UNIT IV

DIELECTRIC MATERIALS

4.1. INTRODUCTION

A dielectric is an insulator, playing an inert role in the electrical circuit. In a dielectric, electrical energy can be stored with minimum dissipation of power. Hence all the dielectrics are insulators but all insulators are not dielectrics. Since the dielectric is an insulator, it does not possess free electrons. However the behaviour of a dielectric can be modified by the application of electric field.

4.1.1. Fundamental definitions and properties

(i) Dielectric Constant (ε_r)

The dielectric constant determines the share of the electric stress which is absorbed by the materials. It is the ratio between the absolute permitivity ε and the permitivity of free space ε_0, and is given by

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$$

'ε_r' is a dimensionless quantity and it is a measure of polarisation in the dielectrics. The value of $\varepsilon_r = 1$ for air or vacuum.

(ii) Electric Polarisation

When an external electric field is applied to the dielectrics, the field exerts a force on each positive charges in its own direction while negative charges are pushed in the opposite directions. Consequently, an electrical dipole is created in all the atoms inside the dielectric. The process of producing electric dipoles inside the dielectrics by an external electric field is called polarisation in dielectrics.

(iii) Polarisation vector

If the strength of the electric field E is increased, the strength of the induced dipole also increases. The induced dipole moment is proportional to the intensity of the electric field.

$$\text{i.e., } \mu = \alpha E$$

where α is the constant of proportionality, called the polarizability.

If μ is the average dipole moment per molecule and N is the number of molecules per unit volume, the polarisation vector P is defined as dipole moment per unit volume of the dielectric materials.

$$P = N\mu$$

(iv) Electric Displacement Vector (D)

Electric displacement vector (or) electric induction D is a quantity which is used for analysing electrostatic fields in the presence of dielectrics, which is given by

$$D = \frac{Q}{4\pi r^2}$$

Electric field intensity $E = \dfrac{Q}{4\pi \epsilon r^2}$

Also, $\quad D = \epsilon_0 E + P$

(v) Electric Susceptibility (χ_e)

The polarisation vector P is proportional to the applied electric field E, for field strengths that are not too large. So we can write

$$P \alpha \ E$$

(or) $\qquad P = \epsilon_0 \chi_e \ E$

χ_e is a characteristic of every dielectric and which is called electric susceptibility.

$$\chi_e = \frac{P}{\epsilon_o E}$$

Since $\dfrac{P}{E} = \epsilon_0 (\epsilon_r - 1)$ we can write

$$\chi_e = \frac{\epsilon_0 \ \epsilon_r - 1}{\epsilon_0}$$

$$\therefore \chi_e = \epsilon_r - 1$$

4.2. INTERNAL FIELD (OR) LOCAL FIELD AND DEDUCTION OF CLAUSIUS - MOSOTTI EQUATION

When a dielectric material is kept in an external field it exerts a dipole moment in it. Therefore two fields are exerted. They are,

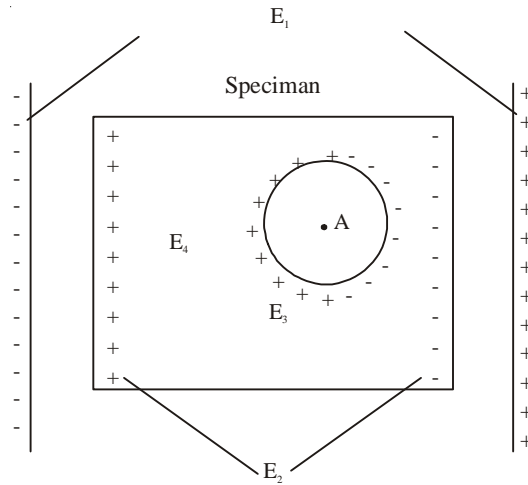1. Due to external field
2. Due to dipole moment

Fig. 4.1. Dielectric in an electric field

This long range coulombic force which is created due to the dipoles is called as internal field or local field. This field is responsible for polarising the individual atoms or molecules.

4.2.1. Lorentz method for finding internal field

Let us assume, a dielectric material to placed in an external field. Consider an imaginary sphere in the solid dielectric of radius 'r'.

Here the radius of the spehere is greater than the radius of the atoms. i.e. there are many atomic dipoles within the sphere. A small elemental ring is cut with thickness ds. Let y be the radius of the small ring as shown in fig. 4.2
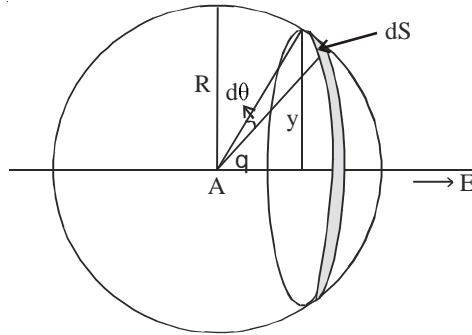
Fig. 4.2. Spherical cavity in a dielectric

The electric field at the centre of the sphere is called internal field, which arises due to the following four factors

$$E_{int} = E_1 + E_2 + E_3 + E_4 \qquad \rightarrow 4.1)$$

where,

$E_1 \rightarrow$ Field due to the charge on the plates. (externally applied)

$E_2 \rightarrow$ Field due to the polarization charges on the plane surface of the dielectric.

$E_3 \rightarrow$ Field due to the polarized charges induced at the spherical surface.

$E_4 \rightarrow$ Field due to the atomic dipoles inside the sphere considered.

Macroscopically, we can take $E = E_1 + E_2$ (i.e.) The field externally applied (E_1) and the field induced on the plane surface of the dielectric (E_2) as a single field (E).

If the dielectric is highly symmetric then the dipoles will cancel with each other and therefore we can take $E_4 = 0$

$\therefore$ Equation (3.1) becomes,

$$E_{int} = E + E_3 \qquad \rightarrow (4.2)$$

To find E_3

In the element ring, let 'q' be on the area ds. Polarization is defined as the surface charges per unit area. If P_N is the component of polarization perpendicular to the area as shown in fig. 4.3.

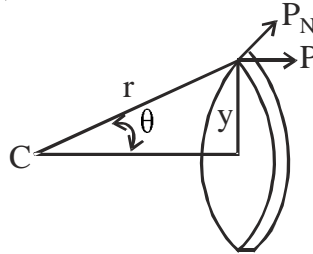Here $P_N = P \cos \theta = q'/ds$ (or) $q' = P \cos \theta \, ds$

Fig 4.3

$\therefore$ Electric field intensity at 'A' due to charge q' is given by

$$E = \frac{q'}{4\pi\varepsilon_0 r^2}$$

$$= \frac{P\cos\theta\, ds}{4\pi\varepsilon_0 r^2}$$

The abvoe intensity is along the radius 'r'. Resolving the intensity into two components, as shown in fig 4.4

Component parallel to the field direction $E_x = E \cos \theta$

$$\therefore E_x = \frac{P\cos^2\theta\, ds}{4\pi\varepsilon_0 r^2} \qquad \rightarrow (4.3)$$

Component perpendicular to the field direction

$$E_y = E \sin \theta$$
$$\therefore E_y = \frac{P\cos\theta \sin\theta\, ds}{4\pi\varepsilon_0 r^2} \qquad \rightarrow (4.4)$$
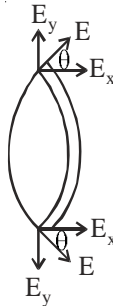

Fig. 4.4

The perpendicular components are in opposite directions (fig. 4.4) and hence cancel each other. So the parallel components are alone taken into consideration.

If the total surface area of the ring is considered as dA then

$$E_x = E = \frac{P\cos^2\theta dA}{4\pi\varepsilon_0 r^2} \qquad \rightarrow (4.5)$$

where $dA = $ circumference $\times$ thickness

$$= 2\pi y \times rd\theta \qquad [\because y = r\,\sin\theta]$$

$$= 2\pi r\,\sin\theta \times rd\theta$$

$$= 2\pi r^2 \sin\theta\,d\theta \qquad \rightarrow (4.6)$$

Substituting equation (3.6) in equation (3.5), we get

Electric field intensity due to the elemental ring

$$= \frac{P\cos^2\theta\sin\theta d\theta}{2\varepsilon_0} \qquad \rightarrow (4.7)$$

$\therefore$ Electrical field intensity due to the whole sphere can be derived by integrating equation (3.7) within the limits 0 to π.

$$E_3 = \int_0^\pi \frac{P\cos^2\theta\sin\theta d\theta}{2\varepsilon_0}$$

$$E_3 = \frac{2}{3}\,\frac{P}{2\varepsilon_0} \qquad \because \int_0^\pi \cos^2\theta\,\sin\theta\,d\theta = \frac{2}{3}$$

$$E_3 = \frac{P}{3\varepsilon_0} \qquad \rightarrow (4.8)$$

Substituting equation (4.8) in equation (4.2) we can write

$$\therefore E_{int} = E + \frac{P}{3\varepsilon_0} \qquad \rightarrow (4.9)$$

where E_{int} is called internal field or Lorentz field.

4.2.2. Clausius - Mosotti relation

In non-polar dielectrics, the molecules do not possess permanent dipole moments. In the presence of an external field, the induced dipole

moment, p is proportional to the local electric field.

$$p = \alpha E_{local}$$

where α is the polarisability of the molecule.

The dielectric constant ε_r can be expressed in terms of the polarisability α. The polarization P is given by,

$$\rightarrow (4.10)$$

where N is the number of molecules per unit volume.

Substituting for E_{local} from eqn. (4.9) in (4.10) we get,

$$P = N\alpha \left[E + \frac{P}{3\varepsilon_0} \right]$$

$$P = \sum_i p_i = N\alpha E_{local}$$

$$\frac{P}{E} = N\alpha \left[1 + \frac{P/E}{3\varepsilon_0} \right]$$

$$\rightarrow (4.11)$$

We know $\quad D = \varepsilon_0 \varepsilon_r E$

Also $\quad D = \varepsilon_0 E + P$

$$\varepsilon_o E + P = \varepsilon_0 \varepsilon_r E$$

$$P = \varepsilon_0 (\varepsilon_r - 1) E$$

$$P/E = \varepsilon_0 (\varepsilon_r - 1)$$

$$\rightarrow (4.12)$$

substituting eqn. (3.12) in eqn. (3.11), we get

$$\varepsilon_0 \ \varepsilon_r - 1 = N\alpha \left[1 + \frac{\varepsilon_0 \ (\varepsilon_r - 1)}{3\varepsilon_0} \right]$$

$$= N\alpha \left[\frac{3\varepsilon_0 + \varepsilon_0(\varepsilon_r - \varepsilon_0)}{3\varepsilon_0} \right] \qquad \rightarrow (4.13)$$

$$= \frac{N\alpha}{3\varepsilon_0} \ \varepsilon_0 \ \varepsilon_r + 2$$

$$\therefore \frac{N\alpha}{3\varepsilon_0} = \frac{\varepsilon_r - 1}{\varepsilon_r + 2}$$

For different kinds of atoms,

$$\frac{\varepsilon_r - 1}{\varepsilon_r + 2} = \frac{\sum\limits_i N_i \alpha_i}{3\varepsilon_0} \qquad \rightarrow (4.14)$$

where α_i is the polarisability of the ith kind of atom.

N_i is the number of ith kind of atoms

Eqn. (3.14) is the Clausius-Mosotti relation. This equation relates the dielectric constant and polarisability of a material.

4.3 TYPES OF POLARISATION

4.3.1. Electronic   Polarisation

Electronic polarisation is the result of the relative displacement of positively charged nucleus and the electron shells of an atom on the application of external field. This kind of polarization is present in all materials. It is proportional to the volume of the atom and is independent of temperature.

In inert gases, the centres of positive and negative charges in an atom coincide giving rise to zero dipole moment. But when an externalfield is applied, the electron charge cloud is displaced relative to the nucleus resulting in a net dipole moment.
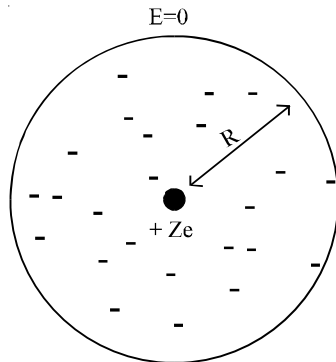
E=0

E →

Fig. 4.5 Atom in the absence
of field

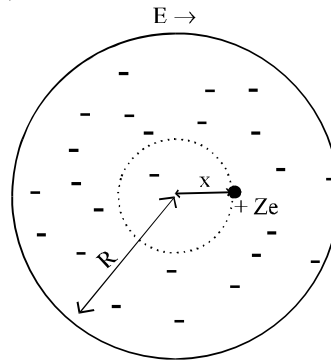Fig. 4.6 Atom in the external field

Consider an atom of a dielectric material is placed in a d.c.electric field E. Since the nucleus and electron cloud of that atom have opposite charges, they are acted on by the opposite Lorentz forces in the presence of an external field. The nucleus and the electron cloud move in opposite directions. When the nucleus and electron cloud are shifted from their equilibrium position, an attractive Coulomb force is created and it will tend to maintain original equilibrium position. But the Lorentz force will tend to separate the nucleus and the electron cloud of that atom from their equilibrium position. Finally a new equilibrium will be reached when the two forces are equal and opposite (fig. 4.6). When there is no external field, the centres of the electron cloud and nucleus of the atom coincide. In the presence of the field, the electron cloud is displaced by a distance x with respect to the centre of the nucleus.

We can assume that charge in the electron cloud is uniformly distributed over a sphere of radius R, and the spherical shape of the electron cloud is not altered on the application of the external field.

The charge density of the whole charged sphere

$$= \frac{Ze}{\frac{4}{3}\pi R^3}$$

Ze is the total negative charge.

Here, the sphere of radius x is also situated inside the sphere of radius R.

∴ The number of negative charges in the sphere of radius x,

$$= \frac{Ze}{\frac{4}{3}\pi R^3} \frac{4}{3}\pi x^3 = Ze\frac{x^3}{R^3}$$

Now the Coulomb force between the nucleus with positive charge Ze and the electron cloud which is displaced at a distance x from the nucleus is given by,

$$= Ze\frac{x^3}{R^3} \frac{Ze}{4\pi\varepsilon_0 x^2}$$

$$= \frac{Z^2 e^2 x}{4\pi\varepsilon_0 R^3}$$

Under equilibrium conditions, the Coulomb attractive force and the Lorentz repulsive force are equal and opposite. Thus,

$$ZeE = \frac{Z^2 e^2 x}{4\pi\varepsilon_0 R^3}$$

$$E = \frac{Zex}{4\pi\varepsilon_0 R^3} \qquad\qquad \rightarrow(4.15)$$

The dipole moment, due to the shifting of electron cloud,

$$p = Zex$$

Also by definition, $p = \alpha_e E$

$$\therefore \ E = \frac{Zex}{\alpha_e} \qquad\qquad \rightarrow(4.16)$$

From eqns. (4.15) and (4.16)

$$\frac{Zex}{\alpha_e} = \frac{Zex}{4\pi\varepsilon_0 R^3} \qquad\qquad \rightarrow(4.17)$$

$$\alpha_e = 4\pi\varepsilon_0 R^3$$

This is the expression for electronic polarisability. It is proportional to the volume of the atom. It can be noted that the electronic polarisability is independent of temperature.

4.3.2. Ionic Polarization

The ionic polarization is due to the relative displacements of cations and anions in opposite directions in an ionic solid, on the application of external field. Ionic solids like NaCl, CsCl exhibit ionic polarisability. Ionic polarization does not occur in covalent crystals such as diamond. Ionic polarisation is also indepenent of temperature.
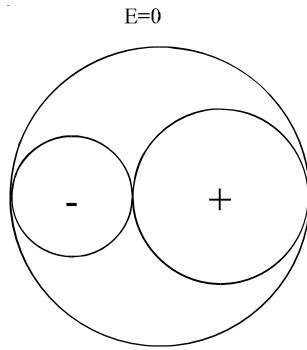
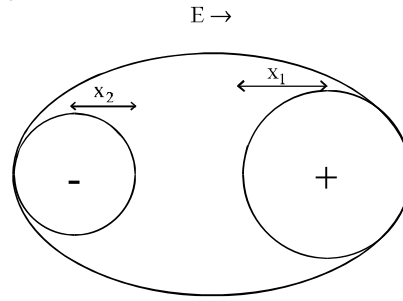Fig. 4.7 (a) Ionic molecule in the absence of external field

Fig. 4.7 (b) Ionic molecule in an external field

Let an electric field E is applied to an ionic molecule in the positive x- direction. Then the positive ion moves to the right and negative ion moves to the left. If there are one cation and one anion in each unit cell of the ionic crystal, the resultant dipole moment per unit cell,

$$p = e \, (\, x_1 + x_2) = \alpha_i E \qquad\qquad \rightarrow (3.18)$$

where x_1 - shift of the positive ion and x_2 – shift of the negative ion with respect to their equilibrium position. α_i - ionic polarisability.

Let F be the force due to the application of static electric field. Also let $\beta_1 x_1$ and $\beta_2 x_2$ be the restoring forces on positive ion and negative ion respectively, where β_1 and β_2 are the restoring force constants which depend on the mass of the ion and angular frequency ω of the molecule.

At equilibrium , $F = \beta_1 x_1 = \beta_2 x_2$

$$\therefore x_1 = \frac{F}{\beta_1} = \frac{Ee}{m_+ \omega_0^2} \qquad\qquad \rightarrow (3.19)$$

where, m_+ - mass of the positive ion.

$$F = Ee \text{ and } \beta_1 = m_+ \omega_0^2$$

Similarly for negative ion,

$$x_2 = \frac{Ee}{m_- \omega_0^2} \qquad \rightarrow (3.20)$$

where m_- is the mass of the negative ion.

∴ From eqns. (4.18), (4.19) and (4.20)

$$\alpha_i E = e \; x_1 + x_2 \; = \frac{Ee^2}{\omega_0^2} \left[\frac{1}{m_+} + \frac{1}{m_-} \right]$$

$$\alpha_i = \frac{e^2}{\omega_0^2} \left[\frac{1}{m_-} + \frac{1}{m_+} \right] \qquad \rightarrow (3.21)$$

Thus the ionic polarisability is inversely proportional to square of the natural vibrating frequency of the ionic molecule.

4.3.3. Orientational Polarisation

Polar molecules are the molecules which have permnent dipole moments even in the absence of an electric field as shown in fig. 4.9

The orientation polarization arises due to the presence of polar molecule is the dielectric medium. When a dielectric which consists of polar molecules is kept in an electric field, the molecules align themselves along the field direction. So there is a resultant dipole moment along the field direction, as shown in figure 4.9.
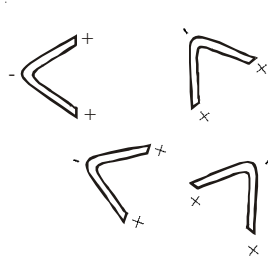
Without field
Fig. 4.8
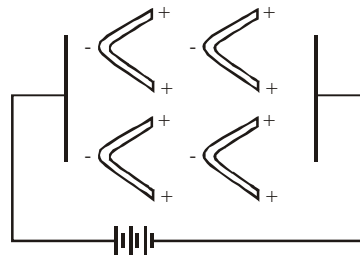
With field
Fig. 4.9

Explanation

In the case of a CH_3Cl molecule, the +ve and –ve charges do not coincide. The Cl^- has more electronegativity than hydrogen. Therefore the chlorine atoms pull the bonded electrons towards it more strongly than hydrogen atoms. Therefore, even in the absence of field, there exists a net dipole moment.

Now, when the field is applied, positive portion align along the direction of field and negative portion align in the opposite direction of the field. This kind of polarisation is called as orientation polarization.

This depends on temperature. When temperature is increased, the thermal energy tends to randomize the alignment.

From Langevin's theory of paramagnetism, net intensity of magnetisation. $\dfrac{N\mu^2 B}{3k_B T}$

Since, the same principle can be applied to the appliction of electric field we can write,

Orientation polarization $P_o = \dfrac{N\mu^2 E}{3k_B T}$

where N is the number of atoms

(or) $\quad P_0 = N\alpha_0 E$

where α_0 - Orientational Polarizability

$$\alpha_0 = \dfrac{\mu^2}{3k_B T} \qquad \rightarrow (4.22)$$

Therefore orientational polarizability is inversely proportional to the temperature of the material.

4.3.4. Space-charge polarization

The space-charge polarization occurs due to diffusion of ions, along the field direction and giving rise to redistribution of charges in the dielectrics.
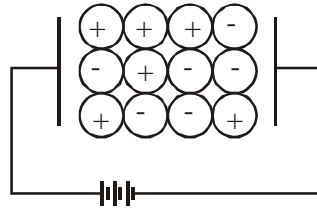
Explanation

Without the application of external field, the ions are orderly arranged as shown in fig. 4.10 (a).

Now, when the field is applied, the ions diffuse with respect to the direction of applied field as shown in fig. 3.36 (b). Thus the polarization occurs, known as space charge polarization.
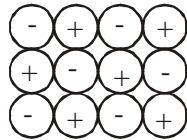
Without field   With field

Fig. 4.10 (a)   Fig.4.11 (b)

Normally, this type of polarization occurs in ferrites and semiconductors and will be very small.

4.4. FREQUENCY AND TEMPERATURE DEPENDENCE OF DIELECTRIC CONSTANT OF POLAR MOLECULES

When field is applied to a dielectric, the polarization occurs as a function of time. The polarization P(t) as a function of time is given by

$$P\left(t \right) = P\left[1 - e^{-t/t_r} \right]$$

Where P is the maximum polarization which occurs at a static field applied for a long time and t_r is the relaxation time, i.e., the time taken for polarization. It is a measure of the time scale of a polarization process.

Relaxation time is the time taken for the polarization process to reach 0.63 of the maximum value of polarization,

The relaxation times are different for different kinds of polarization mechanisms.

Frequency dependence

Electronic polarization is very rapid and will complete at the instant. The voltage is applied the reason is that the electrons are very light elementary particles than ions. Therefore even for very high frequency applied voltage i.e., in the optical range ($=10^{15}$Hz) as shown

in fig. 4.12, this kind of polarization occurs during every cycle of the applied voltage.
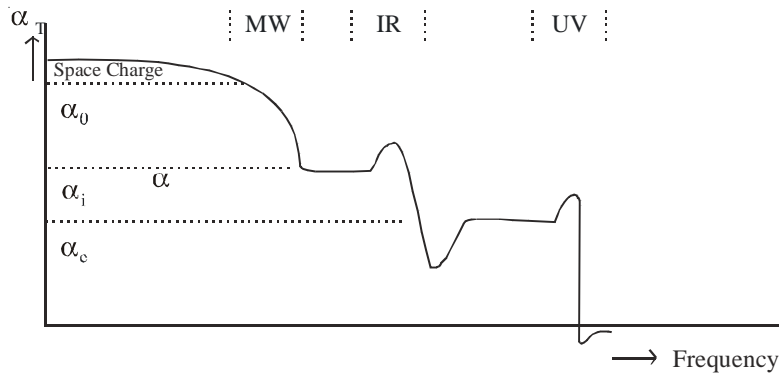

Fig. 3.37

(ii) Ionic polarization is slightly slower than the electronic polarization. Because ions are heavier than the electron cloud. Also the frequency of the applied electric field with which the ions will be displaced is equal to the frequency of the lattice vibrations $(= 10^{13} \text{ Hz})$.

At optical frequencies, there is no ionic polarization. If the frequency of the applied voltage is less than 10^{13} Hz i.e., infrared range as shown in fig, 4.12 the ions have enough time to respond during each cycle of the applied field.

(iii) Orientation Polarization is even slower than ionic polarization. the relaxation time for this case varies with respect to the dielectric materials (i,e., solids or liquids) used. Here the polar molecules in a liquid easily reorient themselves compared to solids. This type of polarization occurs at audio and radio frequency ranges. $(= 10^6 \text{Hz})$ as shown in fig. 4.12.

(iv) Space charge polarization is the slowest process, because in this case ions have to diffuse (jump) over several interatomic distances. Also this process occurs at very low frequency in the order of 10^2Hz as shown in fig. 4.12

Therefore from the fig. 4.12 it is observed that, at lower frequencies all four types of polarizations occur and the total polarization is maximum. And the total polarization value decreases with the increase in frequency and becomes maximum at optical frequency range.

Temperature Dependence

The electronic and ionic polarizations are independent of temperature, whereas orientation and space charge polarizations are temperature dependent.

The orientation polarization decreases with the increase in temperature because the randomizing action of thermal energy decreases the tendency of the permanent dipoles to align along the field direction. Hence in this case ε_r decreases.

But in space charge polarization, when the temperature is increased, the ions can easily overcome the activation barrier and hence they diffuse through the inter atomic distances. Thus it gives rise to polarization. So in this case the ε_r will increase with the increase in temperature.

4.5. DIELECTRIC LOSS

When an a.c. electric field is applied to a dielectric the dipoles tend to follow the field and be in phase with it. However the interaction of the dipole with other dipoles in the medium prevents this. This leads to energy loss known as dielectric loss which appears as heat. This energy loss is connected with ε_r'', the imaginary part of the dielectric constant. Very often the loss is expressed in terms of a quantity called the loss tangent. This is defined as

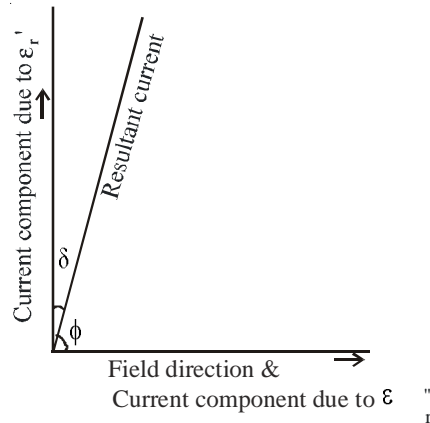$$\tan\delta = \frac{\varepsilon_r''}{\varepsilon_r'}$$

Fig. 4.13 Phase relationship between field and current components

The angle δ is the complement of the phase angle ϕ between the applied electric field and the resultant current vectors as shown in fig. 4.13

Consider a dielectric in a parallel plate capacitor subjected to an electric field,

$$E = E_0 \cos\omega t = R.P.E_0 \exp i\omega t \qquad \rightarrow (4.23)$$

And $\quad D = \varepsilon_0 \varepsilon_r E_0 \cos\omega t$

The current density,

$$J = \frac{\partial D}{\partial t} = R.P.\frac{\partial}{\partial t} \; \varepsilon_0 \varepsilon_r E_0 \exp i\omega t \qquad \left[\because \varepsilon_r = \varepsilon_r' - i\varepsilon_r'' \right]$$

$$= R.P.\frac{\partial}{\partial t} \; \varepsilon_0 \varepsilon_r' E_0 \exp i\omega t \; - i\varepsilon_0 \varepsilon_r'' E_0 \exp +i\omega t$$

$$= R.P. \; \varepsilon_0 \varepsilon_r' E_0 \; i\omega \; \exp i\omega t \; - i\varepsilon_0 \varepsilon_r'' E_0 \; -i\omega \; \exp -i\omega t$$

$$= \omega\varepsilon_0 E_0 \; \varepsilon_r'' \cos\omega t - \varepsilon_r' \sin\omega t \qquad \rightarrow (4.24)$$

Here the current component $\varepsilon_r'' \cos\omega t$ is in phase with the applied field and $\varepsilon_r' \sin\omega t$ is 90° out of phase with the applied field. In an ideal dielectric, where there is no absorption of electrical energy, the value of ε_r' is equal to zero. Therefore in an ideal dielectric, the current density,

$$J = \omega\varepsilon_0 \varepsilon_r' E_0 \sin\omega t$$

$$= \omega\varepsilon_0 \varepsilon_r' E_0 \cos \omega t + 90 \qquad \rightarrow (4.25)$$

i.e. the current leads the voltage by 90°.

Under these circumstances,

$$\tan\delta = \frac{\varepsilon_r''}{\varepsilon_r'} = 0 \quad \text{and} \quad \text{hence } \delta = 0. \qquad \rightarrow (4.26)$$

If there is a resulting current component in phase with the field (i.e. if $\varepsilon_r'' \neq 0$), the resulting current will no longer lead the field by 90° but by 90°-δ. Thus if the relative

permittivity of a material is a real quantity, there is no loss. At low frequencies ε_r is real and there is no loss. At IR and higher frequencies ε_r is complex and there is a loss in energy.

4.6. DIELECTRIC BREAKDOWN AND DIELECTRIC STRENGTH

When the electric field applied to a dielectric exceeds a certain critical value, the dielectric loses its insulating property. At that time large current flows through the dielectric. This phenomenon is known as **dielectric breakdown.**

$$E_{br} = \frac{V_{br}}{t}$$

where E_{br} is the dielectric strength
V_{br} is the breakdown voltage
t is the thickness of the specimen.

The electric field at which the dielectric breakdown occurs is known as **dielectric strength**. The dielectric strength is also defined as the minimum voltage required to produce dielectric breakdown.

4.6.1 Types of breakdown

1. Intrinsic breakdown :

The theory of dielectric breakdown was developed using alkali halides as models. The band gap in these materials is substantial. When strong electric field is applied, the electrons in the valence band gain sufficient amount of energy and cross the energy gap. The electrons promoted to the conduction band move freely inside the dielectric and they are accelerated by the applied field. The fast moving conduction electrons collide with the atoms and dislodge more number of electrons. The process goes on as a chain reaction and results in large current flow. The breakdown occurs in this way is intrinsic breakdown.

Characteristics

    i. This can occur even at low temperature

    ii. Relatively high field.

    iii. Thin samples.

    iv. Does not depend on shape of the sample

2. Thermal breakdown :

When a dielectric material is subjected to an alternating electric field, heat is generated due to dielectric loss. If the heat gained by the material is greater than the heat lost to the surrounding, the temperature goes on increasing. As the temperature increases, the conductivity of the dielectric increases. Thus the material loses its insulating property. This is a much slower process than other electronic processes. Thermal breakdown occurs frequently in polymers.

Characteristics

    i. Occur only at high temperature

    ii. Dielectric strength depends on size and shape

3. Chemical breakdown:

When a dielectric is exposed to atmosphere for a longer time, chemical degradation occurs. This chemical degradation encourages breakdown. e.g., degradation of rubber.

Characteristics

    i.   It occurs only at low temperature.

    ii. It occurs even in the absence of electric field.

    iii. It depends on concentration of ions, magnitude of leakage current.

4. Discharge breakdown :

Some dielectric materials may contain gaseous voids (cavities). The dielectric strength of gas is smaller. When a strong electric field is applied, electric discharge occurs in the voids with accompanying destruction of the adjacent material. Thus the void grows continuously and ultimately breakdown occurs. This can occur at low voltages where there are large number of occluded gas bubbles in the insulating material.

Characteristics

    i. It occurs at low voltages.

    ii. It occurs due to the presence of occluded gas bubbles.

    iii. It depends upon the frequency of the applied voltage.

5. Defect breakdown :

Some dielectric materials may have surface defects like cracks, pores etc. Moisture and other impurities filled up at these places lead to breakdown.

To avoid dielectric breakdown, an insulating material should possess the following properties.

    i. Dielectric and Mechanical strength must be high.

    ii. Thermal conductivity must be high

    iii. Thermal expansion must be low.

    iv. Must be pure and free from surface defects.

4.7. USES OF DIELECTRIC MATERIALS (CAPACITORS AND TRANSFORMERS)

Insulating Materials for Electrical Devices

Almost all electrical devices depend on insulating materials in one way or the other. Most of the failures in such devices may be due to the failure of an insulating part.

In general, an insulating material should have good mechanical and electrical strength and good thermal and chemical stability. The insulating materials are used for power and distribution transformer, rotating machines, capacitors, cables, transmission equipment, switchgear, and electronic equipment.

i) Capacitors:

A capacitor is made up of conducting plates and a dielectric. The dielectric may be air, solid insulating material, or a liquid, depending upon the duty of the capacitor and in different electronic circuits.

Capacitors are used in electrical utilities.

Fig 4.14 shows the different types of capacitors. Power   capacitors use tissue paper and / or polypropylene films as dielectric. This insulation system is impregnated with either mineral oil or   synthetic liquids.

Electrolytic capacitors are produced in two forms, wet and try. The wet type consists of an aluminium can holding, an electrolytic   solution of ammonium borate or sodium phosphate.

(a) Ceramic capacitor
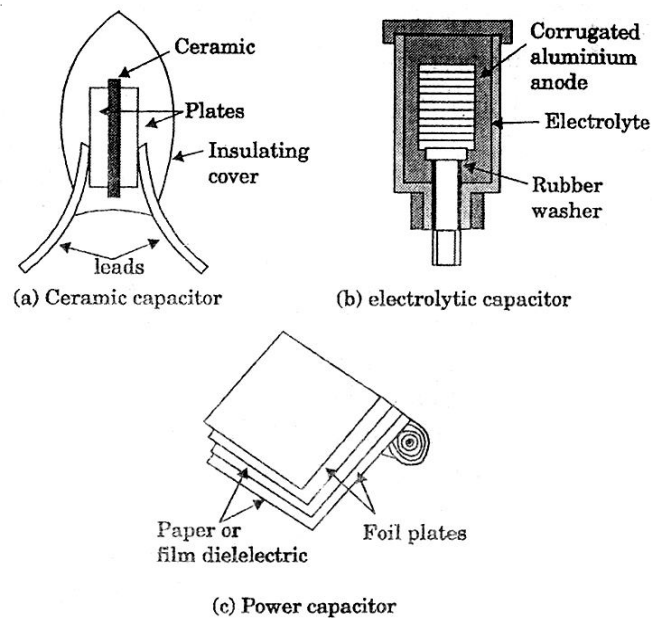
(b) electrolytic capacitor

(c) Power capacitor

Fig 4.14 Different types of capacitors

This can form the negative electrode, while the positive   electrode is made from corrugated aluminium foil, held in electrolyte by a stem which passes through a rubber gland. They are used for D.C supply. In wet type capacitors, the disadvantages are that they must be placed vertically and the electrolyte evaporates.

The dry type capacitor is made from two very thin aluminium foil strips separated from one another by two layers of circulating   papers saturated with a electrolytic paste of glycol and ammonium tetraborate.

Many types of capacitors are now used specially for D.C applications.

These are in addition to paper capacitors (paper with impregnants like castor oil, synthetic oils, mineral oil, polyesters etc), electrolytic capacitors with aluminium or tantalum,   ceramic capacitors with variety of ceramic bodies (tubular, disc, blocking etc) and film dielectric (polystyrene, Teflon, polyethylene etc) capacitors.

ii) Power and distribution transformers

The insulating materials used in power and distribution transformers must possess the following properties.

* Good electrical properties to withstand the power frequency voltages and impulse over voltages.

* Good mechanical properties to withstand fabrication and handling during manu facture and electromagnetic forces during over load, whort circuit and normal operating conditions.

* Good thermal stability and low ageing effect.

The insulating materials for different parts are indicated below:

Low voltage coil to ground and high voltage coil to low voltage coil	Thick radial spacers or tubes made-up of pressboard, paper glass fabric, paper filled plastic laminates, or porcelain
Turn to Turn	organic enamel, paper, glass tapes
Layer to layer, coil to coil	Craft paper, glass fabric press board, varnished paper
Fluid (used as insulating and cooling media)	Mineral oil, air, nitrogen
Bushings	Porcelain, phenolic bonded tubes

Ferroelectric materials (Active dielectrics)

Materials which exhibit electric polarisation even in the absence of the applied electric field are known as Ferroelectric materials.

These have permanent dipole moment in each atom or molecule. The dielectric constants of these materials are some three orders of magnitude larger than that in ordinary dielectrics. **Ferroelectricity refers to the creation of enormous value of induced dipole moment in a weak electric field as well as existence of electric polarisation even in the absence of applied electric field.**

Ferroelectricity is a result of dielectric hysteresis. Since these materials exhibit hysteresis effects, similar to those observed in ferromagnetic materials, they are called *ferroelectric materials.*

Barium titanate ($BaTiO_3$), Potassium dihydrogen phosphate (KH_2PO_4), Ammonium dihydrogen phosphate ($NH_4H_2PO_4$), Lithium Niobate ($LiNbO_3$) and Rochelle salt ($NaKC_4H_4O_6, 4H_2O$) are the typical examples of ferroelectric materials.
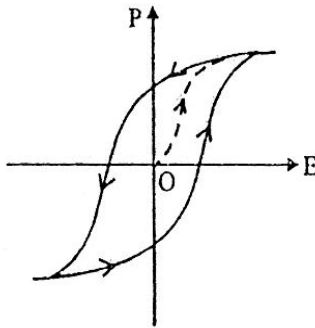

Fig 4.15 Dielectric hysteresis in Ferroelectric materials

Properties of Ferroelectric materials

1.   Ferroelectric materials can be easily polarised even by very weak   electric fields.

2.   They exhibit dielectric hysteresis. Lagging of polarisation   behind the applied electric field is called dielectric hysteresis. Ferroelectricity is a result of dielectric hysteresis (figure4.15)

3. Ferrelectric materials possess spontaneous polarisation, which is polarisation that persists when the applied field is zero.

4. They possess permanent electric dipoles and internal electric field which develop spontaneous polarisation at ferroelectric curie temperature.

5. Ferroelectric materials exhibit ferroelectricity when the temperature T T_c, Where T_c = ferroelectric curie temperature. When $T > T_c$, they are converted into Paraelectric materials.

6. They exhibit domain structure as in the case of ferromagnetic materials.

7. Ferroelectric materials exhibit piezoelectricity. Piezoelectricity means the creation of electric polarisation by mechanical stress. Pyroelectricity means the creation of electric polarisation by thermal stress.

Piezoelectric materials are used to make pressure transducers, ultrasonic transducers and microphones.

(**Examples:** (i) Quartz, Lithium Niobate and Barium Titanate among the crystalline materials.

(ii) Lead Zirconium Titanate, Calcium Barium Titanate and Lead Barium Niobate among the ceramic materials)

Pyroelectric materials are used to make high sensitive infrared detectors.

(**Examples:** Barium Titanate, Triglycine sulphate, Lithium Niobate, Lithium Tantalate and Polyvinyl fluoride)

8. Some ferroelectric semiconductors like $BaTiO_3$ - $SrTiO_3$, $BaTiO_3$ - $PbTiO_3$ and $SrTiO_3$ - $PbTiO_3$ are used to make posistors which are used to measure and control temperature like thermistors. These have positive temperature coefficient of resistance.

9. **Electrets** are ferroelectric materials and are electrostatic analong of permanent magnets. Electrets possess a gross permanent magnets. Electrets possess a gross

permanent electric dipolemoment. They are manufactured from certain types of waxes, plastics and ceramics.

When these waxes are subjected to high electric fields ($\approx 10^6$ V/m) they are polarized in their molten state and retain a permanent polarisation after solidifying even though the external polarising field is removed .

Electrets are used in capacitor microphones and gas filters to capture submicron particles by electrostatic attraction. Further the electret bondages are used over the fractured bones to speed up the bealing process.

Condition for spontaneous polarisation

Consider the equation

$$p = \frac{N\alpha_e E}{1 - \dfrac{N\alpha_e}{3\varepsilon_0}}$$

If the denominator becomes zero we get a polarisation catastrophe. This can be interpreted as that there is polarisation even when there is no external field or in other words there is spontaneous polarisation just as there is spontaneous magnetisation in ferromagnetics. The condition for spontaneous polarisation is given by

$$= 1 \frac{N\alpha_e}{3\varepsilon_0}$$

We may not conclude that $\dfrac{N\alpha_e}{3\varepsilon_0} = 1$, the dielectric constant will

become infinite, but we may conclude that the substrate will become spontaneously polarised.

Some important ferroelectric materials (active dielectrics)

(a) Barium Titanate

Barium Titanate is very useful ferroelectric materials and an active dielectric. It is used in ultrasonic transuducers, harmonic generators, electrets, etc.

(b) Lithium niobate

1. It is an artificial (or) synthetic ferrolectric materials.

2. It is the only materials with highest curie temperature, 1210°C. So this is the suitable piezoelectric material for space applications.

3. It has high electric polarizability and low loss optical transmission. It is an uniaxial crystal with two refractive indices. It exhibits non linear optical characteristics.

4. Even though it is a dielectric materials, at high temperature it becomes electrically conductive due to lattice distortion and   ionic conductivity.

5. It is a high frequency single crystal piezoelectric materials. Due to its high electrome chanical coupling and low attenuation for elastic waves up to 2 GHz, it is primarily used in SAW devices as delay lines and narrow band and UHF filters.

6. Its dielectric constant is roughly about 44. It varies from 27 to 84. Rapid change of temperature can result high field strength on the surface leading to break down.

(c) Lithium tantalate ($LiTaO_3$)

It is similar to Lithium Niobate in may physical properties and its curie point is 660°C and melting point is 1650°C. The domain size is much smaller than $LiNbO_3$ domains. Further the domains are   antiparallel polar domains. It has low temperature coefficient of   resonance and so it can be used in resonator.

It is the more efficient electrooptic modulator materials than $LiNbO_3$. If we take X cut plates of $LiNbO_3$ and $LiTaO_3$' $LiNbO_3$ has the advantage of combining higher coupling factors and lower   mechanical impedance values.

(d) Barium sodium niobate ($Ba_2NaNb_5O_{15}$)

It is synthetic ferroelectric materials. At room temperature it is in orthorhombic belonging to the pyroelectric crystallographic point group (mm_2). The curie point is 560oC

and its melting point is approximately 1500ºC. Above 300ºC, it is converted in to tetrago-nal, belonging to point group (4 mm). Thus this material is different from others like $LiNbO_3$ and $LiTaO_3$ since the phase transition takes place at a temperature between room temperature and the curie temperature. These show nonlinear optical effects like others.

4.8. Applications of Ferroelectric materials

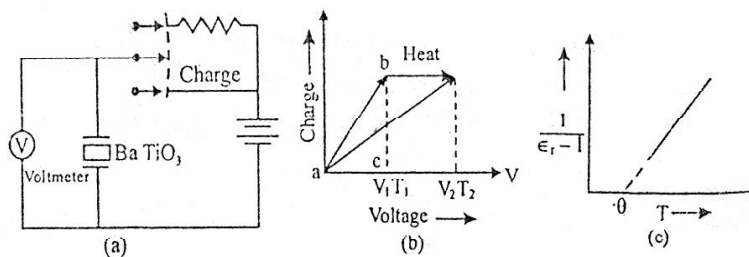## 1. Ferroelectric energy converter

Ferroelectric crystals exhibit the pyroelectric effect. i.e. a change in the temperature of the crystal produces a change in its polarisation. Using this effect, one can convert heat energy in to useful electrical energy. First the capacitor with $BaTiO_3$ is charged to a voltage of V_1 at a temperature T_1 just below the curie temperature 'θ' (figure 4.16)

$$\text{Now } Q = C_1 V_1$$

Where C1 is the capacitance of the capacitor.

Inital energy $Q V_1$ = area of the triangle abc (figure 4.16).

Now the capacitor is isolated from the battery and it is heated up to T2. Therefore, the dielectric constant ε_r decreases. For $BaTiO_3$, when we increase the temperature from 15ºC to 30ºC, (figure 4.16).

Fig . 4.16 Ferroelectric energy conversion

Value of dielectric constant at 150ºC

Value of dielectric constant at 30ºC

Since the dielectric constant value decreases, the capacitance value also decreases and at temperature T_2, the capacitance of the capacitor is equal to C_2.

i.e $C_2 < C_1$

Since the charge Q in the capacitor is constant and $C_2 < C_1$,

$Q = C_1 V_1 = C_2 V_2$

$$\therefore V_2 > V_1$$

(or) $V_2 = V_1 C_1 / C_2 = V_1 \varepsilon_{r1} / \varepsilon_{r2}$

Increase in energy $W = Q (V_2 - V_1)$

There capacitor is now discharged through a load resistor 'R' and a rechargeable battery of voltage V_1 to get electrical power. The capacitor should be cooled to T_1 to complete the cycle.

2.   The high dielectric constant of ferroelectic crystals is also useful   for storing energy in small sized capacitors in electrical circuits.

3.   In optical communication, the ferroelectric crystals are used for optical modulation.

4.   These are used in electro acoustic transducers such as microphone.

5.   Ferroelectric crystals exhibit the piezoelectric property. Using this, we can find enormous applications of ferroelectric materials.