Dielectric Materials

Introduction:

Dielectric materials are electrically non- conducting materials. Examples are glass, cardboard, ebonite, mica, rubber paper etc.. Dielectric materials are group of insulating materials in which dipoles can be produced by applying an external electric potential. Thus, all dielectric materials are insulators but all insulators are not dielectric materials.

Significant properties:

- Very high resistivity and so very low conductivity
- Forbidden energy gap is more than 3 eV
- Localized electrons i.e, electrons engaged in bonding
- A negative temperature coefficient of resistance i.e, resistance decreases with increase in temperature

Basic Definitions

i) **Electric dipole**: A pair of two equal and opposite charges separated by a distance is termed as electric dipole shown in Fig.1

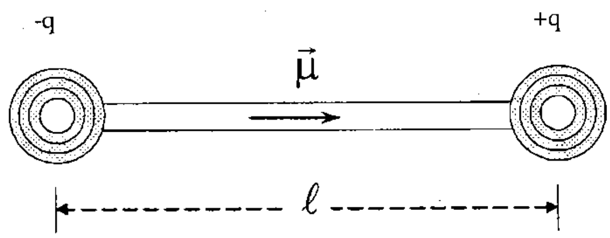


Fig.1 Electric dipole

ii) Electric dipole moment (μ): The product of magnitude of any one of the charge of the electric dipole and the distance between two charges is called electric dipole moment and is denoted by $\mu = q \, X \, l$, where q is the charge of the dipole and l is the distance between the charges of the dipole. It is a vector quantity and its direction is from negative charge to positive charge. The units of electric dipole moment: coulomb-meter.

iii) Dielectric Polarization (P): The electric dipole moment per unit volume is called electric polarization and is denoted by P. That is,

It is numerically equal to surface charge density. It is a vector quantity and the direction is along the direction of the dipole moment. The Units of polarization: farad/metre^2,

$$P = \frac{\mu}{V} = \frac{q \times l}{A \times l} = \frac{q}{A}$$

iv) Polarizability (α): The dipole moment induced in an atom is proportional to the electric filed E i.e.

$$\mu \propto E \quad \text{(or)} \quad \mu = \alpha E$$

Here α is the constant of proportionality called the Polarizability. The induced dipole moment per unit electric field is called Polarizability. If there are N molecules per unit volume, the polarization of the solid,

$$P = N\mu = N\alpha E$$

The Units of Polarizability: coulomb/metre^2.

v) Electric field: The region surrounding an electric charge or group of charges, in which another charge experiences a force is called electric field.

vi) Electric field intensity *(E)*: The force experienced by a unit positive charge placed at a point in the electric field is called electric field intensity and is denoted by *E*. That is,

$$E = F/q$$

It is a vector quantity. Its direction is along the direction in which a unit positive charge tends to move in the electric field. The intensity of electric field is inversely proportional to square of the distance from the charge to a point in the electric field and is given by,

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

The Units of electric field intensity: Newton/coulomb (or) volt/meter.

vii) Electric flux (Φ): The number of electric lines of force emanating from **a** charge is called electric flux and is denoted by Φ. The units of electric flux: Weber.

viii) Electric Flux Density:
The number of electric lines of force passing normally through a surface per unit cross-sectional area is called electric flux density or electric displacement. It is proportional to the electric field intensity,

$$D \propto E \quad \text{or} \quad D = \varepsilon E = \varepsilon_0 \varepsilon_r E$$

Here ε is the permittivity of medium, $\varepsilon = \varepsilon_o \varepsilon_r$, ε_o *is* the permittivity of free space

$\varepsilon_0 = 8.854 \times 10^{-12}$ Faray/meter and ε_r is the relative permittivity of the medium.

The electric field intensity is, $E = \dfrac{q}{4\pi\varepsilon r^2}$

Thus,

$$D = \varepsilon E \Rightarrow \varepsilon\left(\frac{q}{4\pi\varepsilon r^2}\right) = \frac{q}{4\pi r^2} = \frac{q}{A}$$

Here A is the area of dielectric.

The surface charge density per unit area is called electric flux density. Units of electric flux density are: coulomb/metre^2

ix) Dielectric constant (ε_r): For isotropic materials the electric field intensity and the electric flux density D are related by the equation, $D = \varepsilon E = \varepsilon_0 \varepsilon_r E$, where ε is the absolute permittivity of the medium, $\varepsilon = \varepsilon_0 \varepsilon_r$, ε_0 is the permittivity of free space $\varepsilon_0 = 8.854 \times 10^{-12}$ farad/meter and, ε_r is the relative permittivity of the medium and is also called the dielectric constant. ***The dielectric constant is defined as the ratio of the permittivity of the medium to the permittivity of free space.***

The capacitance of parallel plate capacitor when the space between the plates is air is given by $C_o = \varepsilon_0 A / d$ Also the capacitance of the parallel plate capacitor when the space between the plates is filled with a medium of dielectric constant ε_r is $C = \varepsilon_0 \varepsilon_r A/d$ Therefore, the dielectric constant, $\varepsilon_r = \dfrac{C}{C_0}$

Thus, the dielectric constant is also defined as the ratio between the capacitance with dielectric between the plates to the capacitance with air between the plates.

The dielectric constant ε_r is a physical quantity which depends on the structure of atoms of which the material is composed. The value of ε_r is different for different materials. It has no units.

x) Electric susceptibility (χ): When a dielectric is placed in an electric field, then the dielectric is set to be polarized. The polarization vector P is proportional to the applied electric field E. That is, $P \,\alpha\, E \quad or \quad P = \chi E$

Here, χ is a constant and is called susceptibility of dielectric material. **Susceptibility is defined as the polarization per unit electric field intensity. It has no units.**

xi) Relation between three electric vectors *D, E* and *P*: When a dielectric material is placed between the plates of a charged capacitor then the charges are induced on the surface of dielectric. Let q' be the induced charge on the dielectric and the electric field (E^1) due to these charges is in the opposite direction to the electric field (E_Q) due to the charges on the capacitor plates. The resultant electric field between the plates is $E = E_0 - E^1$

Here, $E_0 = \dfrac{q}{\varepsilon_0 A}$ and $E^1 = \dfrac{q^1}{\varepsilon_0 A}$

$$\therefore \quad E = \frac{q}{\varepsilon_0 A} - \frac{q^1}{\varepsilon_0 A} \Rightarrow \varepsilon_0 E = \frac{q}{A} - \frac{q^1}{A} \Rightarrow \frac{q}{A} = \varepsilon_0 E + \frac{q^1}{A} \Rightarrow D = \varepsilon_0 E + P$$

Since, $D = \frac{q}{A}$ and $P = \frac{q^1}{A}$

This is the relation between three electric vectors.

Relation between dielectric constant (ε_r) and electrical susceptibility χ :

The electric displacement is $D = \varepsilon_0 E + P$.

$$D = \varepsilon_0 E + P \Rightarrow \varepsilon_0 \varepsilon_r E = \varepsilon_0 E + P \Rightarrow P = \varepsilon_0 (\varepsilon_r - 1) E \Rightarrow \varepsilon_0 \chi E$$

$$\chi = \frac{P}{\varepsilon_0 E} \Rightarrow \chi = (\varepsilon_r - 1) \Rightarrow \varepsilon_r = 1 + \chi$$

Types of Polarization

The polarization occurs due to several microscopic mechanisms. When the specimen is placed inside a *d .c.* electric filed, the specimen is polarized. The various types of polarization mechanisms are

i) Electronic polarization ii) Ionic polarization

iii) Dipolar polarization iv) Space charge polarization.

Electronic Polarization

An electric strain produced in an atom due to the application of electric field is called electronic polarization. It is the result of the displacement of positively charged nucleus and the electrons of an atom in the opposite direction to the applied electric field. The extent of displacement of charges is proportional to the strength of the electric field. Therefore, the dipole is created within each atom and the dipole moment is proportional to the electric field strength. That is the induced dipole moment, $\mu_e \infty E \Rightarrow \mu_e = \alpha_e E$

Here α_e is constant, called electronic Polarizability.

Electronic polarization can be observed in all dielectric materials. Hence electronic polarization exists at all frequencies even when the frequency of the applied voltage is in the optical range i.e., 10^{15} Hz. Mono atomic gases exhibit only this type of polarization.

Expression for electronic Polarizability:

Let us consider an atom of a dielectric material is placed in an electric field of strength *E.* Assume the charge of the nucleus be Ze is surrounded by an electron cloud of charge $-Ze$ is uniformly distributed in the atom of radius *R.* Since the nucleus and the electron cloud of an atom have opposite charges, they are acted upon by the opposite Lorentz forces in the presence of an applied electric field. The nucleus will move in the opposite direction of the electric field with displacement of x as shown in figure.

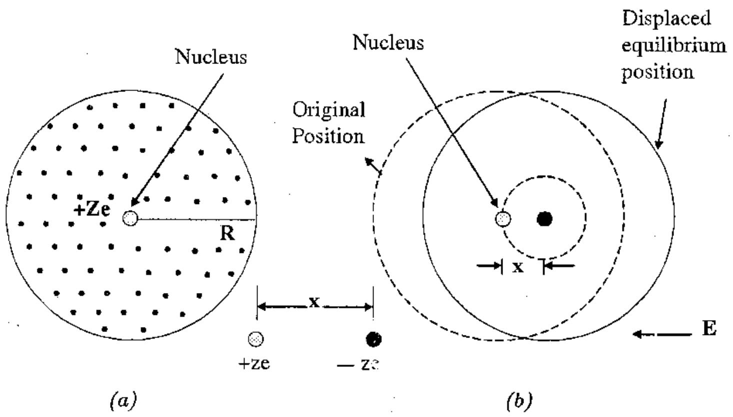


Fig. Electronic polarization (a) unpolarized atom (b) polarized atom

The charge density for an atom of radius R is,

$$\rho = \frac{\text{Total negative charge}}{\text{Volume of the atom}} = -\frac{Ze}{\left(\frac{4}{3}\pi R^3\right)} = -\frac{3}{4}\frac{Ze}{\pi R^3} \quad ......(1)$$

The positively charged nucleus and negatively charged electron cloud experience a Lorentz force F_L in opposite directions. The Lorentz force is given by $F_L = ZeE$.

The Coulomb force of attraction F_C between nucleus and electron cloud separated by a distance x is $F_C = \frac{1}{4\pi\varepsilon_0}\frac{Q_p Q_e}{x^2}$ ....(2)

The total negative enclosed in a sphere of radius x is

$$Q_e = \rho \times \frac{4}{3}\pi x^3 \Rightarrow -\frac{3}{4}\frac{Ze}{\pi R^3}\left(\frac{4}{3}\pi x^3\right) \quad ....(3)$$

The total positive charge enclosed in a sphere of radius x is $Q_p = +Ze$ ....(4)

Substitute eq 3 and eq 4 in eq 2, The Coulomb force of attraction F_C is

$$F_C = \frac{1}{4\pi\varepsilon_0}\left(-\frac{3}{4}\frac{Ze}{\pi R^3}\left(\frac{4}{3}\pi x^3\right)(+Ze)\right) \Rightarrow -\frac{Z^2e^2x}{4\pi\varepsilon_0 R^3}$$

At equilibrium the Lorentz force must be equal to Coulomb force.

$$F_L = -F_C \Rightarrow ZeE = \frac{Z^2e^2x}{4\pi\varepsilon_0 R^3} \Rightarrow x = \frac{4\pi\varepsilon_0 R^3 E}{Ze} \quad ......(5)$$

Due to the displacement of charges from their equilibrium positions, the atom gains dipole moment. The induced dipole moment is,

$$\mu_{\text{ind}} = (\text{magnitude of charge} \times \text{diaplaceme nt})$$
$$= Zex \quad ....(6)$$

The dipole moment is given as $\mu_{\text{ind}} = \alpha_e E$ ....(7)

Substitute eq 5 in eq 6.

$$\mu_{\text{ind}} = (\text{magnitude of charge} \times \text{diaplaceme nt})$$
$$= Ze\left(\frac{4\pi\varepsilon_0 R^3 E}{Ze}\right) \quad ......(8)$$

Equating eq 7 & 8,

$$\alpha_e E = Ze\left(\frac{4\pi\varepsilon_0 R^3 E}{Ze}\right) \Rightarrow \alpha_e = 4\pi\varepsilon_0 R^3$$

Here, α_e is the electronic polarizability of dielectric material.

The induced dipole moment per unit electric field is called Polarizability. If there are N molecules per unit volume, the polarization of the solid,

$$P = N\mu = N\alpha_e E \quad .....(9)$$

But, $P = \varepsilon_0(\varepsilon_r - 1)E \quad ....(10)$

Equating 9 and 10, $N\alpha_e E = \varepsilon_0(\varepsilon_r - 1)E \Rightarrow \alpha_e = \dfrac{\varepsilon_0(\varepsilon_r - 1)}{N}$

Ionic Polarization: Ionic polarization occurs in ionic materials. It occurs when an electric field is applied to an ionic material then cations and anions get displaced in opposite directions that give rise to a net diploe moment. Examples: Polyatomic gases, NaCl

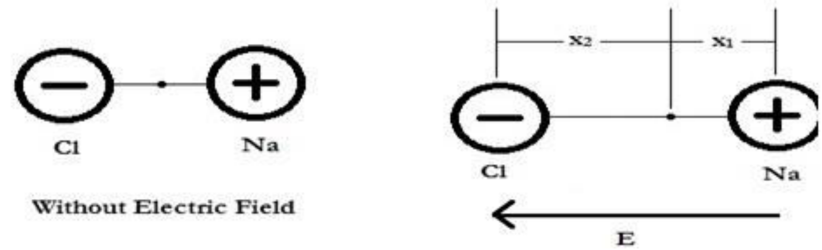


Fig. Ionic polarization (a) unpolarized Ions (b) polarized Ions

When an electric field E is applied across an ionic dielectric, there is a displacement of one ion with respect to another. Figure shows the positive ion Na^+ is displaced through a distance x_1 in the direction of applied electric field and the negative ion Cl^- is displaced by a distance x_2 in opposite direction. Let us assume there is one anion and one cat ion in each unit cell of a ionic crystal. The net distance between two ions is $x = x_1 + x_2$. The Lorentz force acting on positive ions is eE and on negative ions is $-eE$. Where e is the charge of electron. When the ions are displaced from their respective directions from mean position, a restoring force is developed on the ions, which tends to move the ions back to the mean position.

The restoring force acting on the positive ion is k_1x_1.

The restoring force acting on negative ion is k_2x_2.

Here, $k_1 = M\omega_0^2$ is the restoring force constant with angular velocity ω_0 and $k_2 = m\omega_0^2$.

Here, M and m are the masses of positive and negative ions respectively.

At equilibrium position, the Lorentz force is equal to restoring force in opposite direction.

$$eE = k_1x_1 \qquad\qquad eE = k_2x_2$$

$$\Rightarrow x_1 = \frac{eE}{k_1} \qquad \text{And} \quad \Rightarrow x_2 = \frac{eE}{k_2}$$

$$= \frac{eE}{M\omega_0^2} \quad ......(2) \qquad\qquad = \frac{eE}{m\omega_0^2} \quad ......(3)$$

Substituting equation (2) and equation (3) in equation (1)

$$x = x_1 + x_2$$

$$= \frac{eE}{M\omega_0^2} + \frac{eE}{m\omega_0^2}$$

$$= \frac{eE}{\omega_0^2}\left(\frac{1}{M} + \frac{1}{m}\right)$$

Therefore, induced dipole moment is,

$$\mu_i = ex$$

$$= \frac{e^2E}{\omega_0^2}\left(\frac{1}{M} + \frac{1}{m}\right)$$

But, $\mu_i = \alpha_i E$

Hence the ionic polarizability is,

$$\mu_i = \alpha_i E$$

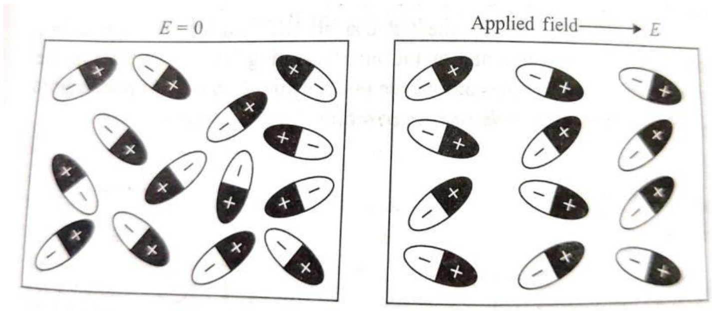
$$\frac{e^2E}{\omega_0^2}\left(\frac{1}{M} + \frac{1}{m}\right) = \alpha_i E$$

$$\alpha_i = \frac{e^2}{\omega_0^2}\left(\frac{1}{M} + \frac{1}{m}\right)$$

Thus, the ionic polarizability is inversely proportional to the square of the natural frequency of the ionic molecule.

(iii) Dipolar or Orientational polarization:

The Orientational polarization is a characteristic of polar dielectrics. Some materials have permanent dipole moments even in the absence of any electric field. In the presence of an applied electric field, the molecular dipoles tend to orient themselves along the direction of electric field.



Orientation polarization results from a permanent dipole, e.g., that arising from the 104.45° angle between the asymmetric bonds between oxygen and hydrogen atoms in the water molecule, which retains polarization in the absence of an external electric field. The assembly of these dipoles forms a macroscopic polarization.

The dipole moment due to Orientational polarization is,

$$\mu_0 \infty E$$
$$\mu_0 = \alpha_0 E$$

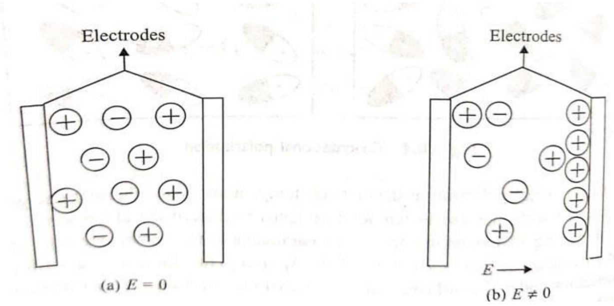
In this polarization the dipole moment is counteracted by thermal agitation. So, Orientational polarization strongly depends on temperature.

$$\alpha_0 = \frac{\mu_0^2}{3k_B T}$$

Orientational polarization occurs only in polar dielectrics such as H_2O, HCl etc.

(iv) Space charge polarization:

The space charge polarization occurs in multi-phase dielectric materials in which there is a change of resistivity between different phases. When such materials are subjected to an external electric field the charges are accumulated at the interface because of sudden change in the conductivity across the boundary. The low resistivity in the phase domain accumulates due to opposite polarity occurs at opposite parts. Space charge polarization occurs in ferrites and semiconductors.



Space charge Polarization

Langevin- Debye Equation: (OR) Total Polarization

Total polarizability due to various polarization mechanisms is $\alpha = \alpha_e + \alpha_i + \alpha_0$. The contribution of space charge polarization is negligibly small.

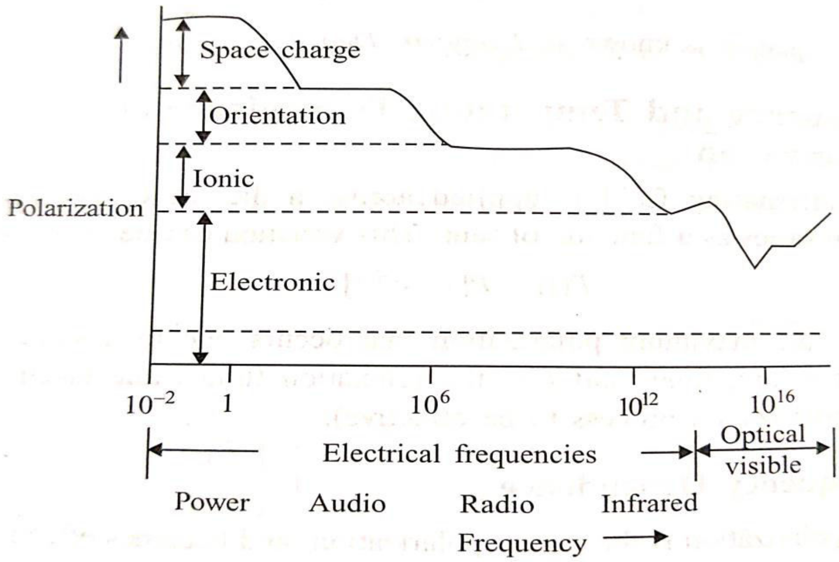
$$\alpha = \alpha_e + \alpha_i + \alpha_0$$
$$= 4\pi\varepsilon_0 R^3 + \frac{e^2}{\omega^2}\left(\frac{1}{M} + \frac{1}{m}\right) + \frac{\mu^2}{3kT}$$

The total polarization is $P = N\alpha E \Rightarrow NE\left(4\pi\varepsilon_0 R^3 + \frac{e^2}{\omega^2}\left(\frac{1}{M} + \frac{1}{m}\right) + \frac{\mu^2}{3kT}\right)$

This equation is known as Langevin-Debye Equation.

Frequency dependence on polarization:

When a dielectric is placed in an alternating electric field the dipoles attempt to maintain alignment with the field. This process requires a finite time that is different for each polarization mechanism. At the relaxation frequency the dipoles will only just be able to reorient themselves in time with the applied field. The variation is expressed as $P(t) = P\left[1 - e^{-t/t_r}\right]$ P is the maximum polarization and t_r is the relaxation time. ***Electronic polarization*** is the fastest polarization and becomes effective at the instant the field applied. This is due to fastest movement of electrons which are lighter than ions. Electronic polarization is effective for very high frequency applied electric fields 10^{15} Hz that falls in optical frequency range. ***Ionic polarization*** is little slower than electronic polarization. Ions being heavier than electrons the time taken by displacement is larger. Ionic polarization occurs at frequency 10^{13} Hz of applied electric field which falls in infrared range. ***Orientational polarization*** is even slower than ionic polarization. This type of polarization occurs only at electrical frequency (audio and radio frequency range 10^6 Hz ***Space charge polarization*** is the slowest polarization process because ions have to diffuse over several atomic distances to reach the interfaces. This process occurs at very low frequencies (10^2 Hz).



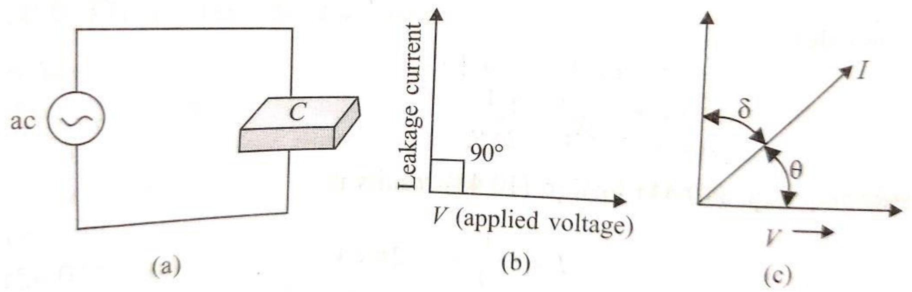
Frequency dependence on various polarization processes

Figure shows that at lower frequencies all four types of polarization occur. The total polarization is maximum at power frequency range. The total polarization decreases with increase in frequency and becomes minimum in optical frequency range.

Dielectric losses:

A dielectric is placed under the influence of an external voltage. All dielectrics absorb a portion of applied electrical energy, which is dissipated in the form of heat. This dissipated energy forms the dielectric loss. Dielectric loss occurs for direct as well as alternating voltages.

When an ac voltage is applied to a dielectric no loss of energy takes place. For an ideal dielectric the charging current leads the applied voltage by a phase angle of 90°.



Dielectric loss graph of a material

Power loss is

$$P_L = VI\cos\theta$$

$$\theta = 90^\circ$$

$$\Rightarrow P_L = 0$$

Thus an ideal dielectric insulator shows no power loss. In a real dielectric the leakage current does not lead the applied voltage by 90°. The phase angle is always less than 90°.

Then the power loss is

$$P_L = VI\cos(90^\circ - \delta)$$

$$= \text{VI}\sin\delta$$

From Ohm's law,

$$V = IR$$

If the capacitive reactance is X_C then $V = IX_C \Rightarrow I = \dfrac{V}{X_C}$

The frequency of a capacitor is $f = \dfrac{1}{2\pi RC}$

The frequency of a capacitor with capacitive reactance X_C is $f = \dfrac{1}{2\pi X_C C}$

The capacitive reactance X_C is $X_C = \dfrac{1}{2\pi f\, C}$

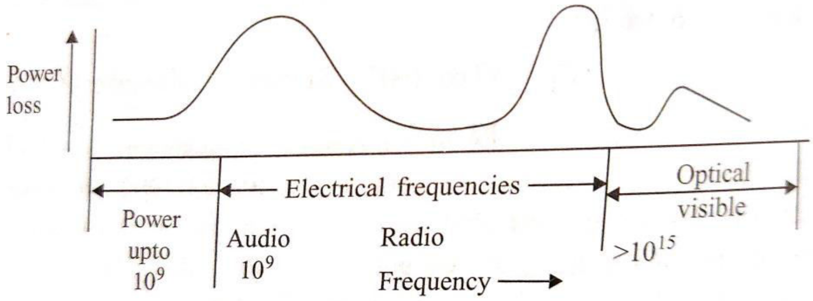
Then leakage current is, $I = \dfrac{V}{X_C} \Rightarrow \dfrac{V}{\dfrac{1}{2\pi f\, C}} = 2\pi f\, CV$

The power loss is $P_L = \text{VI}\sin\delta \Rightarrow V(2\pi f\, CV)\sin\delta \Rightarrow 2\pi f\, CV^2\ \sin\delta \approx 2\pi f\, CV^2\ \tan\delta$

For smaller values of δ $\sin\delta \approx \tan\delta$

Thus the dielectric power loss is $P_L = 2\pi f\, CV^2\ \tan\delta$

The dielectric power loss is directly proportional to $\tan\delta$ if voltage, frequency and capacitance are kept constant. $\tan\delta$ is called power factor of a dielectric.



Variation of power loss frequency

The variation of power loss frequency is shown in figure. Power loss is high in the electrical frequency range and low in optical frequency range.

Q. No		Assignment questions	Mar	CO	RBT
1	A	Explain about electronic polarization in atoms and obtain expression for electronic polarizability in terms of radius of the atom	8	CO3	Understand
	B	Define polarizability and write its units	2	CO3	Understand
2	A	Derive the relation among three electric vectors (D,E and P)	5	CO3	Understand
	B	Explain the dielectric loss and its importance.	5	CO3	Understand
3	A	Describe how the frequency dependence on polarizability.	6	CO3	Understand
	B	The hydrogen gas contains 9.7×10^{26} atoms/m ^{3} and the radius of atom is $0.52\ A^0$. Calculate the electronic polarizability.	4	CO3	Apply
4	A	Demonstrate the Orientational polarization in dielectrics.	4	CO3	Understand
	B	The hydrogen gas contains 9.7×10^{26} atoms/m ^{3} and the radius of atom is $0.52\ A^0$. compute the dielectric constant,	6	CO3	Apply
5	A	Describe about ionic polarization in dielectrics and derive the expression for ionic Polarizability.	7	CO3	Understand
	B	Argon gas contains 2.7×10^{26} atoms/m ^{3} at 0^0 C and 1 atm pressure. Calculate the dielectric constant if the diameter of argon atom is 0.384 nm	3	CO3	Apply
6	A	Deduce the relation among three Magnetic Vectors (B,H & I)	5	CO3	Understand
	B	Derive the relation between Dielectric constant and Electric susceptibility	5	CO3	Understand
7	A	How the magnetic moment is originated at atomic level. Describe it	6	CO3	Understand
	B	Find the relative permeability of a ferromagnetic material if a field of strength 220 amp/meter produces a magnetization of 3300 amp/m in it.	4	CO3	Apply
8	A	Compare the dia, para and ferro magnetic materials with examples	10	CO3	Understand
9	A	Differentiate the Soft & Hard Magnetic Materials	7	CO3	Understand
	B	A magnetic material has a magnetization of 3300 amp/m and flux density of 0.0044 Weber/m^2. Calculate the magnetizing field.	3	CO3	Apply

		($\mu_0 = 4\pi \times 10^{-7}$ Henry/metre)			
10	A	Draw the Hysteresis Curve and explain its significance	7	CO3	Understand
	B	Determine the relative permeability of a ferromagnetic material if a field of strength of 200 amp/meter produces a magnetization of 3300 amp/m in it.	3	CO3	Apply

Q. No	Viva questions from Unit-3	Mar	CO	RBT
1	What is meant by electric dipole moment? Write its units.	2	CO3	Understand
2	Define Electric Polarization. Write its expression.	2	CO3	Understand
3	What do you mean by dielectric Constant? Write its expression	2	CO3	Understand
4	Deduce the relation between three electric vectors.	2	CO3	Apply
5	Realize the relation between dielectric constant and electrical susceptibility	2	CO3	Apply
6	Describe electronic & ionic polarizations	2	CO3	Understand
7	Explain the Langevin-Debye Equation for total polarizability	2	CO3	Understand
8	Explicate Orientational Polarizability. Write its expression	2	CO3	Understand
9	Describe the magnetic dipole moment? Write its units.	2	CO3	Understand
10	Discriminate Hard & Soft Magnetic materials.	2	CO3	Understand
11	Work out the relation between three magnetic vectors.	2	CO3	Apply
12	How the magnetic materials are classified? List out them.	2	CO3	Understand
13	Mark any two properties of Anti-Ferro magnetic materials	2	CO3	Understand
14	Write any two properties of ferrimagnetic materials	2	CO3	Understand
15	Draw the B-H curve and Label it	2	CO3	Apply

Numerical Problems on Unit-3
The hydrogen gas contains 9.7×10^{26} atoms/m^3 and the radius of atom is $0.52\ A^0$. Calculate the electronic polarizability.
Argon gas contains 2.7×10^{26} atoms/m^3 at 0^0 C and 1 atm pressure. Calculate the dielectric constant if the diameter of argon atom is 0.384 nm
Find the relative permeability of a ferromagnetic material if a field of strength 220 amp/meter produces a magnetization of 3300 amp/m in it.
A magnetic material has a magnetization of 3300 amp/m and flux density of 0.0044 Weber/m^2. Calculate the magnetizing field. ($\mu_0 = 4\pi \times 10^{-7}$ Henry/metre)
Determine the relative permeability of a ferromagnetic material if a field of strength of 200 amp/meter produces a magnetization of 3300 amp/m in it.