Electrotechnical Materials

Chapter 3

Dielectric Materials

I. INTRODUCTION

Dielectric materials play a vital role in electrical and electronic systems as they provide insulation and store electrical energy. In this chapter, we explore their fundamental properties, polarization mechanisms, and behavior under electric fields. Special attention is given to parameters such as permittivity, dielectric loss, and breakdown strength, which determine their performance in practical applications. Understanding dielectrics is essential for designing capacitors, cables, insulators, and high-voltage equipment, where material selection directly influences efficiency, reliability, and safety. When a dielectric material is placed between the plates of a capacitor and a voltage is applied, an electric field develops within it. This field causes a slight displacement of positive and negative charges inside the material, creating small electric dipoles that align opposite to the applied field — a process known as polarization. Through this mechanism, the dielectric reduces the effective electric field and increases the capacitor's ability to store electric energy, as expressed by the relation

$$Q = CV.$$

Dielectrics therefore play a vital role in electrical and electronic systems: they act as insulating media that prevent current flow while enhancing energy storage and controlling electric fields.

In this chapter, we explore the fundamental properties of dielectric materials, the mechanisms of polarization, and their influence on permittivity, losses, and dielectric strength. Understanding these principles is essential for the design of capacitors, cables, and high-voltage insulation systems.

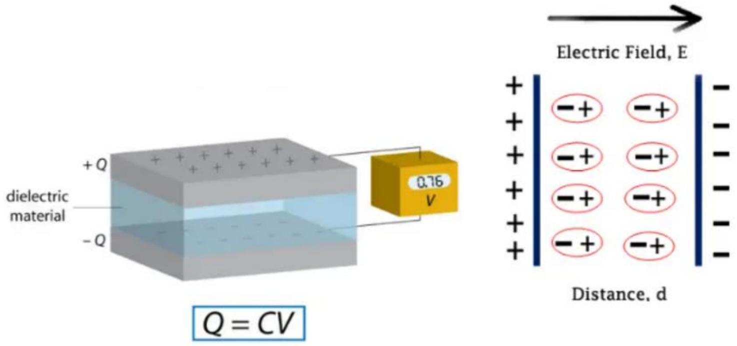


Figure 1. Polarization of a dielectric material placed between the plates of a capacitor under an applied electric field

I. 1. Definition of an Insulator

An insulator is a material designed to prevent electrical conduction between conductive elements. It has very low - practically negligible- electrical conductivity and is used to separate conductive parts maintained at different electric potentials.

From a microscopic point of view, an insulating material is characterized by a completely filled valence band, separated from the conduction band by a wide energy gap. This gap is so large that transferring electrons from the valence band to the conduction band requires a significant amount of energy , often high enough to cause electrical breakdown.

Figure 2. Types of Insulators

I.2. Definition of a Dielectric

A dielectric is a collection of atoms or molecules composed of negatively charged electrons and positively charged nuclei, forming an overall electrically neutral system. It is a medium that does not conduct electric current and is therefore often referred to as an electrical insulator. Such materials include glass, ceramics, and many plastics. Although dielectric media cannot conduct current, they exhibit several important electrical properties. When subjected to an external electric field, a slight displacement of positive and negative charges occurs within the material. However, the electrons in a dielectric cannot move freely over large distances — their motion is limited to very small displacements within atoms or molecules.

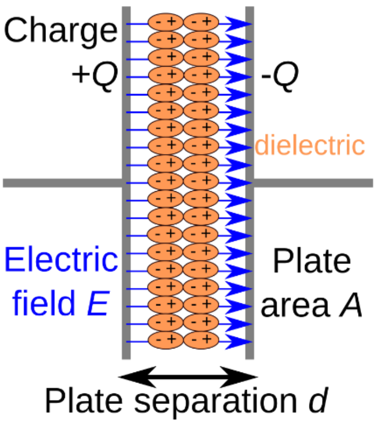


Figure 3. A polarized dielectric material, between two metal plates

II. Dielectric Characteristics of Insulators

II.1. Relative permittivity

Permittivity, or more precisely dielectric permittivity, is a physical property that describes the response of a material to an applied electric field. It is a macroscopic property that plays an essential role in electrostatics and in the electrodynamics of continuous media.

Consider a parallel-plate capacitor in a vacuum (or in air).

Its capacitance is given by :

$$C_0 = \varepsilon_0 \frac{S}{d}$$

Where

- C_0 is the capacitance in vacuum,
- ε_0 is the permittivity of free space**,**
- S is the surface area of the plates, and
- d is the distance between them.

If the same capacitor is filled with an insulating material (a dielectric), its capacitance becomes:

$$C = \varepsilon C_0 = \varepsilon_r \varepsilon_0 \frac{S}{d}$$

Where

- ε is the absolute permittivity of the dielectric,
- ε_0 is the permittivity of free space,
- ε_r is the relative permittivity (also called the dielectric constant),
- S is the surface area of the plates, and
- d is the distance between them.

➢ The relative permittivity is defined by the ratio:

$$\varepsilon_r = \frac{C}{C_0}$$

➢ and the absolute permittivity is expressed as:

$$\varepsilon = \varepsilon_r \varepsilon_0$$

Dielectric Properties of Materials

Material	Relative Permittivity (εr) at 10^6 Hz	Loss Factor (tan δ)	Breakdown Voltage ($\times 10^6$ V/m)
Reference Media			
High vacuum	1	0	100
Dry air (patm)	1	$< 10^{-5}$	2
Sulphur hexafluoride (SF_6, patm)	1.1	$< 10^{-5}$	7
Water	80	0.1	10
Chlorinated carbons	4 – 6	$(1 – 4) \times 10^{-5}$	50 – 100
Ceramics and Minerals			
Alumina (Al_2O_3)	4.5 – 9	2×10^{-3}	6
Mica	7	1×10^{-3}	40
Porcelain	6 – 8	$(2 – 4) \times 10^{-2}$	50
Titanates	15 – 12,000	0.2 – 2	3 – 12
Soda-lime glass*	7	$(1.3 – 3.2) \times 10^{-3}$	300 – 500
Zirconia (ZrO_2)	7 – 10	$(4 – 2) \times 10^{-2}$	3 – 50
Polymers and Elastomers			
Natural rubber	3 – 4	10^{-2} – 10	12 – 24
Nylon (Polyamide 6-6)	3	10^{-2} – 10	24
Polyvinyl chloride (PVC)	3 – 4	10^{-2} – 10	20
Polyethylene (PE)	2.3	10^{-4} – 12	60 – 80
Polytetrafluoroethylene (PTFE)	2	10^{-4}	16
Epoxy resin (EP)	3 – 6	$(2 – 2) \times 10^{-2}$	18

II.2. Dielectric Strength

When the voltage applied to an insulator exceeds a certain critical value — known as the breakdown voltage — an electric arc appears within the insulating material. This arc corresponds to an intense current passing through the insulator along a path formed by ionized molecules.

In this situation, the insulator is said to be punctured, resulting in dielectric breakdown or electrical breakdown.

For solid insulators, this damage is irreversible, often leading to carbonization.

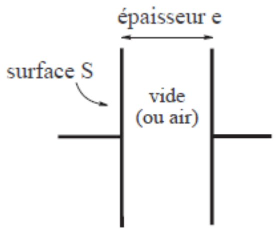
For gaseous and liquid insulators, the process can be reversible, as ions recombine with electrons once the voltage is removed.

The dielectric strength (G) of an insulating material is defined as the ratio between the breakdown voltage (U) and the distance (L) between the two points where the voltage is applied. It is usually expressed in kilovolts per millimeter (kV/mm):

$$G = \frac{U}{L}$$

Depending on the relative orientation of the electric field direction and the main surfaces of the insulator, the dielectric strength can be classified as either:

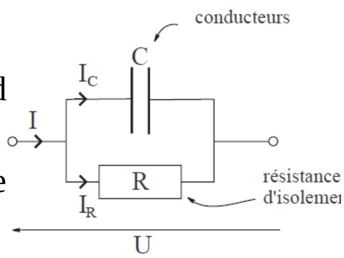
Transverse dielectric strength, or longitudinal dielectric strength.



The dielectric strength depends on several factors:

* The frequency, waveform, and duration of the applied voltage;
* The temperature, pressure, and humidity of the surrounding atmosphere;
* The presence of impurities within the insulator (such as air bubbles or moisture

II.3 Equivalent circuit of an AC insulator



An insulator placed between two conductors can be simplified modeled by the following equivalent circuit:

La capacity C represents the conductors and the resistance R is the insulation resistance of the insulator, it is always $\geq 10^{12}\ \Omega$.

II.3 Calculation of the Dielectric Loss Angle

The concept of dielectric losses can be introduced using the Fresnel diagram.

When an alternating voltage $U = U_0 e^{i\omega t}$ is applied to the terminals of a perfect capacitor, the current is 90 degrees ahead of the voltage and is expressed as follows:

$$I = \omega\varepsilon_r^* C_0 U_0 e^{i(\omega t + \frac{\pi}{2})} = i\omega\varepsilon_r^* C_0 U$$

Considering the phenomenon of dielectric losses that reduce the capacitor's ability to store electrical charges and by integrating the equation $\varepsilon_r^* = \varepsilon_r' - i\varepsilon_r''$ (the complex relative permittivity), we obtain:

$$I = i\omega(\varepsilon_r' - i\varepsilon_r'')C_0 U = \omega\varepsilon_r'' C_0 U + i\omega\varepsilon_r' C_0 U$$

According to this expression, the circuit is traversed by a current that has two components:

A component (I_p) called loss current [A]: $I_p = \omega\varepsilon_r'' C_0 U$

A component (I_C) called the load current [A]: $I_C = \omega\varepsilon_r' C_0 U$

This diagram highlights the existing phase shift between these two quantities.

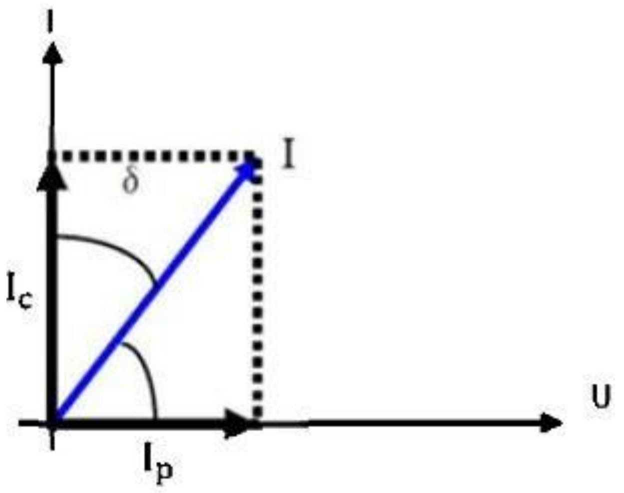


Figure 4. Fresnel diagram.

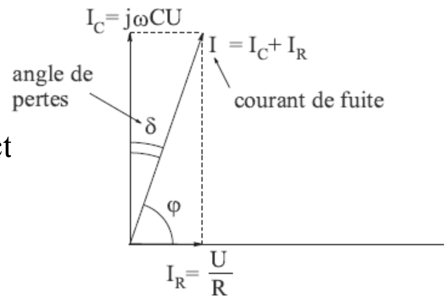
The angle δ, known as the dielectric loss angle, represents the angular difference between the currents for a perfect dielectric and a real dielectric (Grossin 2006, Sahraoui 2008). The tangent of the loss angle is called the dielectric dissipation factor. It is given by the following relation:

$$\tan\delta = \frac{|I_p|}{|I_C|} = \frac{\varepsilon_r''}{\varepsilon_r'}$$

This term defines the degree of electrical energy absorption converted into heat by a dielectric material at a given frequency. It represents the ratio of the energy dissipated in the dielectric to the energy accumulated.

The loss angle δ is defined as the complementary angle of the phase shift between the voltage U between the conductors and the leakage current I flowing through the insulator:

$$tan\varphi = \frac{CU\omega}{\frac{U}{R}} = RC\omega \Rightarrow tan\delta = \frac{1}{tan\varphi} = \frac{1}{RC\omega}$$



The value of (tanδ) is called the dielectric dissipation fact

The loss angle characterizes the quality of an insulator:

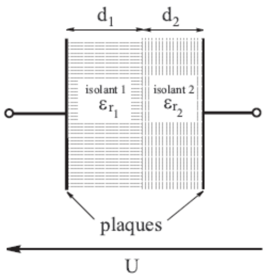
Good insulator → Insulation resistance R high → δ low;

Bad insulator → R low → δ high.

In practice, the dissipation factor tanδ varies between 10^{-2} and 10^{-4}. It depends on the frequency of the applied voltage according to a more complex law than that determined previously from the simplified model: tanδ presents maxima at certain frequencies.

III. Electric Field Calculation in an Insulator

One wants to calculate the fields E1 and E2 respectively in insulator 1 and in insulator 2 shown below.



On a : $\begin{cases} E_1 d_1 + E_2 d_2 = U \\ \varepsilon_{r1} E_1 = \varepsilon_{r2} E_2 \end{cases} \Rightarrow \begin{cases} E_1 = \dfrac{U}{d_1 + \frac{\varepsilon_{r1}}{\varepsilon_{r2}} d_2} \\ E_2 = \dfrac{U}{d_2 + \frac{\varepsilon_{r2}}{\varepsilon_{r1}} d_1} \end{cases}$

IV. Physical Bases for Dielectric Polarization:

IV.1. A dielectric medium:

A neutral insulating medium where there are no free and mobile electric charges. It is formed of atoms and molecules.

On the other hand, the conductors have free charges whose carriers can move throughout the entire mass of the material.

Let's consider a conductor in thermodynamic equilibrium:

$\vec{F} = q\vec{E}, \vec{E} = \vec{0}, -\overrightarrow{grad} = \vec{0}, V_{int} = C^{st}$

Or $div\vec{E} = \frac{\rho}{\varepsilon_0} = 0 \Rightarrow \rho_{int} = 0$, all charges are distributed over the surface of the conductor.

IV.2. Electric Dipole

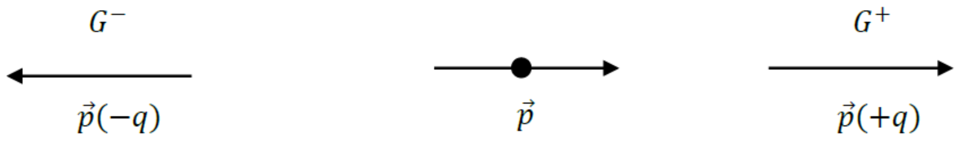
Let $E_0=0$ be the applied external electric field:

- When $E_0=0$, the electrons remain bound to the nucleus, and the centers of gravity of the negative and positive charges (G^- and G+) coincide.
- When $E_0 \neq 0$, the charges experience an electric force given by $F=qE0$

Each atom (or molecule) with charge then behaves like an electric dipole and acquires a dipole moment defined as:

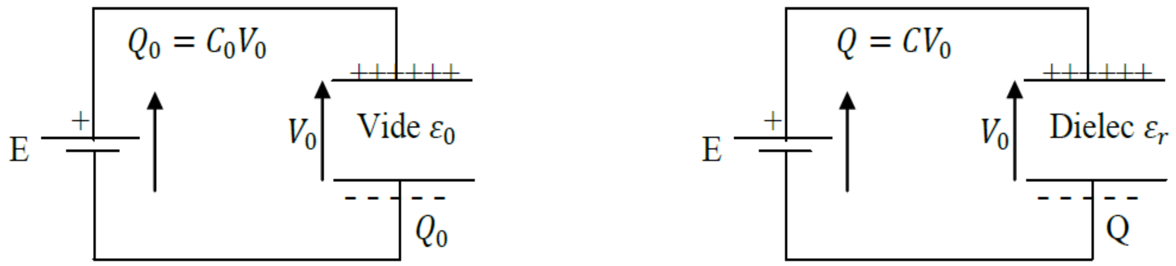
$$\vec{p} = q\overrightarrow{G^{-}G^{+}}$$

Where p is the dipole moment, q is the charge, and G− G+ represents the separation distance between the centers of the negative and positive charges.



IV.3. Faraday's Experiment:

The introduction of a dielectric between the plates of a capacitor increases its capacitance. In the presence of the dielectric, to maintain $V_0 = c^{st}$ the generator $Q_0 = C_0 V_0$ must supp y a greater quantity of electricity Q than Q_0 so that Q> Q_0



The introduction of a dielectric plate leads to the addition of charges. $\overline{E}\rightarrow 0$ penetrates into the dielectric and acts on the charge carriers. However, these electrons and ions cannot move under $\overline{E}\rightarrow 0$. They remain attached to atomic, molecular, or crystalline groups, hence their name “bound charges”. In volume, the charge carriers neutralize each other. There is the appearance of induced charges, of opposite sign to those armature, on the faces of the dielectric called “polarization charges”.

VI.4. Mechanism of Polarization:

A dielectric under $\bar{E}\rightarrow 0$ behaves like a set of dipoles oriented in the direction of

$\bar{E}\rightarrow 0$ (- towards ´+). It is said that the dielectric is polarized by the field, and two mechanisms of polarization are distinguished.

- **Dipole Polarization:**

The dielectric is formed of permanent dipoles (e.g., H_2 O). The field $\bar{E}\rightarrow 0$ makes them orient.

- **Electronic Polarization:**

The dielectric does not have permanent dipoles (e.g., CO_2). The field $\vec{E} \rightarrow 0$ creates them and then orients them in its direction.

V. Classification and Physical Properties

Several methods can be adopted to classify insulators:

V.1. Classification according to temperature resistance:

NFC 51-111 standard defines classes of insulation according to their temperature resistance, which depends on the insulating material, but also on the agglomeration and impregnation materials.

V.2. Classification according to physical state:

* solid : mica, wood, ceramics, plastics...
* liquid : oils, pyralene, varnish...
* gas : dry air, nitrogen, SF6...

V.3. Classification according to origin :

* Mineral: Mica, Porcelain, Glass, Asbestos, …Etc.
* Organic: Wood, Paper, Cotton, Silk, Rubber (Latex),.
* synthetic:

- Plastics (thermoplastic or thermosetting),
- Silicones: molecules whose carbon atoms have been replaced by silicon.
- Thermoplastics: plastics softened by heat (it can then be molded, formed or extruded), and hardened by cold. The process is reversible.
- Thermosets: plastics hardened by a thermal process. The process is irreversible.

V.4. Physical Properties:

In addition, the electrical insulators all have approximately the following characteristics:

- Poor temperature resistance <200°C in general (except for asbestos, glass and mica)
- High Electrical Rigidity : ~10 kV/mm
- Very High Electrical Resistivity: $>10^6$ Ωm
- relative dielectric constant $\varepsilon_R > 1$ (~2 to 8)
- poor thermal conductivity: thermal insulator
- Solid, liquid or gas.
- density close to 1

V.5. Application of dielectric materials:

V.5.1. Machine windings:

- low voltage : Enameled conductive wires
  - High voltage: conductive bars insulated by paper, mica, glass, bakelite, resin (coating, impregnation).

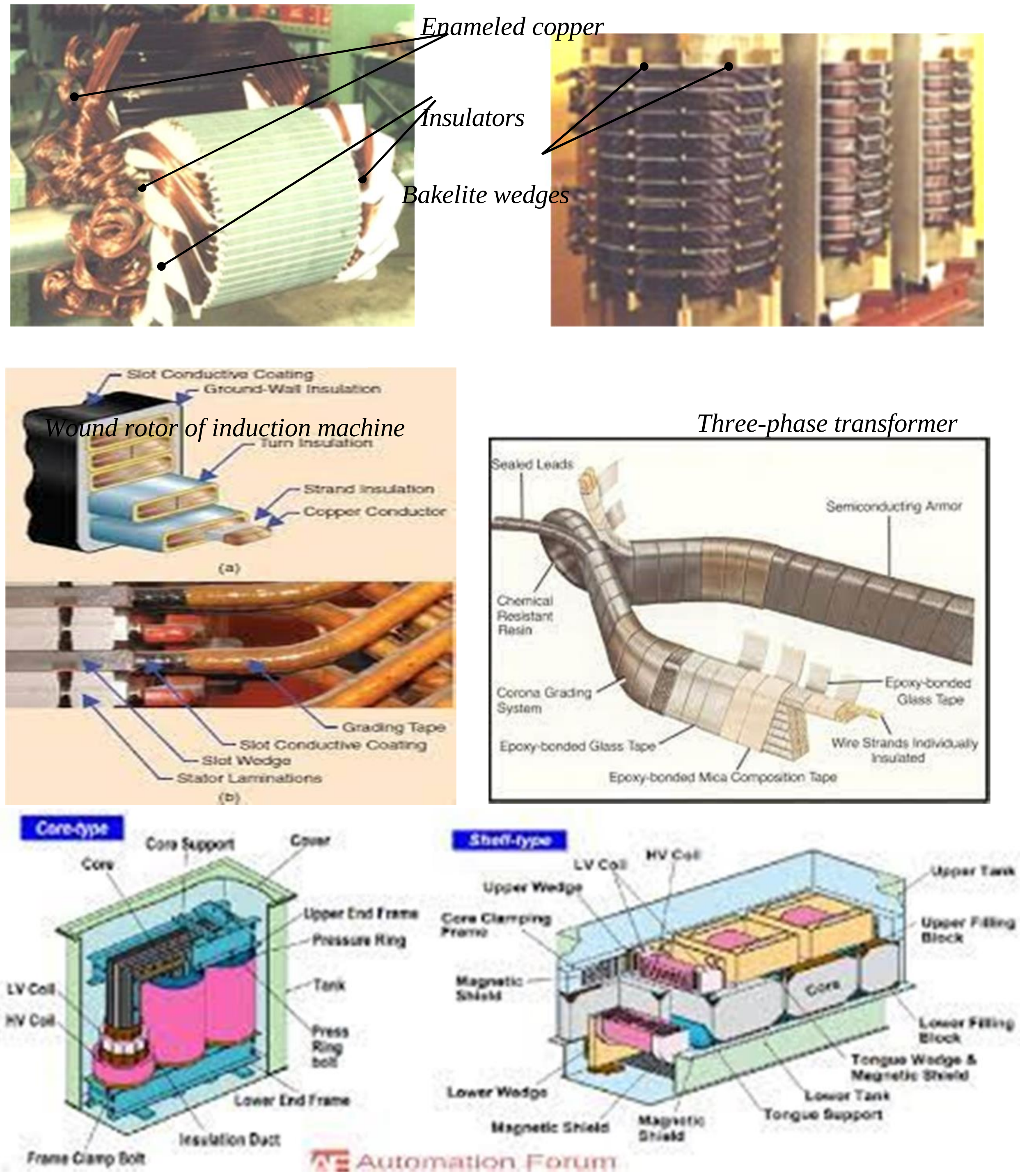


Figure. 5. Example of the application of insulators in Machine windings, Transformer

V.5.2. The electric cables:

A cable is made up of a metallic conductive core (Cu or Al) covered with insulation, a screen and an exterior covering, supplemented if necessary by a sealing sheath and "armor".

The insulating envelope, but also the sheaths and exterior covering are made of synthetic materials (thermoplastics and elastomers):

- PVC: Polyvinyl Chloride.
- PE: Polyethylene.
- PR: Cross-Linked Polyethylene.
- EPR: Ethylene-Propylene.
- Silicone Rubber.

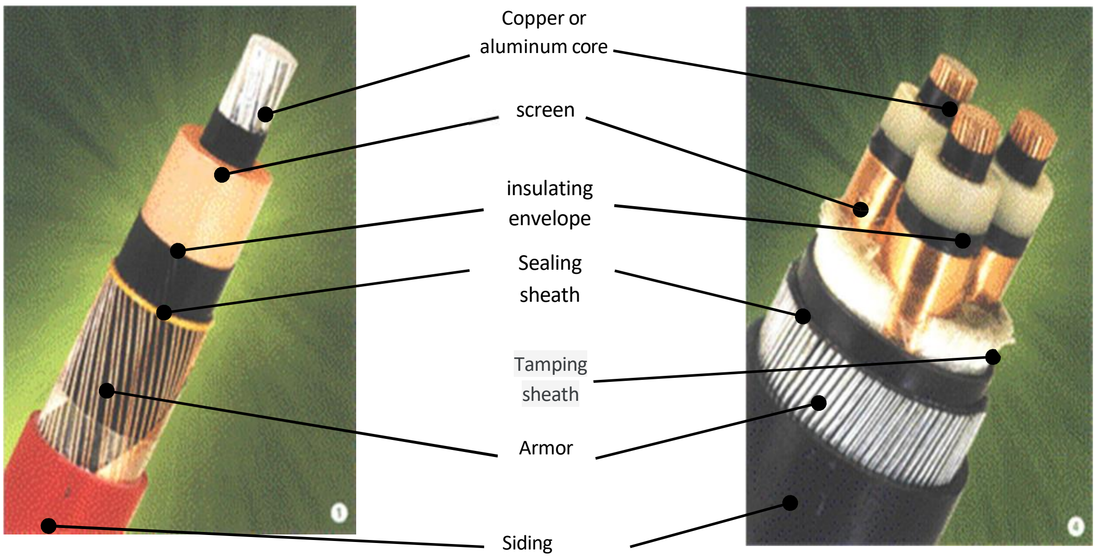
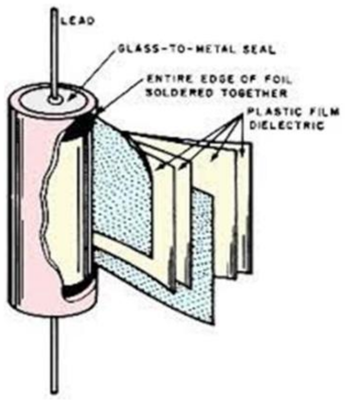
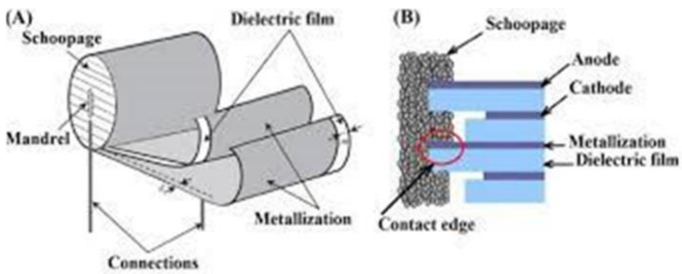


Figure 6. Example of The Application of insulators in electric cables

V.5.3. Capacitors:

Schematically, a capacitor is formed from a dielectric ($\varepsilon_R>1$) clamped between two electrodes. The insulating dielectrics used are ceramic, paper, glass, mica or plastic technologies.





MFC's cylindrical element (A) and contact edge cross-section (B)

Plastic capacitor

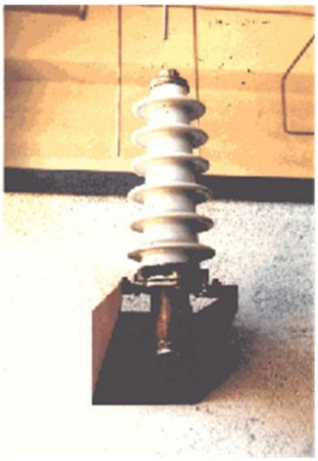
Ceramic capacitors

Figure.7. Example of The Application of insulators in Capacitors

V.5.4. Insulators:

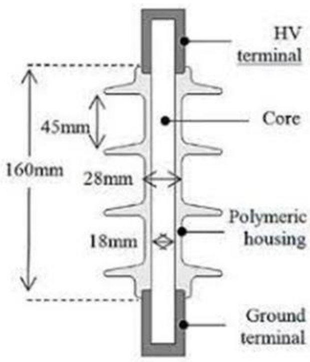
They are made of glass or porcelain and are used to insulate:

- The output terminals of high voltage equipment (disconnector, circuit breaker, transformer, rolling stock, etc.).
- high voltage cables from electrical energy transmission pylons



a)

b)



C)

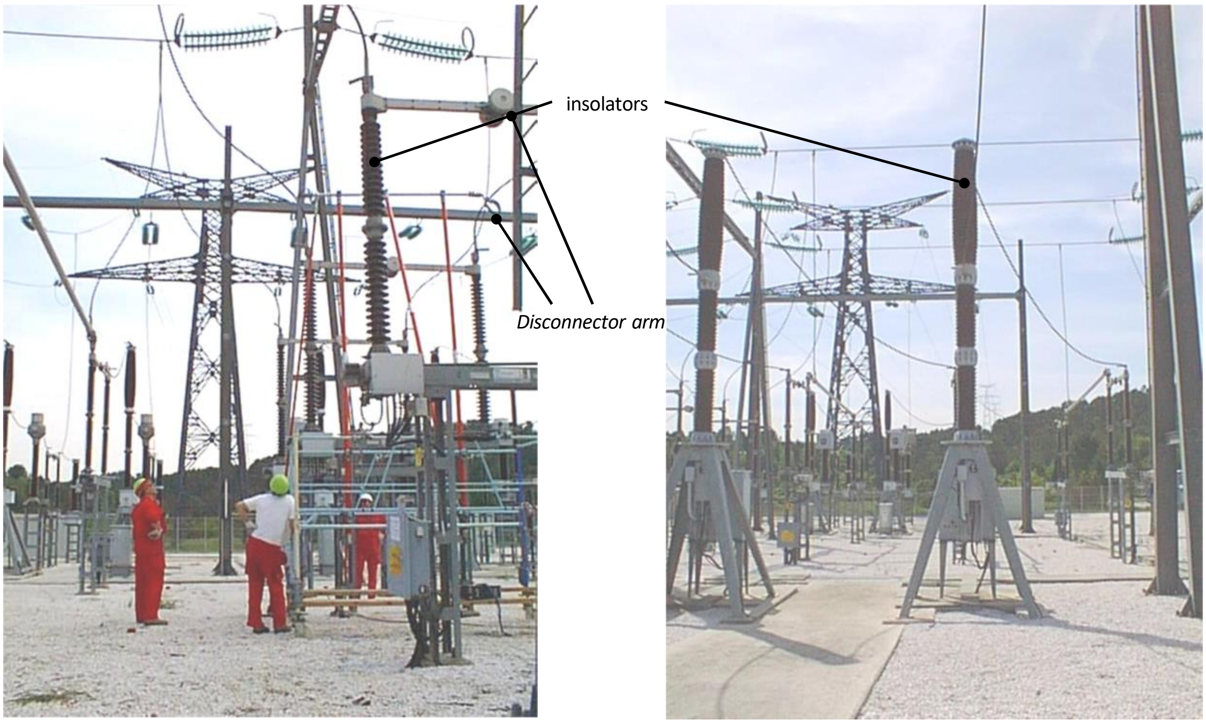
d)

Figure.8. Example of The Application dielecterc as insulators:
a) tram insulator b) 225/63 kV oil-immersed transformer.c) Structor of a logue isolator fut.d) Different types of over head line insulator

V.5.5. High voltage equipment:

Internal insulation is reinforced by additional insulation:

- ✓ ***solid*** : resin, elastomer (high voltage electronics).
- ✓ ***Liquid*** : mineral oil, askarel (banned since 1986) in power transformers.
- ✓ ***gas*** : SF6 in high voltage circuit breakers.



a) b)

Figure 9. Example of The Application of insulators in High voltage equipment :

a) 63 kV disconnected b) 63 kV SF6 circuit breaker