CHAPTER 2

ELECTROSTATIC POTENTIAL AND CAPACITANCE

Syllabus

- *Electric potential, potential difference, electric potential due to a point charge, electric dipole and system of charges; equi-potential surfaces, electrical potential energy of a system of two point charges and of electric dipole in an electrostatic field.*
- *Conductors and insulators, free charges and bound charges inside a conductor, dielectrics and electric polarisation, capacitors and capacitance, combination of capacitors in series and in parallel, capacitance of a parallel plate capacitor with and without dielectric medium between the plates, energy stored in a capacitor.*

Revision Notes

Electric Potential

Electric potential

- Electric potential is the amount of work done by an external force in moving a unit positive charge from infinity to a point in an electrostatic field without producing an acceleration.
- It is written as $V = \frac{W}{q}$

  where, W = work done in moving charge q through the field, q = charge being moved through the field.
- The SI units of electric potential are $\frac{\text{J}}{\text{C}}$, Volt, $\frac{\text{Nm}}{\text{C}}$.

Potential difference

- Electric potential difference is defined as the amount of work done in carrying a unit charge from one point to another in an electric field.

  $$\text{Electric potential difference} = \frac{\text{Work}}{\text{Charge}} = \frac{\Delta PE}{\text{Charge}} = \frac{W}{q}$$

  Between two points A and B, $W_{AB} = -V_{AB} \times q$

  where, $V_{AB} = V_B - V_A$ is potential difference between A and B.
- In a region of space having an electric field, the work done by electric field dW, when positive point charge q, is displaced by a distance ds, then,

  $$dW = q\vec{E}.\vec{ds}$$

Electrostatic Potential and Capacitance

Electric potential

- Work done per unit test charge by an external agent in moving the test charge from reference point to the desired point. Its SI unit is J/C

$V_0 = W/q_0$.

Electric potential due to a point charge

$V_P = Q/4\pi\varepsilon_0 r$

Potential due to a system of charges

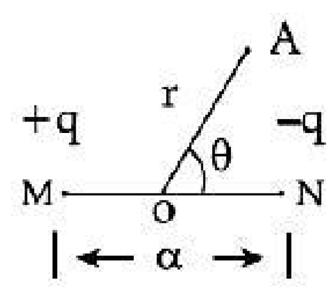
$V = \frac{1}{4\pi\varepsilon_0}\sum \frac{Q_i}{r_i}$

Potential due to a dipole

$V = \frac{1}{4\pi\varepsilon_0}\frac{p\cos\theta}{r^2}$

Where, $p = qd$

$\theta = \angle AON$



At $\theta = 0°$, $V = \frac{1}{4\pi\varepsilon_0}\frac{p}{r^2}$ [axial position]

At $\theta = 90°$, $V = 0$ [equitorial position]

In 1774, Alessandro Volta wrote treatise"on the forces of attraction of electric fire".

Conductors & Insulators

Conductors	Insulators
A material which when placed in an electric field, the free electrons move in a direction opposite to the field.	material in which electrons are tightly bound, and when exposed in an electric field, electrons do not move *i.e.* having no free electrons.

- Electric field inside a conductor is always zero.
- Electric field is always perpendicular to the charged surface.
- In static state, there will be no additional charge in a conductor.

Dielectric

- $F = \frac{q_1 q_2}{4\pi K\varepsilon_0 r^2}$, K = dielectric constant of medium
- A dielectric is an electrical insulator that can be polarized by "application of" electric field.

Capacitance, $C = \frac{Q}{V}$

Capacitance of a parallel plate capacitor,

$C = K\varepsilon_0 A/d$, K = dielectric constant

Capacitance when material slab is inserted between the plates

$C = K\varepsilon_0 A/[Kd - x(K-1)]$

where, x = thickness of the slab inserted

Capacitance of a spherical capacitor,

$C = 4\pi\varepsilon_0 / \left(\frac{1}{R_1} - \frac{1}{R_2}\right)$

For isolated sphere,

$C = 4\pi\varepsilon_0 R$

Energy stored in a capacitor,

$U = \frac{1}{2}CV^2 = \frac{Q^2}{2C} = 1/2\, QV$

Series grouping of capacitors,

$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + - - - + \frac{1}{C_n}$

For two, $C = \frac{C_1 C_2}{C_1 + C_2}$

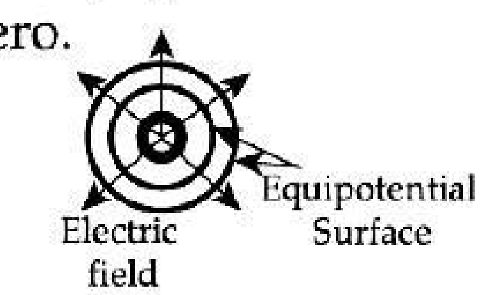
Parallel grouping of capacitors,

$C = C_1 + C_2 + C_3 + - - - - + C_n$

for two capacitors, $C = C_1 + C_2$

Equipotential surface

- Potential is same at all the points of the surface.
- Component of electric field parallel to an equipotential surface is zero.



Electric potential energy

- It is negative count of work done by the electric force as the configuration of the system changes.
- $U_{r_2} - U_{r_1} = -W = \frac{q_1 \cdot q_2}{4\pi\varepsilon_0}\left(\frac{1}{r_2} - \frac{1}{r_1}\right)$
- If the separation between charges is 'r', then $U_{(r)} = \frac{q_1 \cdot q_2}{4\pi\varepsilon_0 r}$
- Potential Difference,

$V_B - V_A = \frac{U_B - U_A}{q}$

$U_B - U_A$ = Change in Potential energy

q = Test charge

Potential energy of a dipole

$dU = pE\sin\theta d\theta$

If we choose P.E. of dipole to be zero when

$\theta = 90°$, then

$U_\theta - U_{90°} = \int_{90°}^{\theta} pE\sin\theta\, d\theta$

If it is rotated through angle θ against the torque,

$U_\theta = -pE\cos\theta = -\vec{p}\cdot\vec{E}$

How to understand Mind Map?

First Level · Second Level · Third Level

$$\Delta V = V_{AB} = V_B - V_A = -\frac{W_{AB}}{q} = -\frac{\int_A^B q\vec{E}.\vec{ds}}{q} = -\int_A^B \vec{E}.\vec{ds}$$

Electric potential due to point charge

- The electric potential by point charge *q*, at a distance *r* from the charge, can be written as,

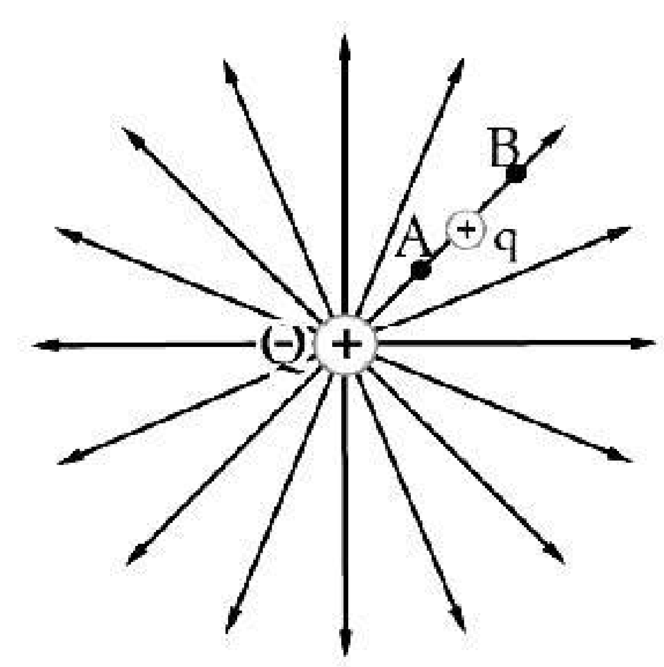
$$V_E = \frac{1}{4\pi\varepsilon_0}.\frac{q}{r}$$

where, ε_0 is permittivity of vacuum (free space).

- Electric potential is a scalar quantity.
- Dimension of Electric potential is $[M L^2T^{-3}A^{-1}]$.
- For a single point charge *q*, the potential difference between *A* and *B* is given by,

$$\Delta V = V_B - V_A = -\int_A^B \vec{E}.\vec{ds} = -\int_A^B Eds\cos 0° = -E\int_A^B ds$$

where, *E* is the field due to a point charge, $ds = dr$, so that,



$$V_B - V_A = -\int_{r_A}^{r_B} \frac{q}{4\pi\varepsilon_0}.\frac{dr}{r^2} = \frac{q}{4\pi\varepsilon_0}\left[\frac{1}{r}\right]_{r_A}^{r_B} = \frac{q}{4\pi\varepsilon_0}\left[\frac{1}{r_B} - \frac{1}{r_A}\right]$$

- If $r_B = \infty$, then $V_B = 0$ so,

$$V_A = \frac{1}{4\pi\varepsilon_0}.\frac{q}{r_A} = \frac{kq}{r_A}$$

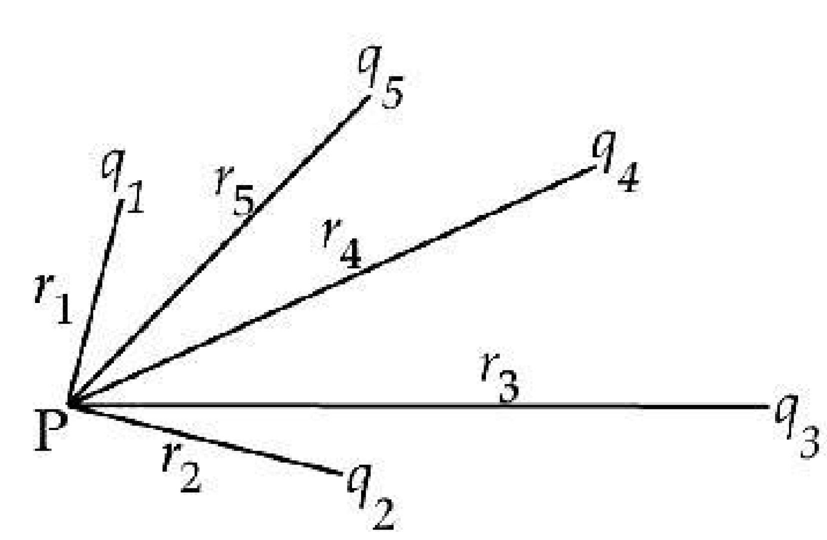
Dipole and system of charges

- Electric dipole consists of two equal but opposite electric charges which are separated by a distance.
- The net potential due to a dipole at any point on its equatorial line is always zero. So, work done in moving a charge on an equatorial line is always zero.
- Electric potential due to dipole at a point at distance *r* and making an angle θ with the dipole moment *p* is given by, $V = \frac{1}{4\pi\varepsilon_0}.\frac{p\cos\theta}{r^2} = \frac{1}{4\pi\varepsilon_0}.\frac{\vec{p}.\hat{r}}{r^2}(r >> a)$
- Potential at a point due to system of charges is the sum of potentials due to individual charges.
- In a system of charges $q_1, q_2, q_3, \ldots q_n$ having positive vectors $r_1, r_2, r_3, \ldots r_n$ relative to point *P*, the potential at point P due to total charge configuration is algebraic sum of potentials due to individual charges, so,

$$V = V_1 + V_2 + V_3 + \ldots + V_n$$

$$= \frac{1}{4\pi\varepsilon_0}\left(\frac{q_1}{r_1} + \frac{q_2}{r_2} + \frac{q_3}{r_3} + \ldots + \frac{q_n}{r_n}\right)$$

$$V = \frac{1}{4\pi\varepsilon_0}\sum_{i=1}^{n}\frac{q_i}{r_i}$$



- It is known that in a uniformly charged spherical shell, here electric potential outside the shell is given as:

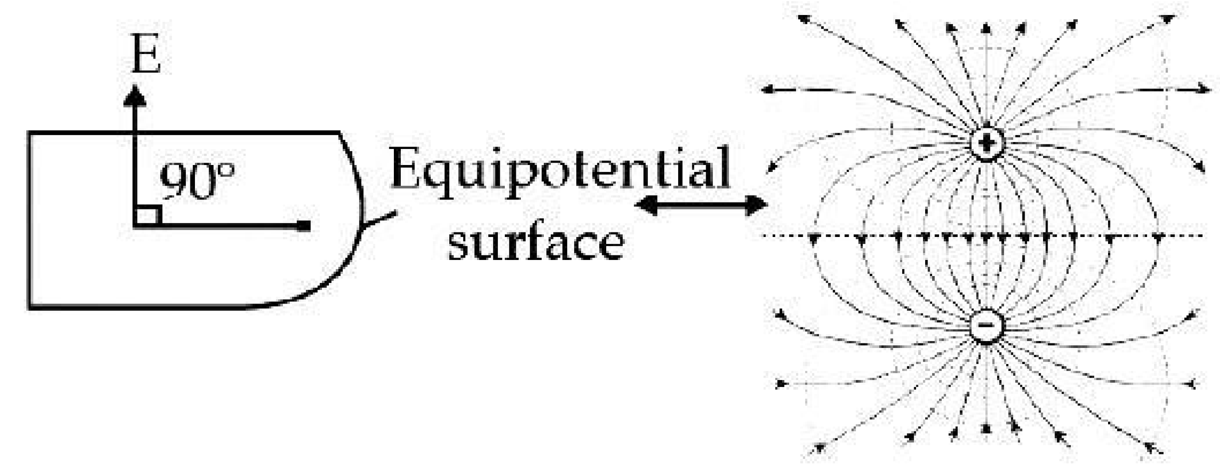
$$V = \frac{1}{4\pi\varepsilon_0}.\frac{q}{r} \qquad (r \ge R)$$

where, *q* is the total charge on shell and *R* is the shell radius.

Equi-potential surfaces

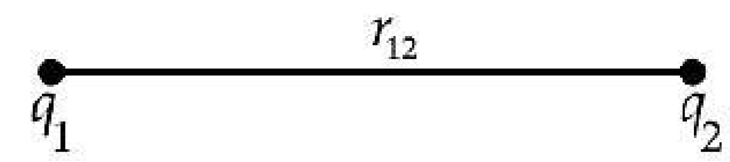
- Equi-potential surface is a surface in space on which all points have same potential. It requires no work to move the charge on such surface, hence the surface will have no electric field, so *E* will be at right angle to the surface.
- Work done in moving a charge over equi-potential surface is always zero.
- Electric field is always perpendicular to the equi-potential surface.

- Spacing among equi-potential surfaces allows to locate regions of strong and weak electric field.
- Equi-potential surfaces **never intersect** each other. If they intersect then the intersecting point of two equi-potential surfaces results in two values of electric potential at that point, which is impossible.



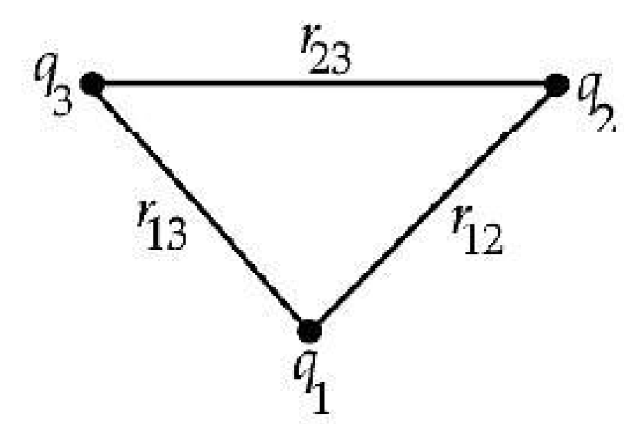
- Potential energy of a system of two charges,

$$U = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r_{12}}$$



- Potential energy of a system of three charges,

$$U = \frac{1}{4\pi\varepsilon_0}\left(\frac{q_1 q_2}{r_{12}} + \frac{q_1 q_3}{r_{13}} + \frac{q_2 q_3}{r_{23}}\right)$$



- Potential energy due to single charge in an external field:

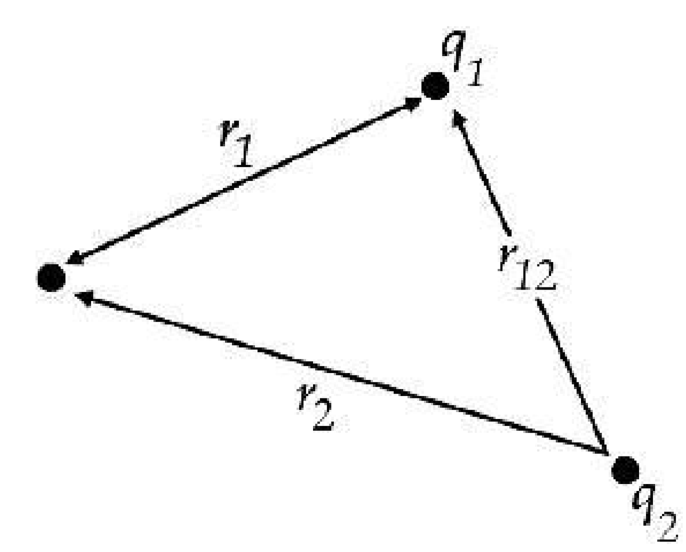
  Potential energy of a charge q at a distance r in an external field,

  $$U = qV(\vec{r})$$

  Here, $V(\vec{r})$ is the external potential at point r.

- Potential energy due to two charges in an external field,

  $$U = q_1 V(\vec{r_1}) + q_2 V(\vec{r_2}) + \frac{1}{4\pi\varepsilon_0}\cdot\frac{q_1 q_2}{r_{12}}$$



- Potential energy of a dipole in an external field:

  When a dipole of charge $q_1 = +q$ and $q_2 = -q$ having separation '$2a$' is placed in an external field ($\vec{E}$).

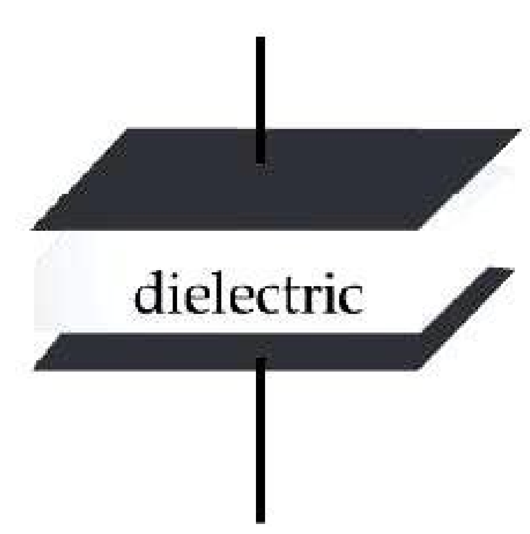
  $U(\theta) = -pE\cos\theta$

  Here, $p = 2aq$ and θ is the angle between electric field and dipole.

Capacitance

Conductors and insulators

- Conductors are the materials through which charge can move freely. **Examples:** Metals, semi-metals as carbon, graphite, antimony and arsenic.
- Insulators are materials in which the electrical current does not not flow easily. Such materials cannot be grounded and do not easily transfer electrons. **Examples:** Plastics and glass.



Dielectrics

- These are the materials in which induced dipole moment is linearly proportional to the applied electric field.
- Electrical displacement or electrical flux density, $D = \varepsilon_r \varepsilon_0 E$.
  where, ε_r = Electrical relative permittivity, ε_0 = Electrical permittivity of free space and E is electric field.
- If a dielectric is kept in between the plates of capacitor, capacitance increases by factor 'κ' (kappa) known as dielectric constant, so $C = \kappa\varepsilon_0 \frac{A}{d}$

  where, A = area of plates

  κ = dielectric constant of material is also called relative permittivity $\kappa = \varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$

Material	Dielectric Constant (κ)	Dielectric strength (10^6 V/m)
Air	1.00059	3
Paper	3.7	16
Pyrex Glass	5.6	14
Water	80	-

- In dielectric, polarisation and production of induced charge takes place when dielectric is kept in an external electric field.

Electric polarization

- Electric polarization P is the difference between electric fields D (induced) and E (imposed) in dielectric due to bound and free charges written as $P = \frac{D-E}{4\pi}$
- In term of electric susceptibility: $P = \chi_e E$
- In MKS: $P = \varepsilon_0 \chi_e E$,
- The dielectric constant κ is always greater than 1 as $\chi_e > 0$

Capacitor

- A capacitor is a device which is used to store charge.
- Amount of charge 'Q' stored by the capacitor depends on voltage applied and size of capacitor.
- Capacitor consists of two similar conducting plates placed in front of each other where one plate is connected to positive terminal while other plate is connected to negative terminal.
- Electric charge stored between plates of capacitor is directly proportional to potential difference between its plates, *i.e.*,

$$Q = CV$$

where, C = Capacitance of capacitor, V= potential difference between the plates

- In capacitor, energy is stored in the form of electrical energy, in the space between the plates.

Capacitance

- Capacitance of a capacitor is ratio of magnitude of charge stored on the plate to potential difference between the plates, written as $C = \frac{Q}{\Delta V}$

where, C = capacitance in farads (F), Q = charge in Coulombs (C), ΔV = electric potential difference in Volts (V),

- SI unit of capacitance is farad (F)
- $1\ F = \frac{1\ C}{1\ V} = 9 \times 10^{11}$ stat farad,

Where, stat-farad is electrostatic unit of capacitance in C.G.S. system

- Capacitance of a conductor depends on size, shape, medium and other conductors in surrounding.
- Parallel plate capacitor with dielectric among its plates has capacitance which is given as:

$$C = \kappa\varepsilon_0 \frac{A}{d},$$

where, $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m

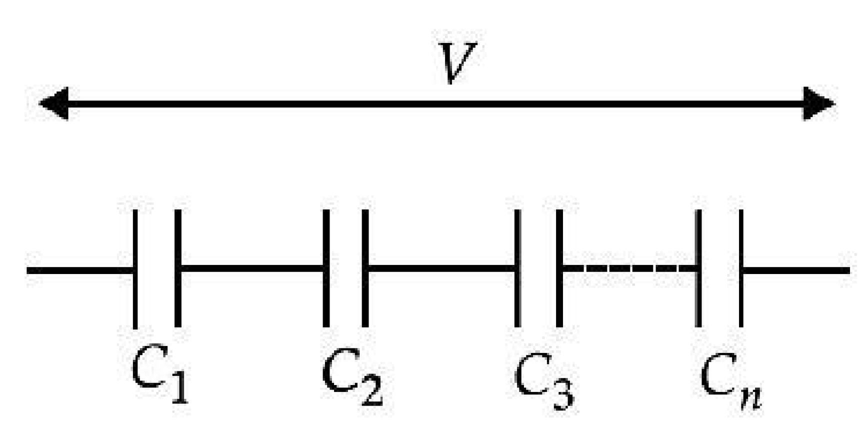
- Capacitor having capacitance of 1 Farad is too large for electronics applications, so components with lesser values of capacitance such as μ (micro), n (nano) and p (pico) are applied such as:

PREFIX	MULTIPLIER	
μ	10^{-6} (millionth)	$1\ \mu F = 10^{-6}$ F
n	10^{-9} (thousand-millionth)	$1\ nF = 10^{-9}$ F
p	10^{-12} (million-millionth)	$1\ pF = 10^{-12}$ F

Combination of capacitors in series and parallel

Capacitors in series

- (i) If a number of capacitors of capacitances C_1, C_2, C_3, ... C_n are connected in series, then their equivalent capacitance is given by:



$$\frac{1}{C_s} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots\ldots\ldots\ldots \frac{1}{C_n}$$

- In series combination, the charge on each capacitor is same, but the potential difference on each capacitor depends on their respective capacitance, *i.e.*,

$q_1 = q_2 = q_3$ .... $q_n = q$

- If V_1, V_2, V_3, ..., V_n be the potential differences across the capacitors and V be the emf of the charging battery, then

$V = V_1 + V_2 + V_3 + \ldots\ldots\ldots + V_n$

- As charge on each capacitor is same, therefore

$$q = V_1C_1 = V_2C_2 = V_3C_3 \ldots\ldots\ldots\ldots$$

the potential difference is inversely proportional to the capacitance, *i.e.*,

$$V \propto \frac{1}{C}$$

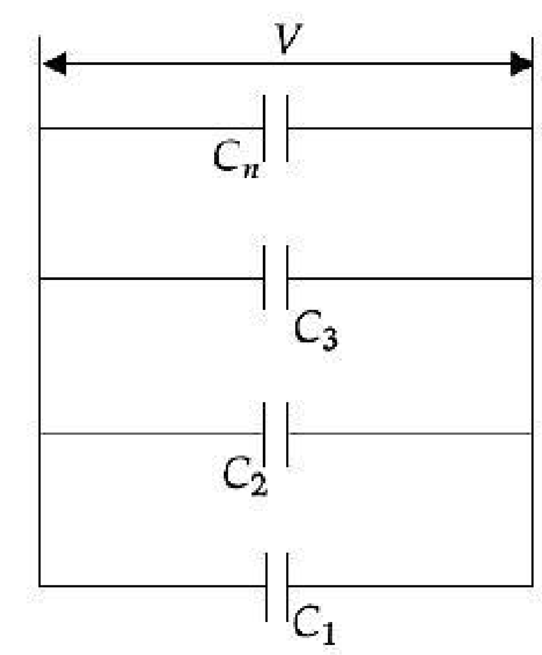
- In series, potential difference across largest capacitance is minimum.
- The equivalent capacitance in series combination is less than the smallest capacitance in combination.

Capacitors in parallel

- (i) If a number of capacitors of capacitances $C_1, C_2, C_3 \ldots\ldots\ldots\ldots\ldots C_n$ are connected in parallel, then their equivalent capacitance is given by,

$$C_p = C_1 + C_2 + C_3 + \ldots\ldots\ldots\ldots\ldots + C_n$$

- In parallel combination, the potential difference across each capacitor is same and equal to the emf of the charging battery, *i.e.*,



$$V_1 = V_2 = V_3 = \ldots\ldots\ldots\ldots\ldots = V_n = V$$

while the charge on different capacitors may be different.

- If $q_1, q_2, q_3, \ldots\ldots\ldots\ldots\ldots, q_n$ be the charges on the different capacitors, then

$$q_1 + q_2 + q_3 + \ldots\ldots\ldots\ldots\ldots + q_n = VC_p$$

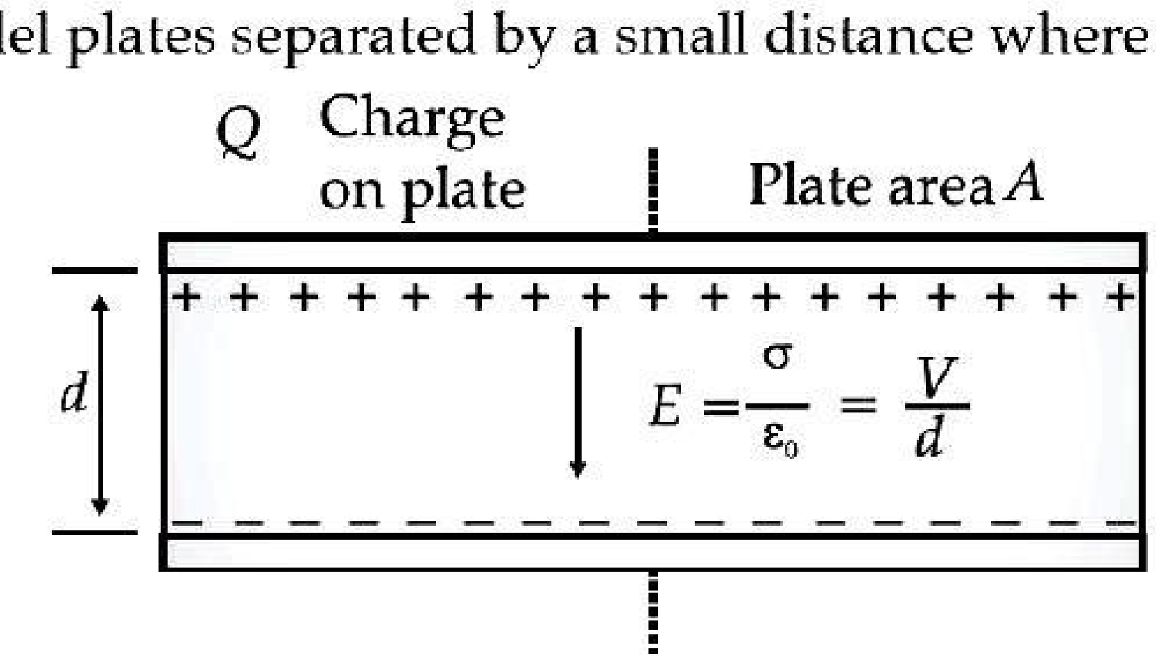
- As potential drop across each capacitor is same, so

$$\Rightarrow \qquad V = \frac{q_1}{C_1} = \frac{q_2}{C_2} = \frac{q_3}{C_3} = \ldots\ldots\ldots = \frac{q_n}{C_n}$$

- The charges on capacitors are directly proportional to capacitances, *i.e.*, $q \propto C$
- Parallel combination is useful when large capacitance with large charge gets accumulated on combination.
- Force of attraction between parallel plate capacitor will be $F = \frac{1}{2}\left[\frac{QV}{d}\right] = \frac{1}{2}QE$ where Q is charge on capacitor.

Capacitance of parallel plate capacitor with and without dielectric medium between the plates

- Parallel plate capacitor is a capacitor with two identical plane parallel plates separated by a small distance where space between them is filled by dielectric medium.
- The electric field between two large parallel plates is given as:



$$E = \frac{\sigma}{\varepsilon_0},$$

Where, σ = charge density and ε_0 = permittivity of free space

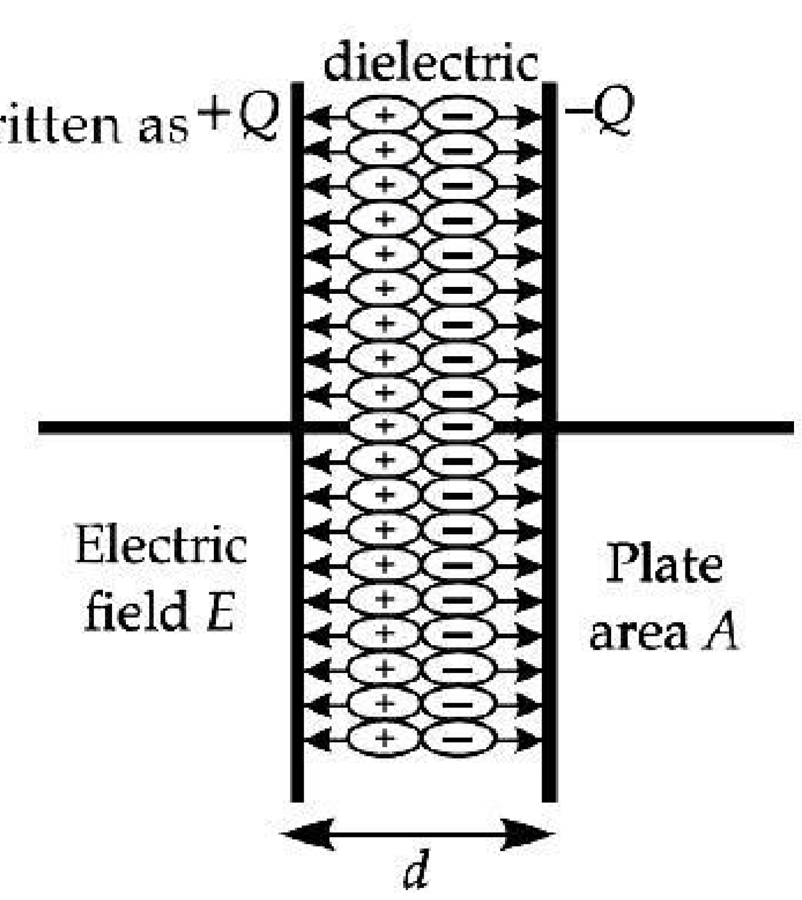
Surface charge density,

$$\sigma = \frac{Q}{A},$$

where, Q = charge on plate and A = plate area

- Capacitance of parallel-plate capacitor with area A separated by a distance d is written as

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d}$$



- If a dielectric slab is placed in between the plates of a capacitor, then its capacitance will increase by certain amount.
- Capacitance of parallel plate capacitor depends on plate area A, distance d between the plates, medium between the plates (κ) and not on charge on the plates or potential difference between the plates.
- If we have number of dielectric slabs of same area as the plates of the capacitor and thicknesses $t_1, t_2, t_3 \ldots.$ and dielectric constant $\kappa_1, \kappa_2, \kappa_3 \ldots\ldots$ between the plates, then the capacitance of the capacitor is given by

$$C = \frac{\varepsilon_0 A}{\frac{t_1}{\kappa_1} + \frac{t_2}{\kappa_2} + \frac{t_3}{\kappa_3} + \ldots.},$$

Where, $d = t_1 + t_2 + t_3 + ...$

- If slab of conductor of thickness t is introduced between the plates, then

$$C = \frac{\varepsilon_0 A}{\frac{t}{\kappa} + \frac{(d-t)}{1}} = \frac{\varepsilon_0 A}{\frac{t}{\infty} + \frac{(d-t)}{1}}$$

$$C = \frac{\varepsilon_0 A}{d - t} \qquad (\because \kappa = \infty \text{ for a conductor})$$

- When the medium between the plates consists of slabs of same thickness but areas $A_1, A_2, A_3,...$ and dielectric constants $\kappa_1, \kappa_2, \kappa_3...$, then capacitance is given by

$$C = \frac{\varepsilon_0(\kappa_1 A_1 + \kappa_2 A_2 + \kappa_3 A_3 ....)}{d}$$

$$\therefore \quad \kappa = \frac{C_m}{C_0} = \frac{\text{Capacitance in medium}}{\text{Capacitance in vacuum}}$$

- When space between the plates is partly filled with medium of thickness t and dielectric constant κ, then capacitance will be:

$$C = \frac{\varepsilon_0 A}{d - t + \frac{t}{\kappa}} = \frac{\varepsilon_0 A}{d - t\left(1 - \frac{1}{\kappa}\right)}$$

When there is no medium between the plates, then $\kappa = 1$, so $C_{vacuum} = \frac{\varepsilon_0 A}{d}$

- Capacitance of spherical conductor of radius R in a medium of dielectric constant κ is given by,

$$C = 4\pi\varepsilon_0\kappa R$$

Energy stored in capacitor

- In capacitor, energy gets stored when a work is done on moving a positive charge from negative conductor to positive conductor against the repulsive forces.

$$U = \frac{1}{2}\frac{Q^2}{C} = \frac{1}{2}QV = \frac{1}{2}CV^2$$

- **Polar atom:** Atom in which positive and negative charges possess asymmetric charge distribution about its centre.
- **Polarisation:** The stretching of atoms of a dielectric slab under an applied electric field.
- **Dielectric strength:** The maximum value of electric field that can be applied to dielectric without its electric breakdown.
- **Dielectric:** It is an electrically insulated or non-conducting material considered for its electric susceptibility.
- **Permittivity:** It is a property of a dielectric medium that shows the forces which electric charges placed in medium exerts on each other.

OR

It is the measure of resistance that is encountered when forming an electric field in a particular medium. More specifically, permittivity describes the amount of charge needed to generate one unit of electric flux in a particular medium.

Mnemonics

Concept: Characteristics of equi-potential surface

Mnemonics: Exclusive peace and No war Noble India is super power

Interpretation:

Exclusive peace and: Electric field is perpendicular to the surface

No war: No Work is done on moving a charge on the surface

Noble India is: Never Intersects

Super Power: Same potential everywhere on the surface

Key Formulae

- Electric Potential, $V = \frac{W}{q}$, measured in volt; 1 volt = 1 Joule / coulomb.
- Electric potential difference or "voltage" $(\Delta V) = V_f - V_i = \frac{\Delta U}{q} = \frac{W}{q}$
- Electric potential due to a point charge q at a distance r away: $V = \frac{1}{4\pi\varepsilon_0}.\frac{q}{r}$
- Finding V from E: $V_f - V_i = -\int_i^f \vec{E}.d\vec{S}$
- Potential energy of two point charges in absence of external electric field: $U = \frac{1}{4\pi\varepsilon_0}\left[\frac{q_1 q_2}{r_{12}}\right]$
- Potential energy of two point charges in presence of external electric field: $q_1 V(r_1) + q_2 V(r_2) + \frac{q_1 q_2}{4\pi\varepsilon_0 r_{12}}$

  Note: All symbols have their usual meanings.
  Concept: Characteristics of equi-potential surface.
  Exclusive peace and No war Noble India is super power.
  Interpretation:
  Electric field is perpendicular to the surface.
  No Work is done in moving a charge on the surface.
  Never intersects.
  Same potential everywhere on the surface.
- Capacitance, $C = \frac{Q}{V}$, measured in Farad; 1 F = 1 coulomb/volt
- Parallel plate capacitor:
  $$C = \kappa\varepsilon_0 \frac{A}{d}$$
- Cylindrical capacitor:
  $$C = 2\pi\kappa\varepsilon_0 \frac{L}{ln(b/a)}$$
  where, L= length [m], b= radius of the outer conductor [m], a = radius of the inner conductor [m]
- Spherical capacitor:
  $$C = 4\pi\kappa\,\varepsilon_0\left(\frac{ab}{b-a}\right)$$
  where, b = radius of the outer conductor [m], a = radius of the inner conductor [m]
- Maximum charge on a capacitor:
  $$Q = VC$$
- For capacitors connected in series, the charge Q is equal for each capacitor as well as for the total equivalent. If the **dielectric constant** κ is changed, the capacitance is multiplied by κ, the voltage is divided by κ and Q is unchanged. In vacuum, $\kappa = 1$ and when dielectrics are used, replace ε_0 with $\kappa\,\varepsilon_0$.
- Electrical energy stored in a capacitor: [Joules (J)]
  $$U_E = \frac{QV}{2} = \frac{CV^2}{2} = \frac{Q^2}{2C}$$
- Surface charge density or Charge per unit area: [C/m^2]
  $$\sigma = \frac{q}{A}$$
- **Energy density:**
  - Electric energy density is also called Electrostatic pressure.
  - Electric force between plates of capacitor,

$$F = \frac{1}{2}\varepsilon_0 E^2 \cdot A$$

- Energy stored in terms of Energy density,

$$\frac{E}{A \times d} = \frac{1}{2}\varepsilon_0 E^2$$

$$U = \frac{1}{2}\varepsilon_0 E^2$$

where, U = energy per unit volume [J/m^3], ε_0= permittivity of free space, = 8.85×10^{-12} C^2/Nm^2, E = energy [J]

- **Capacitors in series:**

$$\frac{1}{C_{eff}} = \frac{1}{C_1} + \frac{1}{C_2} \ldots$$

- **Capacitors in parallel:**

$$C_{eff} = C_1 + C_2 \ldots$$

STAND ALONE MCQs (1 Mark each)

Q.1. The electrostatic potential on the surface of a charged conducting sphere is 100 V.

Two statements are made in this regard :

S_1 : At any point inside the sphere, electric intensity is zero.

S_2 : At any point inside the sphere, the electrostatic potential is 100 V.

Which of the following is a correct statement?

(A) S_1 is true, but S_2 is false.

(B) Both S_1 and S_2 are false.

(C) S_1 is true, S_2 is also true and S_1 is the cause of S_2.

(D) S_1 is true, S_2 is also true but the statements are independent.

Ans. Option (C) is correct.

> ***Explanation:*** The relation between electric field intensity E and potential (V) is,
>
> $$E = -\frac{dV}{dr}$$
>
> Where, Electric field intensity, E = 0 inside the sphere
>
> So that, $\frac{dV}{dr} = 0$
>
> This means that V = constant. So, if E = 0 inside charged sphere, the potential is constant or V = 100V everywhere inside the sphere and it verifies the shielding effect also. So, it verifies the option (C).

Q. 2. Equipotential at a great distance from a collection of charges whose total sum is not zero are approximately

(A) spheres. **(B)** planes.

(C) paraboloids. **(D)** ellipsoids.

Ans. Option (A) is correct.

> ***Explanation:*** For equipotential surface, these surfaces are perpendicular to the field lines. So there must be electric field, which cannot be without charge.
>
> So the algebraic sum of all charges must not be zero. Equipotential surface at a great distance means that space of charge is negligible as compared to distance. So the collection of charges is considered as a point charge.
>
> Electric potential due to point charge is,
>
> $$V = k_e \frac{q}{r}$$
>
> which explains that electric potentials due to point charge is same for all equidistant points. The locus of these equidistant points, which are at same potential, forms spherical surface.

Q. 3. A positively charged particle is released from rest in an uniform electric field. The electric potential energy of the charge

(A) remains a constant because the electric field is uniform.

(B) increases because the charge moves along the electric field.

(C) decreases because the charge moves along the electric field.

(D) decreases because the charge moves opposite to the electric field.

Ans. Option (C) is correct.

> *Explanation:* As we know that, an equipotential surface is always perpendicular to the direction of electric field. Positive charge experiences the force in the direction of electric field. When a positive charge is released from rest in uniform electric field, its velocity increases in the direction of electric field. So K.E. increases, and the P.E. decreases due to law of conservation of energy.

Q. 4. Figure shows some equipotential lines distributed in space. A charged object is moved from point A to point B.

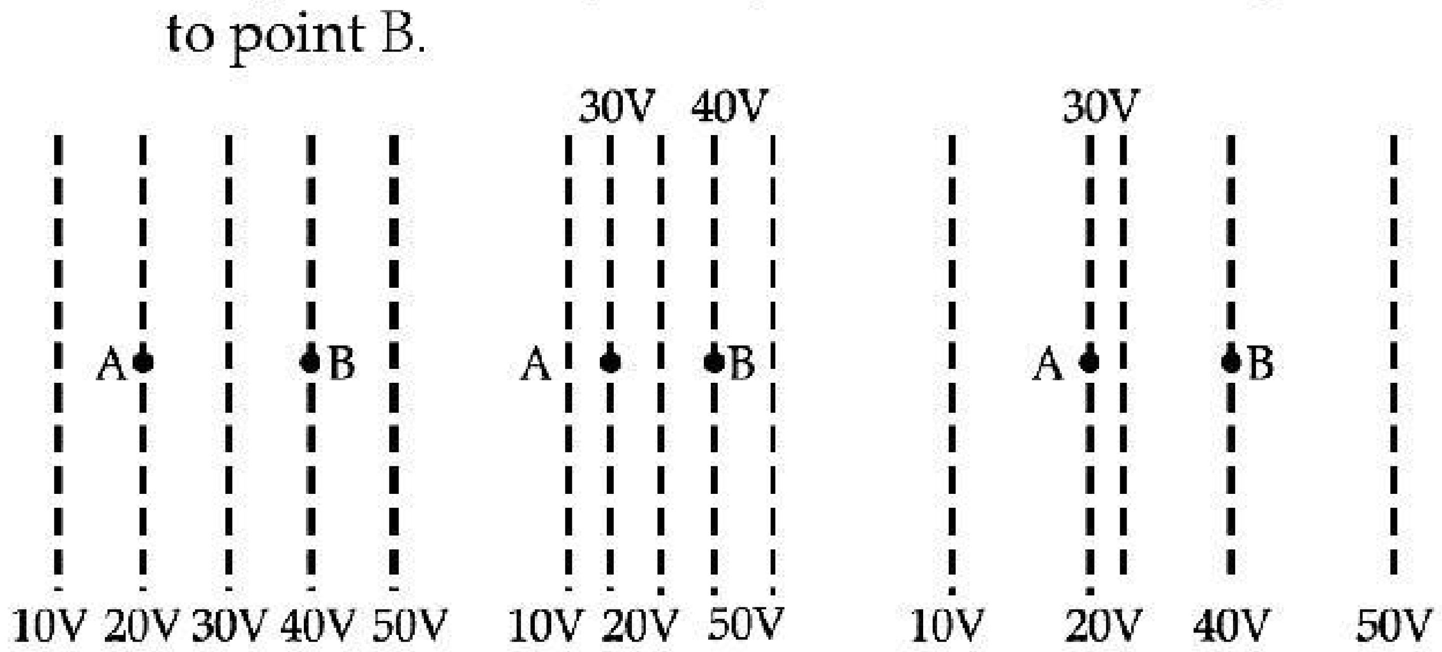


Fig. (i) **Fig. (ii)** **Fig. (iii)**

(A) The work done in Figure (i) is the greatest.

(B) The work done in Figure (ii) is least.

(C) The work done is the same in Figure (i), Figure (ii) and Figure (iii).

(D) The work done in Figure (iii) is greater than Figure (ii), but equal to that in Figure (i).

Ans. Option (C) is correct.

> *Explanation:* The work done by the electrostatic force is given by $W_{12} = q\,(V_2 - V_1)$
> As the potential difference between *A* and *B* in all three figures are equal, 20 V, so work done by any charge in moving from *A* to *B* surface will be equal.

Q. 5. The work done to move a charge along an equipotential surface from A to B

(A) cannot be defined.

(B) is a negative quantity.

(C) is zero.

(D) is a positive quantity.

Ans. Option (C) is correct.

> *Explanation:* For an equipotential surface, $V_A = V_B$
> So, work done = 0

Q. 6. The shape of equipotential surfaces due to an isolated charge is

(A) Concentric spherical shells and the distance between the shells increases with the decrease in electric field

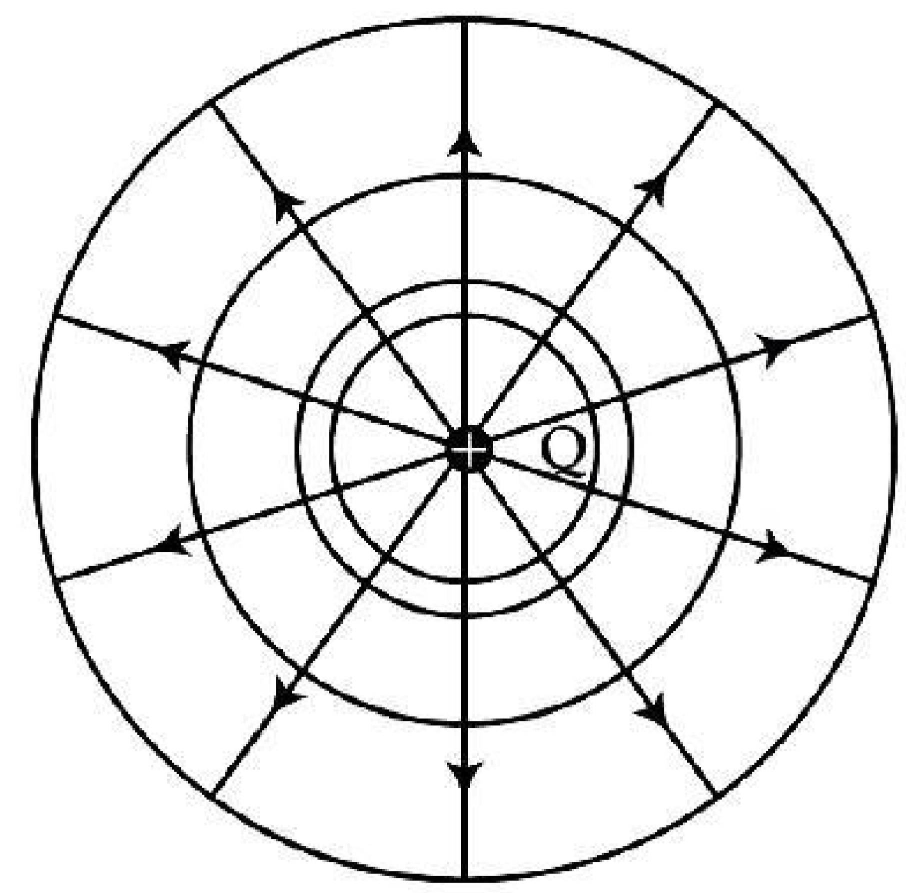
(B) Concentric spherical shells and the distance between the shells decreases with the decrease in electric field

(C) Equi-spaced concentric spherical shells

(D) Changes with the polarity of the charge.

Ans. Option (A) is correct.

> *Explanation:* Concentric spherical shells and the distance between the shells increases with the decrease in electric field. It does not depend on the polarity of the charge.



Q. 7. Electric potential inside a conducting sphere

(A) is zero.

(B) remains constant.

(C) decreases from centre to surface.

(D) increases from centre to surface.

Ans. Option (B) is correct.

> *Explanation:* Inside the sphere, E = 0
> Again $E = -dV/dr$
> So, $dV/dr = 0$
> This is possible when V is constant.

Q. 8. The electric potential at a point on the equatorial line of a electric dipole is

(A) directly proportional to the square of the distance.

(B) indirectly proportional to the square of the distance.

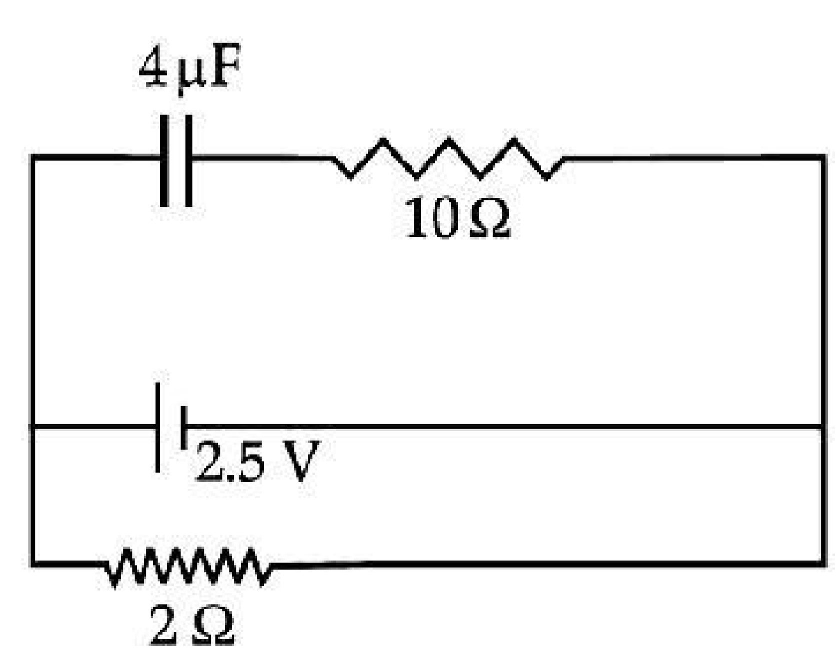
(C) directly proportional to the charge.

(D) None of the above

Ans. Option (D) is correct.

> *Explanation:* The electric potential at a point on the equatorial line of a electric dipole is zero.

Q. 9. A capacitor of 4 μF is connected as shown in the circuit Figure. The internal resistance of the battery is 0.5 Ω. The amount of charge on the capacitor plates will be :



(A) 0 μC (B) 4 μC

(C) 16 μC (D) 8 μC

[NCERT Exemp. Q. 2.1, Page 10]

Ans. Option (D) is correct.

Explanation: As capacitor offer infinite resistance for DC circuit. So current from cell will not flow across branch of 4 μF and 10 Ω. So current will flow across 2 ohm branch.

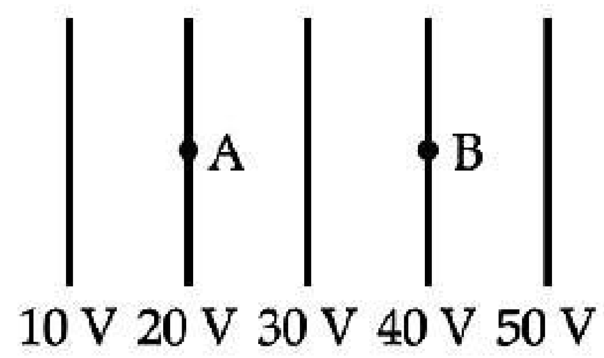


Fig. (i)

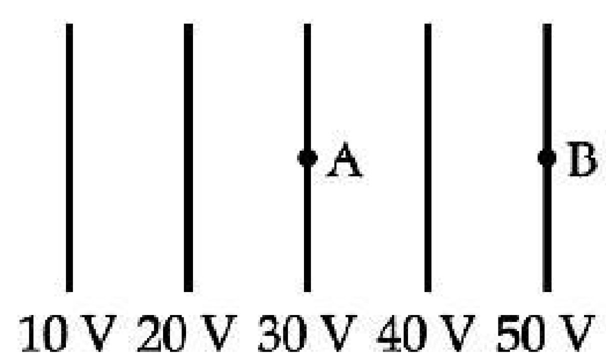


Fig. (ii)

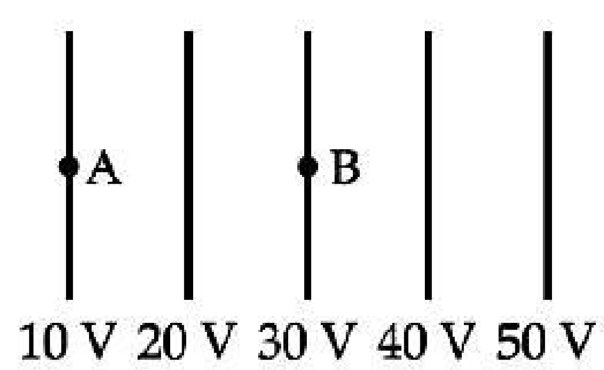
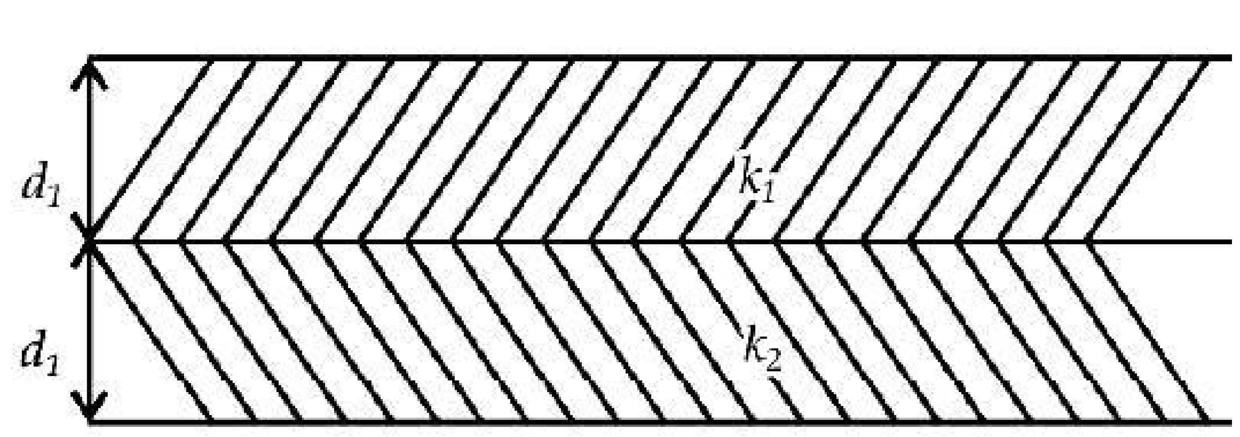


Fig. (iii)

So Potential Difference (PD) across 2 Ω resistance V = RI = 2 × 1 = 2 Volt. As battery, capacitor and 2 branches are in parallel. So PD will remain same across all three branches. As current does not flow through capacitor branch, so no potential drop will be across 10 Ω. So PD across 4 μF capacitor = 2 Volt Q = CV = 2 μF × 2 V = 8 μC

Q. 10. A parallel plate capacitor is made of two dielectric blocks in series. One of the blocks has thickness d_1 and dielectric constant k_1 and the other has thickness d_2 and dielectric constant k_2 as shown in Figure. This arrangement can be thought as a dielectric slab of thickness d (= d_1+d_2) and effective dielectric constant k. The k is :



(A) $\frac{k_1d_1+k_2d_2}{d_1+d_2}$ **(B)** $\frac{k_1d_1+k_2d_2}{k_1+k_2}$

(C) $\frac{k_1k_2(d_1+d_2)}{(k_1d_1+k_2d_2)}$ **(D)** $\frac{2k_1k_2}{k_1+k_2}$

Ans. Option (C) is correct.

Explanation: Capacitance of a parallel plate capacitor filled with dielectric of constant k_1 and thickness d_1 is,

$$C_1 = \frac{k_1\varepsilon_0 A}{d_1}$$

Similarly, for other capacitance of a parallel plate capacitor filled with dielectric of constant k_2 and thickness d_2 is,

$$C_2 = \frac{k_2\varepsilon_0 A}{d_2}$$

Both capacitors are in series so equivalent capacitance C is related as :

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} = \frac{d_1}{k_1\varepsilon_0 A} + \frac{d_2}{k_2\varepsilon_0 A}$$

$$= \frac{1}{\varepsilon_0 A}\left[\frac{k_2d_1 + k_1d_2}{k_1k_2}\right]$$

$$\text{So, } C = \frac{k_1k_2\varepsilon_0 A}{(k_1d_2 + k_2d_1)} \quad \text{...(i)}$$

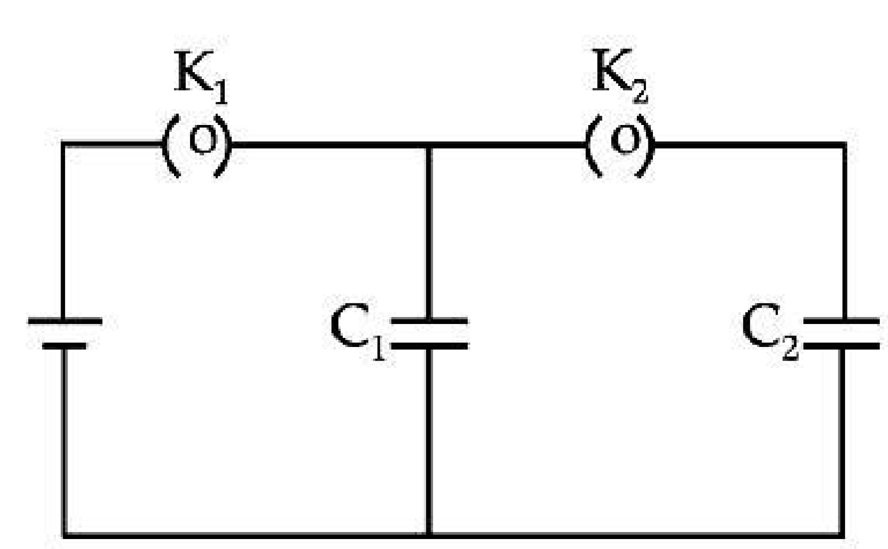
$$C' = \frac{k\varepsilon_0 A}{d} = \frac{k\varepsilon_0 A}{(d_1 + d_2)} \quad \text{...(ii)}$$

where, $d = (d_1+d_2)$

Comparing eqns. (i) and (ii), the dielectric constant of new capacitor is :

$$k = \frac{k_1k_2(d_1+d_2)}{(k_1d_2+k_2d_1)}$$

Q. 11. In the circuit shown in Figure, initially key K_1 is closed and key K_2 is open. Then K_1 is opened and K_2 is closed. Then



(A) Voltage across C_1 = Voltage across C_2

(B) Voltage across C_1 > Voltage across C_2, if $C_1 > C_2$

(C) Charge on C_1 = charge on C_2

(D) None of the above

Ans. Option (A) is correct.

Explanation: Since C_1 and C_2 are in parallel, Voltage across C_1 = Voltage across C_2

Q. 12. Capacitance of a parallel plate capacitor can be increased by

(A) increasing the distance between the plates.

(B) decreasing the distance between the plates.

(C) decreasing the area of plates.

(D) increasing the thickness of the plates.

Ans. Option (B) is correct.

> *Explanation:* $C = k\varepsilon_0 A / d$
> So, capacitance does not increase by increasing the distance between the plates (d) or decreasing the area of the plates (A). Thickness of plates has no connection with the capacitance of the capacitor.

Q. 13. A parallel plate capacitor is charged by connecting it to a battery. Which of the following will remain constant if the distance between the plates of the capacitor is increased in this situation?

(A) Energy stored

(B) Electric field

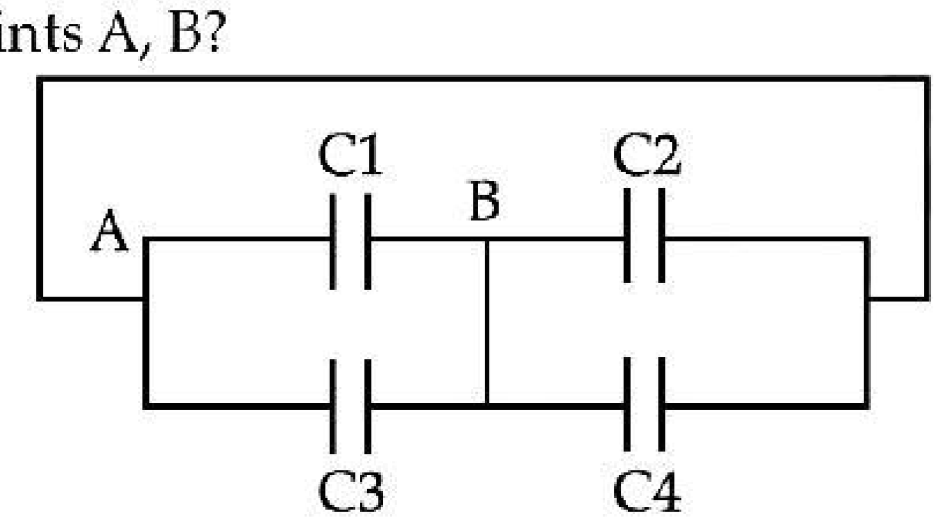
(C) Potential difference

(D) Capacitance

Ans. Option (C) is correct.

> *Explanation:* As the battery remains connected with the capacitor, the potential difference remain constant.

Q. 14. 4 capacitors, each of 2 μF, are connected as shown. What will be the equivalent capacitor across the points A, B?



(A) 0.5 μF **(B)** 2 μF

(C) 8 μF **(D)** 4 μF

Ans. Option (C) is correct.

> *Explanation:* All the capacitors are connected in parallel. So the equivalent capacitance will be 8 μF.

Q. 15. The capacitance of a parallel plate capacitor is 10 μF. When a dielectric plate is introduced in between the plates, its potential becomes 1/4th of its original value. What is the value of the dielectric constant of the plate introduced?

(A) 4 **(B)** 40

(C) 2.5 **(D)** none of the above

Ans. Option (A) is correct.

> *Explanation:* $C' = KC$ (where K is the dielectric constant).
> $V = Q/C$
> $V' = Q/C'$
> $V' = V/4 = Q/C' = Q/KC = V/K$
> $\therefore \quad K = 4$

Q. 16. Two spheres are separately charged and then brought in contact, so

(A) total charge on the two spheres is conserved.

(B) total energy of the two spheres is conserved.

(C) Both (a) and (b)

(D) None of the above

Ans. Option (A) is correct.

> *Explanation:* According to the law of conservation of charge, total charge on the two spheres is conserved.

ASSERTION AND REASON BASED MCQs (1 Mark each)

Directions: In the following questions, A statement of Assertion (A) is followed by a statement of Reason (R). Mark the correct choice as.

(A) Both A and R are true and R is the correct explanation of A

(B) Both A and R are true but R is NOT the correct explanation of A

(C) A is true but R is false

(D) A is false and R is True

Q. 1. Assertion (A): Electric field is always normal to equi-potential surfaces and along the direction of decreasing order of potential.

Reason (R): Negative gradient of electric potential is electric field. **[CBSE SQP 2020-21]**

Ans. Option (A) is correct.

> *Explanation:* $\vec{E} = -\vec{\nabla} V$
> So, The electric field is always perpendicular to equipotential surface.
> Negative gradient of electric potential is electric field. So, direction of electric field must be in the direction of the decreasing order of electric potential.

Q. 2. Assertion (A): Electric field inside a hollow conducting sphere is zero.

Reason (R): Charge is present on the surface of conductor.

Ans. Option (A) is correct.

Explanation: Since no charge resides in the surface of a hollow sphere, the electric field also zero inside. So assertion is true.

For hollow conducting sphere, the charged reside on the surface only. So, reason is also true and it explains the assertion properly.

Q. 3. Assertion (A): Work done in moving a charge between any two points in a uniform electric field is independent of the path followed by the charge between these two points.

Reason (R): Electrostatic forces are non-conservative.

Ans. Option (C) is correct.

Explanation: Work done in moving a charge between any two points in a uniform electric field = charge × potential difference. So, it is independent of the path followed by the charge. Hence the assertion is true.

Electrostatic forces are conservative type. Hence, the reason is false.

Q. 4. Assertion (A): Electric potential and electric potential energy are two different quantities.

Reason (R): For a test charge Q and a point charge Q, the electric potential energy becomes equal to the potential.

Ans. Option (C) is correct.

Explanation: Electric potential and electric potential energy are two different quantities. Hence the assertion is true.

Electric potential is defined as the potential energy per unit charge. Hence V = P.E./q

So, the reason is false.

Q. 5. Assertion (A): When the distance between the parallel plates of a parallel plate capacitor is halved and the dielectric constant of the dielectric used is made three times, then the capacitance becomes three times.

Reason (R): Capacitance does not depend on the nature of material.

Ans. Option (B) is correct.

Explanation: Initial capacitance = $C_1 = \dfrac{A\varepsilon_0 k}{d}$

Finally the capacitance = $C_2 = \dfrac{A\varepsilon_0 3k}{(d/2)}$

So, $C_2 = 6C_1$

Hence the assertion is true.

From the expression of the capacitance, we find that capacitance depends on the area of the plates, dielectric constant and the distance between the plates. It does not depend on the nature of the material of the plates. Hence the reason is also true.

But the reason cannot explain the assertion.

Q. 6. Assertion (A): Circuit containing capacitors should be handled very carefully even when the power is off.

Reason (R): The capacitors may break down at any time.

Ans. Option (C) is correct.

Explanation: Even when power is off capacitor may have stored charge which may discharge through human body and thus one may get a shock.

So, assertion is true.

Breakdown of capacitors requires high voltage. So, reason is false.

Q. 7. Assertion (A): Capacity of a conductor is independent on the amount of charge on it.

Reason (R): Capacitance depends on the dielectric constant of surrounding medium, shape and size of the conductor.

Ans. Option (A) is correct.

Explanation: $C = \dfrac{A\varepsilon_0}{d}$

In the expression, there is no involvement of charge. So, capacitance is independent of charge. Hence the assertion is true.

It depends on permittivity of the surrounding medium and the area of the plate. So, reason is also true.

Reason explains the assertion.

Q. 8. Assertion (A): Two parallel metal plates having charge +Q and –Q are facing at a distance between them. The plates are now immersed in kerosene oil and the electric potential between the plates decreases.

Reason (R): Dielectric constant of kerosene oil is less than 1.

Ans. Option (C) is correct.

Explanation: Electric field for parallel plate capacitor in vacuum = E = σ/ε_0

Electric field in dielectric = E′ = $\sigma/K\varepsilon_0$.

Since the value of K for Kerosene oil is greater than 1, then E′ < E. Hence the assertion is true.

Dielectric constant of Kerosene oil is greater than 1. Hence the reason is false.

CASE-BASED MCQs

Attempt any 4 sub-parts out of 5. Each sub-part carries 1 mark.

I. Read the following text and answer the following questions on the basis of the same:

Super capacitor: Super capacitor is a high capacity capacitor with a capacitance value much higher than normal capacitors but with lower voltage limits. Such capacitors bridges the gap between electrolytic capacitors and rechargeable batteries.

In automobile, bus, train, crane, elevator such capacitors are used for regenerative braking, short term energy storage or burst-mode power delivery. **Super capacitors have many advantages over batteries:** they are very low weight and generally don't contain harmful chemicals or toxic metal. They can be charged and discharged innumerable number of times without ever wearing out.

The disadvantage is that super capacitors aren't well-suited for long-term energy storage. The discharge rate of super capacitors is significantly higher than lithium-ion batteries; they can lose as much as 10-20% of their charge per day due to self-discharge.

Q. 1. Capacity of super capacitor is:

(A) very low. **(B)** medium.
(C) very high. **(D)** may have any value.

Ans. (i) Option (C) is correct.

Explanation: Super capacitor is a high capacity capacitor with a capacitance value much higher than normal capacitors but with lower voltage limits.

Q. 2. Super capacitor makes a bridge between:

(A) electrolytic capacitor and rechargeable battery.
(B) single use battery and electrolytic capacitor.
(C) electrolytic capacitor and dynamo.
(D) electrolytic and non-electrolytic capacitors.

Ans. (ii) Option (A) is correct.

Explanation: Such capacitors bridges the gap between electrolytic capacitors and rechargeable batteries.

Q. 3. Super capacitors can be charged and discharged:

(A) few number of times.
(B) once only.
(C) several number of times but less than rechargeable batteries.
(D) several number of times much more than rechargeable batteries.

Ans. (iii) Option (D) is correct.

Explanation: Super capacitors can be charged and discharged innumerable number of times without ever wearing out.

Q. 4. Self-discharge rate of Super capacitors:

(A) 10-20% of their charge per day
(B) 1 - 2% of their charge per day
(C) 0% of their charge per day
(D) 100% of their charge per day

Ans. (iv) Option (A) is correct.

Explanation: The disadvantage is that super capacitors aren't well-suited for long-term energy storage. The discharge rate of super capacitors is significantly higher than lithium-ion batteries; they can lose as much as 10-20% of their charge per day due to self-discharge.

Q. 5. Super capacitors are used for

(A) degenerative braking.
(B) regenerative braking.
(C) small appliances.
(D) long time charge storage.

Ans. (v) Option (B) is correct.

Explanation: In automobile, bus, train, crane, elevator such capacitors are used for regenerative braking, short term energy storage or burst-mode power delivery.

II. Read the following text and answer the following questions on the basis of the same:

Capacitor Colour Code:

Capacitor values as written on small capacitors are sometimes misleading. Letters like p (pico) or n (nano) are used in place of the decimal point to identify its position and the value of the capacitor. For example, a capacitor labelled as n33 = 0.33nF, 8n2 = 8.2nF, 22n = 47nF and so on. Sometimes capacitors are marked with the capital letter K to signify a value of Kilo pico-Farads. As for example, a capacitor with the markings of 100K would be 1000 × 100 pF = 100 Kpf = 100 nF. Sometimes, a three letter code consists of the two value digits and a multiplier. For example, the digits 471 = 47 × 10 = 470 pF, 332 = 33 × 100 = 3300 pf.

To reduce these confusions an International colour coding scheme was developed almost same as that of resistance colour code.

Band	Digit 1	Digit 2	Multiplier
Colour			
Black	0	0	x1
Brown	1	1	x10
Red	2	2	x100
Orange	3	3	x1,000
Yellow	4	4	x10,000
Green	5	5	x1000,00
Blue	6	6	x1,000,000
Violet	7	7	
Grey	8	8	x0.01
White	9	9	x0.1

The value obtained from colour code is in pf.

Q. 1. What is the value of the capacitor if n27 is written on it?

(A) 0.27 nF **(B)** 0.27 pF
(C) 27 nF **(D)** 27 pF

Ans. Option (A) is correct.

Q. 2. Two capacitors marked as 221 and 220 respectively are joined in parallel. What is the total capacitance value?

(A) 441 pF **(B)** 242 pF
(C) 242 nF **(D)** 441 nF

Ans. Option (B) is correct.

Explanation: The value of the capacitor marked as 221 is 220 pF. The value of the capacitor marked as 220 is 22 pF. When connected in parallel, the total capacitance = 220 pF + 22 pF = 242 pF.

Q. 3. 68*k* is written on a capacitor. What is its value?

(A) 68 pF (B) 68 nF

(C) 68 μF (D) None of these.

Ans. Option (D) is correct.

Explanation: The value of the capacitor = 1000 × 68 pF = 68 kpF = 68 nF

Q. 4. What is the value of the capacitor bearing a colour code: brown, green, brown?

(A) 15 pF (B) 15 nF

(C) 15 nF (D) 150 pF

Ans. Option (D) is correct.

Explanation: Brown, Green, Brown 15 × 10 = 150 pF

Q. 5. What will be the colour code of a 27 nF capacitor?

(A) Red, violet, black (B) Red, violet, brown

(C) Red, violet, orange (D) None of the above

Ans. Option (C) is correct.

Explanation: Red, violet, orange → 27 × 1000 = 27000 pF = 27 nF

III. Read the following text and answer the following questions on the basis of the same:

Power factor corrector capacitor

Power factor correction is a method to reduce the lagging power factor in inductive loads by fixing a high value capacitor across the phase and neutral line close to the load. When the Voltage and Current are in phase with each other in an AC circuit, the energy from the source is fully converted into another form to drive the load and in this case power factor is in unity. When the power factor drops, the system becomes less efficient.

In inductive loads, current "lags" the voltage leading to "lagging power factor". Power factor correction is the method to reduce the lagging power factor in inductive loads by fixing a high value capacitor across the phase and neutral close to the load. These capacitors have leading power factor so that it will neutralize the lagging power factor of the load.

Power capacitors are huge non polarized metal film electrolytic type capacitors.

Capacitors should be sufficiently rated to the load capacity. It should be connected to the lines, only when the loads are running and drawing current

Q. 1. What is meant by power factor correction?

(A) The method to reduce the lagging power factor in inductive loads

(B) The method to enhance the lagging power factor in inductive load

(C) The method to reduce the lagging power factor in capacitive loads

(D) The method to enhance the lagging power factor in capacitive loads

Ans. Option (A) is correct.

Explanation: Power factor correction is the method to reduce the lagging power factor in inductive loads by fixing a high value capacitor across the phase and neutral close to the load.

Q. 2. When the energy from source is fully converted into another form, the power factor is

(A) 0.5 (B) 1.0

(C) 0 (D) ∞

Ans. Option (B) is correct.

Explanation: When the voltage and current are in phase with each other in an AC circuit, the energy from the source is fully converted into another form to drive the load and in this case, power factor is unity. When the power factor drops, the system becomes less efficient.

Q. 3. Power capacitors for power factor correction are

(A) polarized metal film electrolytic type.

(B) non-polarized metal film electrolytic type.

(C) non-polarized metal film non-electrolytic type.

(D) polarized ceramic non- electrolytic type.

Ans. Option (B) is correct.

Explanation: Power capacitors are huge non polarized metal film electrolytic type capacitors.

Q. 4. Power capacitors for power factor correction have

(A) lagging power factor.

(B) leading power factor.

(C) leading or lagging power factor depending on the value of the capacitor.

(D) leading or lagging power factor depending on the type of load.

Ans. Option (B) is correct.

Explanation: Power factor corrector capacitors have leading power factor so that they neutralize the lagging power factor of the inductive load.

Q. 5. Power factor corrector capacitors should be connected

(A) across the phase and ground near the inductive load.

(B) across the phase and neutral away from the inductive load.

(C) across the phase and neutral near the inductive load.

(D) across the neutral and ground near the inductive load.

Ans. Option (C) is correct.

Explanation: Power capacitors are connected across the phase and neutral near the inductive load such as motor.