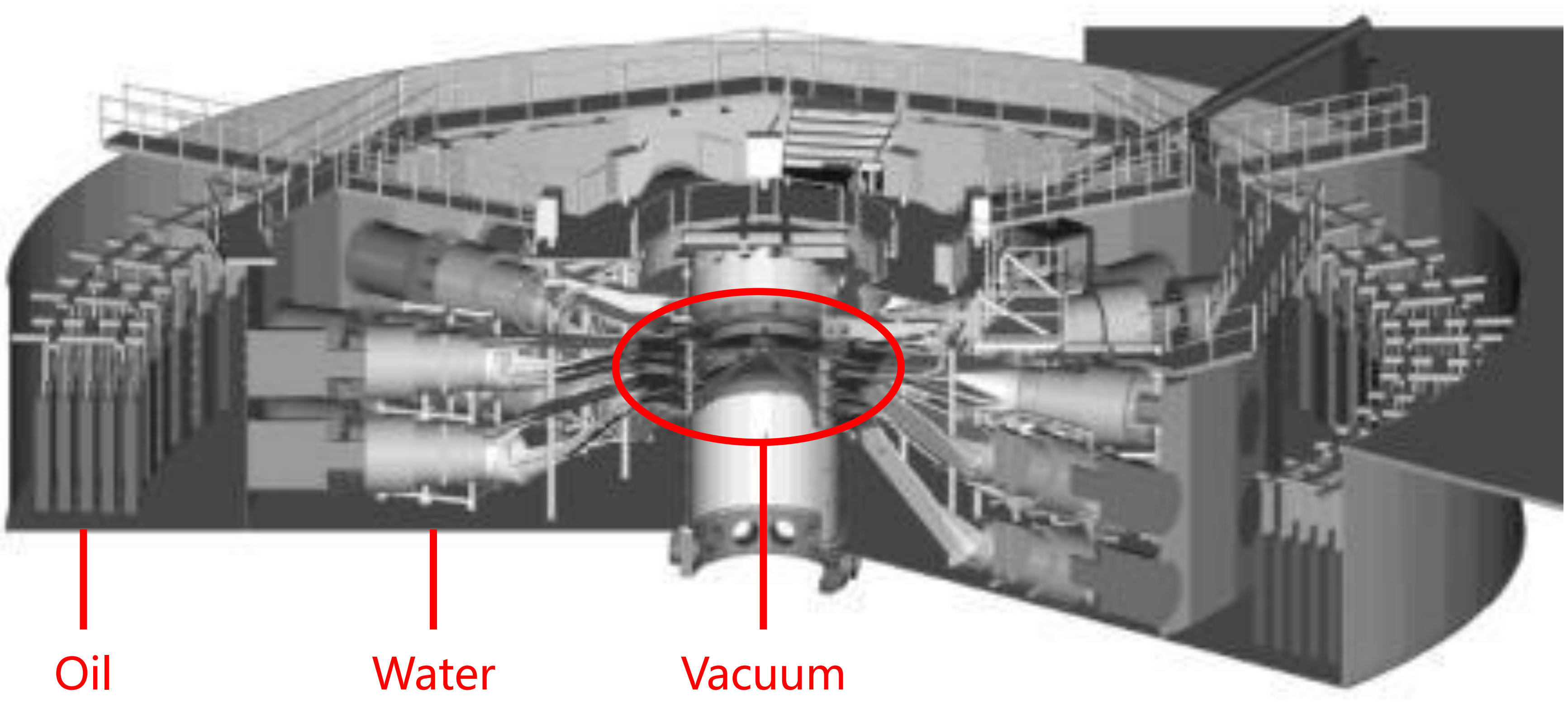
75m/10.5kV/1.5kA HTS power cable system has been grid-connected in Gansu Province in 2004

The Applied Superconductivity Laboratory

By CAS IEE

I. Problems and developments of insulation technology

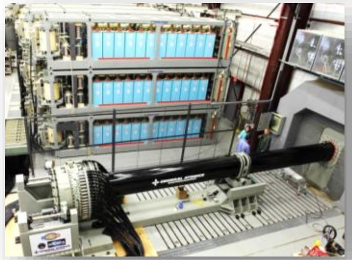
Insulation problems under radiation condition

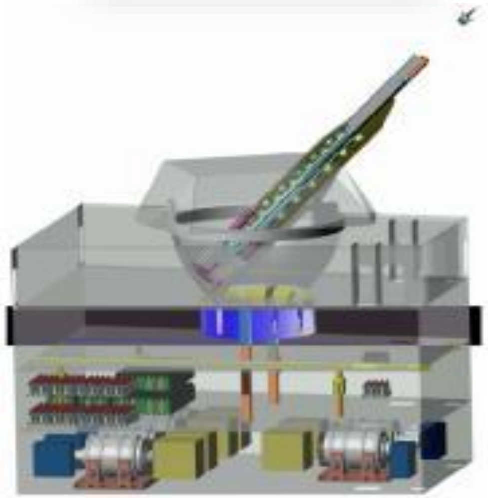
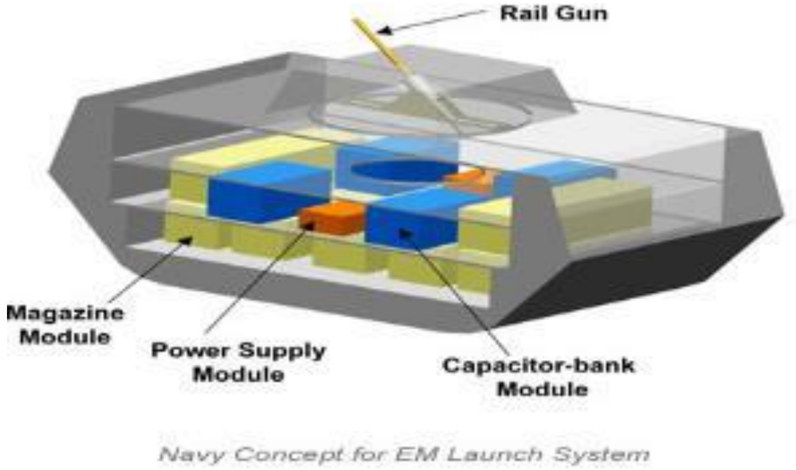


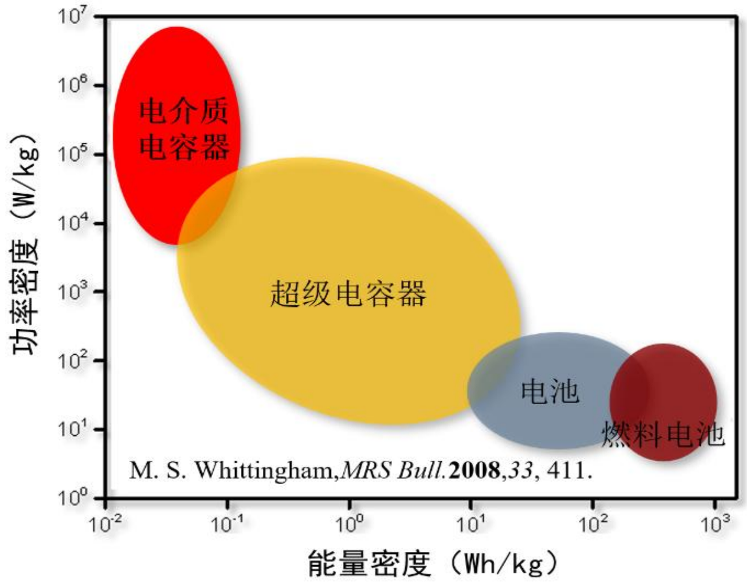
Z-pinch

I. Problems and developments of insulation technology

Insulation problems of high density energy storage





Electromagnetic orbital launch system and railgun

I. Problems and developments of insulation technology

Insulation problems under harmonic and light DC conditions

New Energy Resources Power Generating Technology

Control system of large-scale wind power generator

By CAS IEE

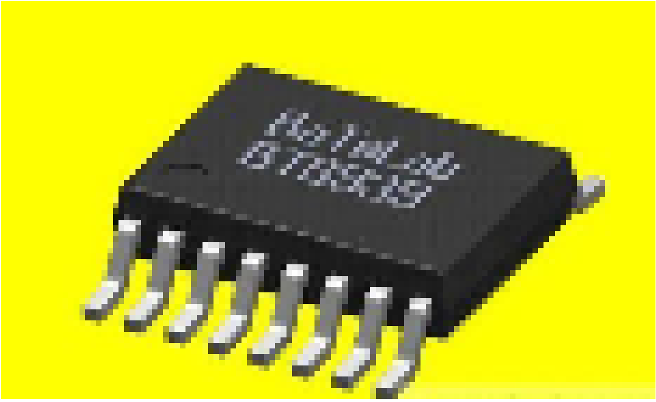
清華大學 Tsinghua University

I. Problems and developments of insulation technology

3. The insulation problem caused by the complexity of the environment and the expansion of the application field

(2) Dielectric applications in information technology and biotechnology

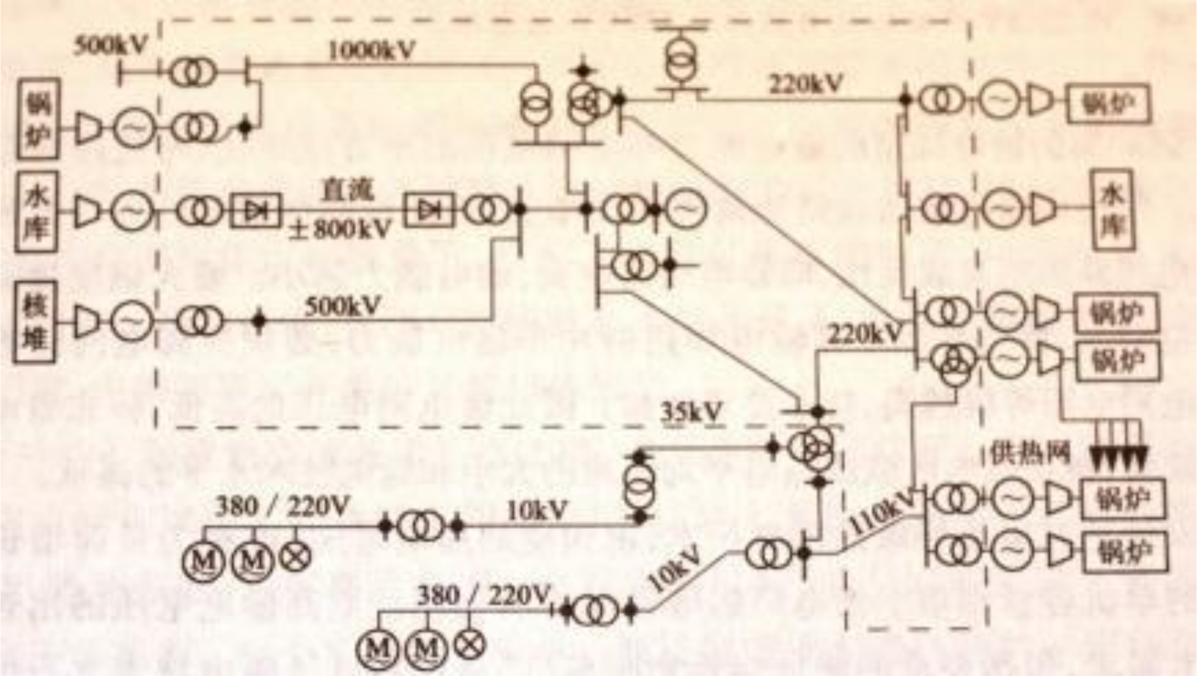
- **Integrated circuit and its package insulation, printed circuit board insulation:** micro and nano processing technology means strong electric field insulation technology
- **Biodielectric:** piezoelectric and pyroelectric effects of biomass



I. Problems and developments of insulation technology

3. The insulation problem caused by the complexity of the environment and the expansion of the application field

(3) Electrical equipment and insulation technology

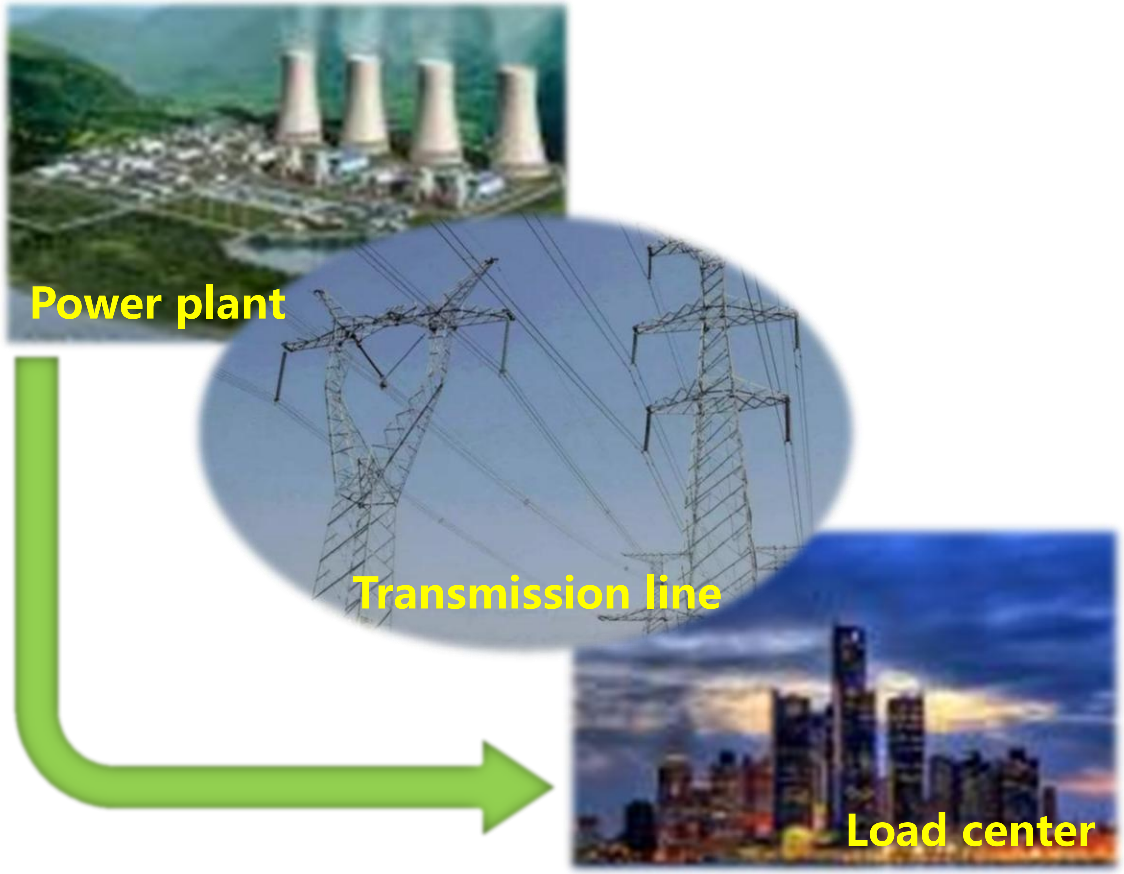


Power system

Generation, transmission/transformation, distribution and usage of electricity

I. Problems and developments of insulation technology

The electrical equipment of the power grid



1000kV substation in southeast Shanxi

I. Problems and developments of insulation technology

Transmission line

Cable tunnel

Overhead line

Gas-insulated transmission line (GIL)

I. Problems and developments of insulation technology

The electrical equipment of the power grid

- Transformer
- Insulator
- Bushing
- Arrester
- Cable
- Circuit breaker/switch
- Capacitor
- Reactor
- GIS
- GIL
- Current transformer
- Voltage transformer
- Converter valve
- Flexible DC insulation
- Overhead line
- Converter transformer
- Generator
- Motor

- These power devices form the basic components of the power system
- Without these devices, there would be no power system
- Without dielectric insulation materials, there is no electrical equipment
- Dielectric insulation material is the decisive foundation of power system safety, reliability and stability!

I. Problems and developments of insulation technology

4. Reliability and economics of electrical equipment

(1) High performance and stability of electrical equipment

(2) Miniaturization of electrical equipment

(3) Economics of electrical equipment

(4) Suitability for a wide range of applications

II. Main study contents of high voltage insulation

1. Insulation theories

2. Insulation materials

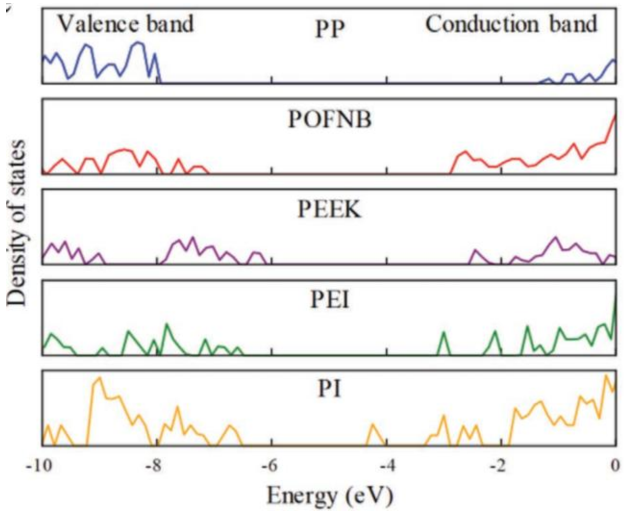
3. Insulation structures

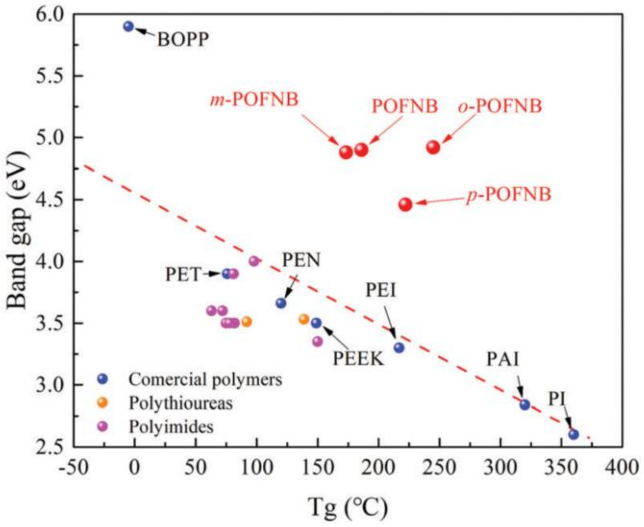
4. Insulation tests

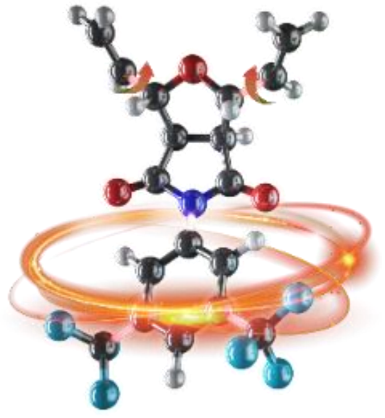
II. Main study contents of high voltage insulation

1. Insulation theories

- From the orbital theory of electron motion, energy level theory, atomic structure theory and mechanical statistics, the quantum mechanical basis of dielectric insulation theory is formed.
- Based on these basic theories, some phenomena and laws of insulation technology are summarized theoretically to guide the insulation technology.







Advanced Materials, vol. 32, p. 2000499, 2020.

II. Main study contents of high voltage insulation

2. Insulation materials

- Knowledge and improvement of material properties, development of new insulating materials.
- The application of insulation materials goes through the process from initial to mature.
  - ✓ SF_6 gas and GIL/GIS，F free gas
  - ✓ Composite insulation with oil and film/film-paper
  - ✓ High fire point oil for transformer
  - ✓ Ceramic/glass outdoor insulation to silicone rubber insulator
  - ✓ BOPP capacitor dielectric to high temperature dielectric film
  - ✓ Degradable dielectrics

II. Main study contents of high voltage insulation

3. Insulation structure

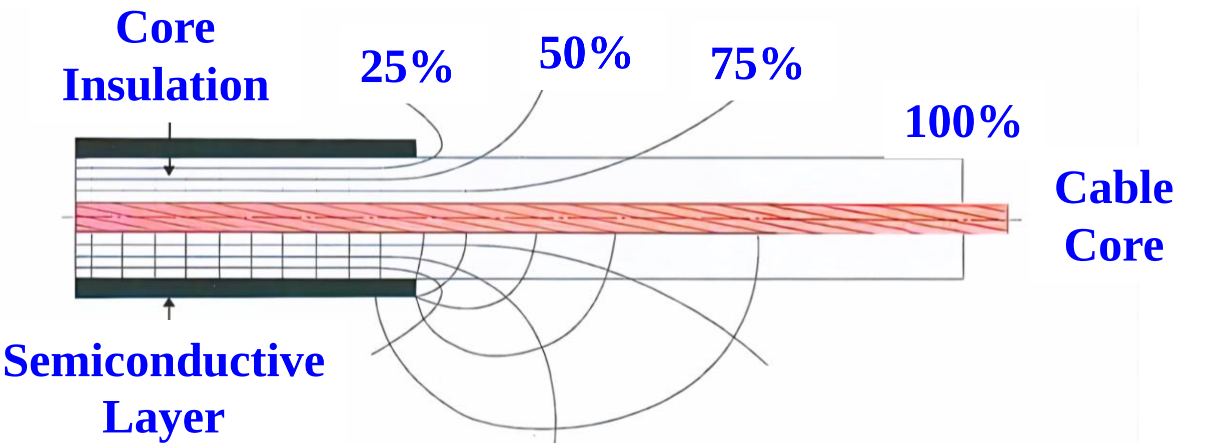
- **Physical and chemical structure of the materials:** the improvement of the insulation technology level is also reflected in the insulation materials that can form a good insulation structure
  - ✓ polyester, polyimide film, enameled wire, solvent-free paint, polyarylamide fiber paper......

- **Equipment insulation structure (combination, optimization and process):** due to the overall requirements, the conversion of insulating materials into insulating structures also needs to go through the necessary process treatment
  - ✓ These insulation processes often have certain uniqueness and determine the quality of the insulation structure to a considerable extent

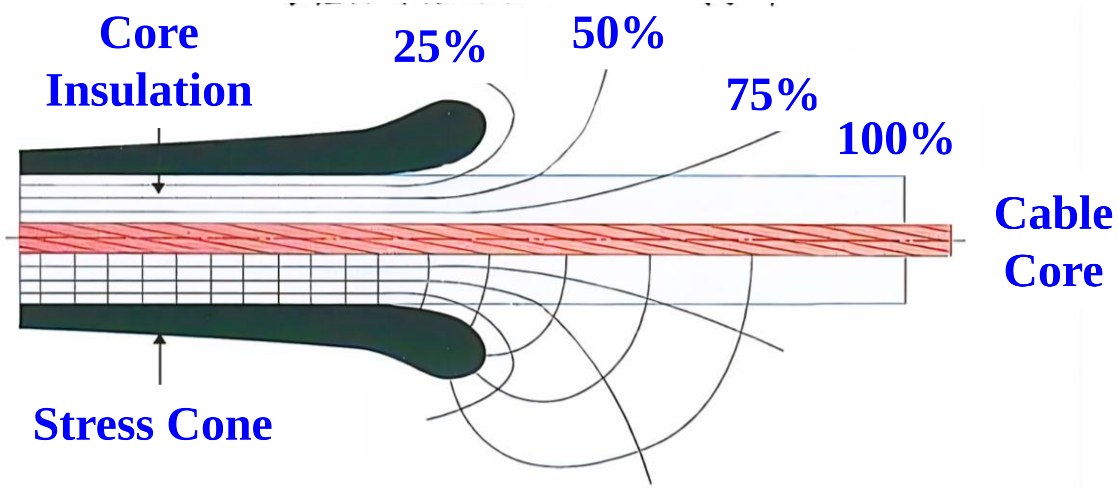
II. Main contents of high voltage insulation research

Structural optimization studies

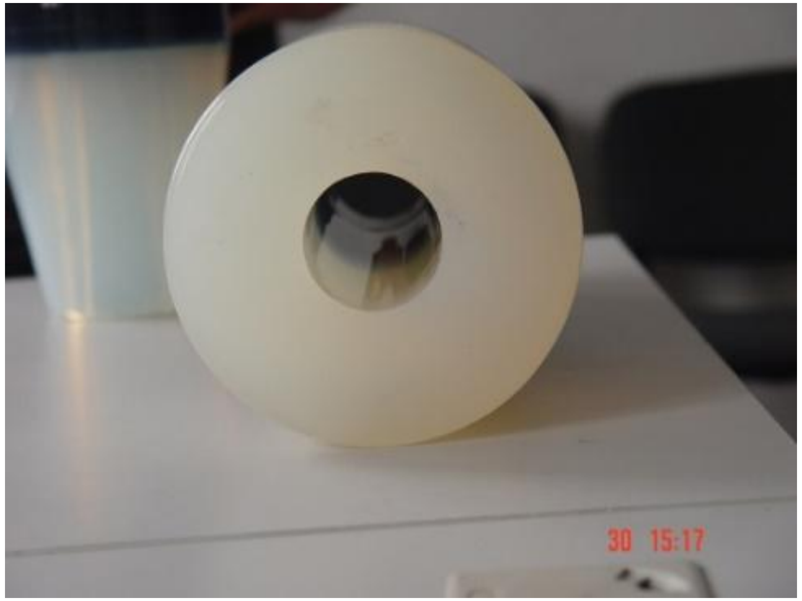
Axial Equipotential Line Distribution without Stress Cone

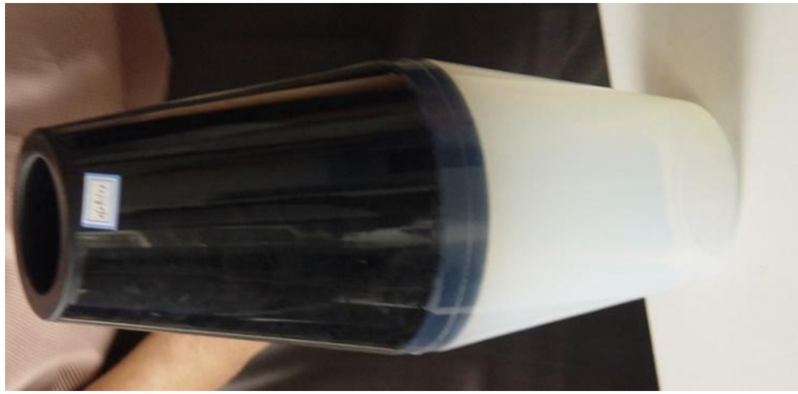


Axial Equipotential Line Distribution with Stress Cone



Some of our research





Stress cone design and computation

II. Main contents of high voltage insulation research

Structural optimization studies

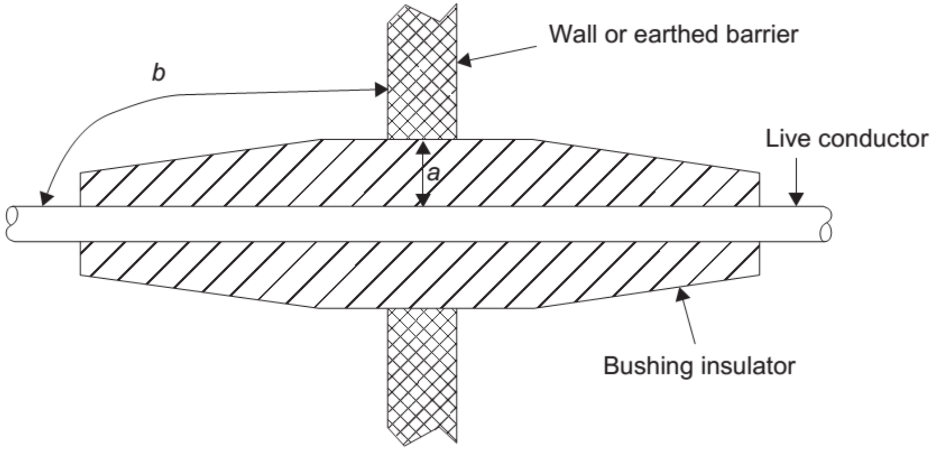


Figure 12.1 Non-condenser bushing

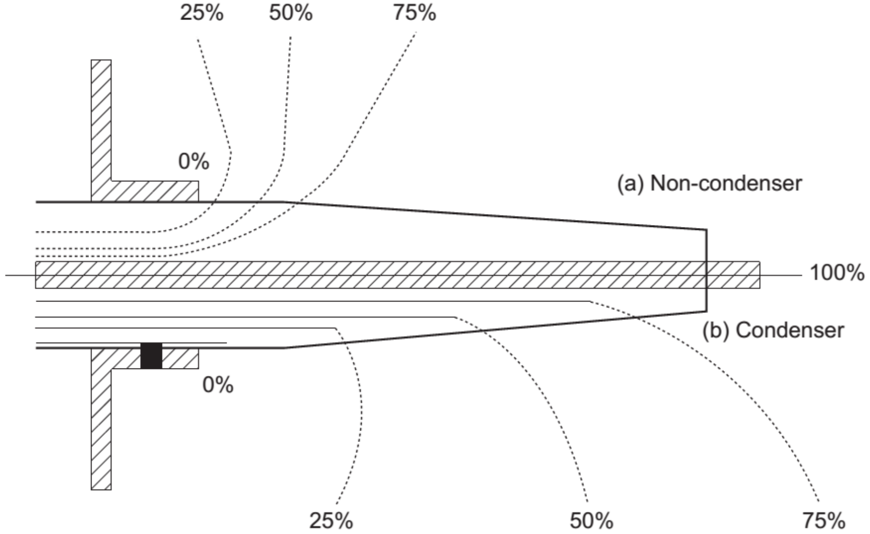


Figure 12.5 Field distribution in non-condenser and condenser bushings

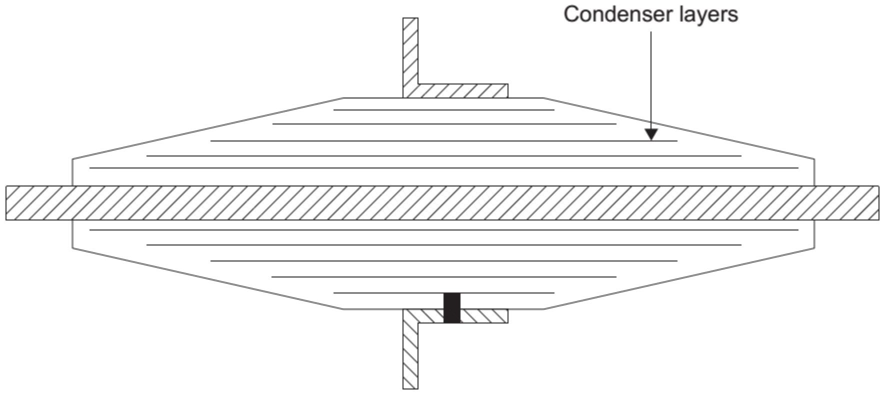


Figure 12.4 Condenser bushing

II. Main study contents of high voltage insulation

4. Insulation tests

- **Equipment insulation testing and diagnosis** (Engineering convention)
  - ✓ Insulation resistance
  - ✓ Leakage current
  - ✓ Partial discharge
  - ✓ Loss factor
  - ✓ Withstand voltage test
  - ✓ ……

- **Material analysis** (Laboratory level)
  - ✓ Microscopy observation
  - ✓ Scanning Electron Microscopy (SEM)
  - ✓ Thermal analysis (DTA/G) (DSC)
  - ✓ X-ray diffraction method (RAD-1A)
  - ✓ Fourier Transform Infrared Spectroscopy (FTIR)
  - ✓ ……

Characterization of insulating materials

III. Dielectrics for study of high voltage insulation

- **Gas insulating dielectrics:** air, SF_6 , discharge mechanism, external insulation
- **Liquid insulating dielectrics:** polarization, conductance, loss, aging, breakdown
- **Solid insulating dielectrics:** polarization, conductance, loss, aging, breakdown

By Summary, main study contents:
Dielectrics, theory, structural design, testing and evaluation

Chapter 4 Electrical properties of liquid and solid dielectrics

4.1 Basic concepts of electrical properties of dielectrics

4.2 Polarization, conductance and loss of liquid and solid dielectrics

4.3 Electric breakdown in liquid dielectrics

4.4 Electric breakdown in solid dielectrics

4.5 Space charge in dielectrics

4.6 Composite insulation

4.7 Other properties of dielectrics

Concepts of this chapter

- **Core concepts:** Electrical properties of dielectrics, the main parameters characterizing the electrical properties of dielectrics
  - ✓ Dielectrics, Polarization, Conductance, Dielectric power loss, Small bridge breakdown (Suspended solid particle mechanism), Electrical breakdown, thermal breakdown
  - ✓ Electrochemical breakdown, aging, cumulative effect, space charge
  - ✓ Oil-paper insulation, electric field in dielectrics
- **Other properties of dielectrics**
  - ✓ Thermal properties, heat resistance grade, cold resistance, mechanical properties
  - ✓ Moisture absorption, chemical properties, biological resistance

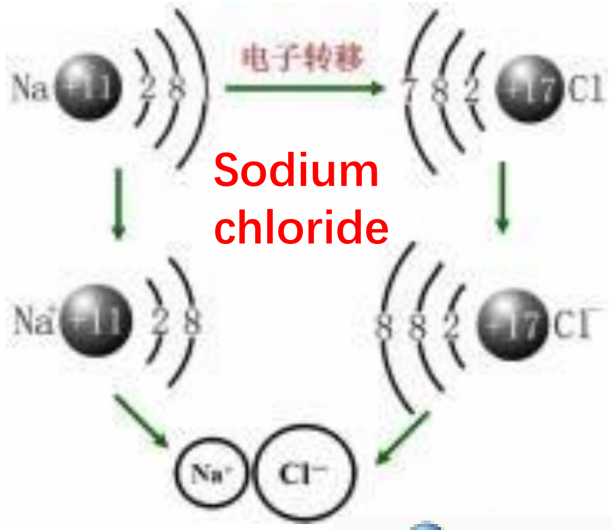
4.1.1 Basic knowledge of dielectric material structure

1. The basic concept of dielectrics

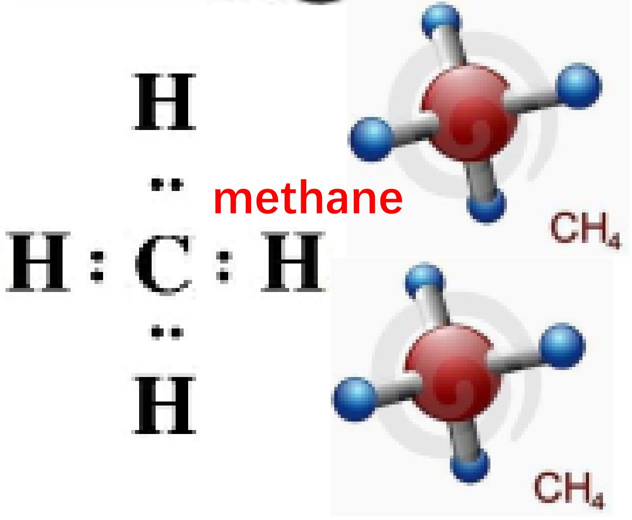
- **The basic concept of dielectrics**
  - ✓ Solids, liquids and gases that have no conductive electrons, and can be polarized in an electric field, are called dielectrics
- **The significance of dielectrics**
  - ✓ Similar to conductors, semiconductors and magnetic materials, dielectrics are an important part of electrical materials and an indispensable basis for electrical equipment
- **The function of dielectric**
  - ✓ **Functional materials:** insulation, energy storage, piezoelectric, pyroelectric, photoelectric, ferroelectric materials
  - ✓ **Insulating materials:** High insulation resistance for electrical insulation, high dielectric constant for energy storage

4.1.1 Basic knowledge of dielectric material structure

2. Various bonds that form molecular and condensed matter



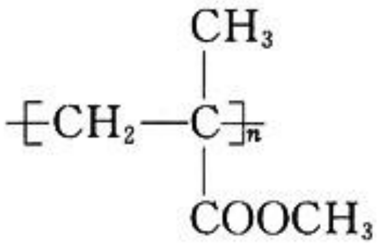
- **Ionic bonds**
  - ✓ Positive and negative ions are combined into molecules by electrostatic coulomb forces, that is, ionic bonds formed between positive and negative ions (such as NaCl)
- **Covalent bonds**
  - ✓ A stable electron layer structure is achieved by combining two or more atoms with equal or little difference in electronegativity through shared electron pairs (such as tetrachloromethane CCl_4, methane CH_4)
- **Molecular bonds**
  - ✓ Molecules are bound together by mutual attraction (van der Waals forces) to form molecular bonds
- **Others?**



4.1.1 Basic knowledge of dielectric material structure

3. Classification of dielectrics (3 categories according to the chemical structure)

- **Non-polar and weakly polar dielectrics**
  - ✓ The dielectrics composed of non-polar molecules are called non-polar dielectrics, such as N_2 and PTFE (polytetrafluoroethylene)
  - ✓ Some non-polar dielectrics are of more or less polar due to the presence of molecular isomerism or branched chains, called weakly polar dielectrics, such as PS (polystyrene)
- **Polar dielectrics**
  - ✓ A dielectric composed of polar molecules, such as PVC (polyvinyl chloride, $-(CH_2-CHCl)_n-$), PMMA (polymethyl methacrylate/plexiglass) and etc.



- **Ionic dielectrics**
  - ✓ There are no individual molecules, only solid forms
  - ✓ Divided into crystal and amorphous two types, such as quartz, mica and ceramics

Generally, Inorganic compounds consist of ionic bonds, and organic compounds consist of molecule bonds. The molecules of organic compounds consist of covalent bonds.

4.1.2 Division of electrical properties of dielectrics

1. Electrical properties of dielectrics

- **Dielectric property**
  - ✓ The polarization and loss characteristics of the dielectrics
- **Electrical conduction property**
  - ✓ Such as carrier drift, electrical conduction under high field strength and etc.
- **Electrical breakdown property**
  - ✓ Including deterioration, breakdown and volt-second curve
- **Secondary effect**
  - ✓ Such as the effect of space charge, trap, local center of state, interface, chemical structure, morphology, impurity and environment

2. Parameters of electrical properties

- **Relative dielectric constant (ε_r)**
- **Resistivity/Conductivity**
- **Breakdown voltage/Electrical strength**
- **Loss angle tangent/Loss factor (tanδ)**

4.1.3 Electric parameters of common liquid and solid dielectrics

1. Classification of dielectrics by polarity

- Electric parameters are closely related to polarity of dielectrics
- According to the polarity, the electric parameters of common liquid and solid dielectrics are divided into non-polarity (or weakly polarity), polarity and strong polarity

2. Electric parameters test conditions

- Temperature, voltage waveform (AC/DC, impulse voltage, frequency), voltage amplitude, the thickness of dielectrics (distance between electrodes)
- For liquids, there are purity requirements (quality)

4.1.3 Electric parameters of common liquid and solid dielectrics

3. Electric parameters of common liquid dielectrics

Types	Liquid dielectrics	Relative dielectric constant	Resistivity / (Ω·cm)	Dielectric loss angle tangent	Breakdown Voltage / kV	Purity
Non-polarity and weak polarity	Transformer Oil	2.2	2×10^{12}	/	/	Unpurified (80℃)
		2.1	5×10^{14}	$<10^{-2}$	>40	Purified (80℃)
		2.1	2×10^{15}	$<10^{-2}$	>40	Twice Purified (80℃)
		2.1	$>10^{15}$	$<10^{-2}$	75	Highly Purified (80℃)
	Capacitor Oil	2.2	10^{15}	$<3\times10^{-3}$(100℃)	>60	
	Cable Oil	2.6	5×10^{15}	9.6×10^{-3}	>60	
	Silicone Oil	2. 53	$>5\times10^{15}$	$<10^{-2}$	65	
Polarity	Polychlorinated Biphenyl (PCB)	5.5	10^{13}	$<10^{-2}$	>50	Engineering Use (80℃)
	Castor Oil	4.5	10^{12}	$<10^{-2}$	>35	Engineering Use (20℃)
Strong polarity	Water	81	10^{7}	/	/	Highly Purified (20℃)
	Ethanol	25.7	10^{8}	/	/	Purified (20℃)

Note: Breakdown voltage is measured with a gap distance of 2.5 mm. Parameters not specified are measured at 20°C under power frequency voltage.

4.1.3 Electric parameters of common liquid and solid dielectrics

4. Electric parameters of common solid dielectrics

Types	Solid dielectrics	Relative dielectric constant	Resistivity / ($\Omega\cdot$cm)	Dielectric loss angle tangent	Breakdown Voltage / ($kV\cdot mm^{-1}$)
Non-polarity and weak polarity	Fluoropolymers	2	10^{16}	$<2\times10^{-4}$(1 MHz)	18
	Polyethylene	2.25~2. 35	10^{15}	3×10^{-4} (1 MHz)	18-24
	High-density Polyethylene (HDPE)	2.2~2.4	10^{15}	<0.05	26~28
	Cross-linked Polyethylene (XLPE)	2.3	10^{16}	5×10^{-4}	35
	Polypropylene	2.0~2.6	$>10^{16}$	$<2\times10^{-4}$	>200(dc),30(ac)
	Polystyrene	2.45-3.1	10^{15}	$<4\times10^{-4}$	>110(dc)
	Asphalt	2.5~3.0	10^{15}~10^{16}	10^{-2}~2×10^{-2}	100~300(dc)
Polarity	Chloroprene Rubber (Neoprene)	6	10^{9}	0.1(1 MHz)	10~20
	Butyl Rubber	2.5~3.5	10^{15}	3~8×10^{-3}(1 MHz)	16~25
	Ethylene Propylene Rubber (EPR)	3.0	10^{15}	3×10^{-3}	30~40
	Silicone Rubber	3.2	10^{13}	0.01(1 MHz)	15~20
	Polyester Film	3.2	10^{16}	3×10^{-3}	>160(dc)
	Epoxy Resin	3. 6	10^{16}	4×10^{-3}~5×10^{-2}	16~18
	Polycarbonate	3.0	10^{16}	0. 005	17~22
	Oil Impregnated Paper	3.3~4.4	10^{15}	10^{-3}	>40
	Cable Oil-paper	3.5	10^{14}	3×10^{-3}	30~40
	Capacitor Paper	2.5~3.4	10^{15}	2×10^{-3}	>30
	Polyvinyl chloride (PVC)	3.3~3.5	10^{14}	0.09~0.10(1 MHz)	12~16
	Nylon 6	4.1	10^{14}~10^{17}	0.08	22
	Nylon 66	4.0	10^{14}	0.01	15~19

4.1.3 Electric parameters of common liquid and solid dielectrics

4. Electric parameters of common solid dielectrics (continued)

Types	Solid dielectrics	Relative dielectric constant	Resistivity / (Ω·cm)	Dielectric loss angle tangent	Breakdown Voltage / (kV·mm^{-1})
Ionic Dielectric	Quartz glass	3.5~4.5	10^{19}	~3×10^{-4}(1~10 MHz)	25~40
	Borosilicate glass	4.5~5.0	>10^{14}	15~35×10^{-4} (1~10 MHz)	20~35
	Lead glass	7~10	>10^{13}	5~40×10^{-4} (1~10 MHz)	5~20
	Phlogopite	5.0~6.0	10^{13}~10^{15}	5~50×10^{-3} (0.1~1kHz)	80~100(dc,0.05~0.1 mm)
	Muscovite	6.0~8.0	10^{14}~10^{15}	1~50×10^{-4} (0.1~1kHz)	90~120(dc,0.05~0.1 mm)
	Electrical porcelain (Talc)	5.5~6.5	10^{14}	3~5×10^{-4} (1~10 MHz)	35~45
	Rutile	100	10^{10}~10^{11}	0.4	15~25
	Barium titanate	Thousands to tens of thousands	10^{11}	0.03	5~20

Brief summary

1. Classification of dielectrics (3 categories according to the chemical structure)

- Electrical insulation
- Causes of insulation problems (three causes)
- The content and purpose of research and study in high voltage insulation
- Electrical equipment in power system

2. Dielectrics

- The bond that forms the dielectrics
- Electrical properties of dielectrics
- Parameters characterizing the electrical properties of dielectrics (electric parameters)
- Common electric parameters of liquid and solid dielectrics