

Chapter-2: Electrostatics Potential and Capacitance

1. Relation between work done, potential energy and potential difference
By the external agent

$$W(i \rightarrow f) = U_f - U_i = \Delta U = V_f - V_i$$

By the conservative force

$$W(i \rightarrow f) = U_i - U_f = -\Delta U = V_i - V_f$$

2. Potential energy of two point charge system (if charges q_1 and q_2 are separated by distance r)

$$U = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r}$$

3. Potential energy of system of charges (due to several charges)
(Charges kept at vertices of triangle or square or rectangle or at any geometrical shape.)

$$U = \frac{1}{4\pi\epsilon_0} \left[\frac{q_3 q_2}{r_{32}} + \frac{q_3 q_1}{r_{31}} + \frac{q_2 q_1}{r_{21}} \right]$$

4. Relation between electric potential and potential energy

$$V = \frac{U}{q_0}$$

(If initial point is at ∞ and final point is say f so work done to bring a charge (say q_0) from infinity to a point (say f) by external force or against electric force)

$$V_f - V_\infty = \frac{U_f - U_\infty}{q_0} = W_{\infty \rightarrow f}$$

[Here V_∞ and U_∞ are zero as seen that $U \propto \frac{1}{r}$ and $\propto \frac{1}{r}$]

5. Relation between electric potential and electric field intensity

$$dV = -\vec{E} \cdot d\vec{r}$$

Or,

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$$\int_{V_B}^{V_A} dV = - \int_{r_B}^{r_A} \vec{E} \cdot d\vec{r}$$

6. Electric potential difference say V_{AB} or $V_A - V_B$ in a uniform electric field

$$V_B - V_A = \vec{E} \cdot (\vec{r}_A - \vec{r}_B)$$

7. Electric potential at a point

At distance r due to a point charge q

$$V = \frac{1}{4\pi\epsilon_0} \left(\frac{q}{r} \right)$$

At position vector r due to a point charge q kept at position vector r_0

$$V = \frac{1}{4\pi\epsilon_0} \left(\frac{q}{|\vec{r} - \vec{r}_0|} \right)$$

At position vector r due to system of charges $q_1, q_2, q_3, \dots$ kept at positions $r_1, r_2, r_3, \dots$ respectively

$$V = \frac{1}{4\pi\epsilon_0} \sum_{i=1}^n \frac{q_i}{|\vec{r} - \vec{r}_i|}$$

At distance is same (r) from each charge

$$V = \frac{1}{4\pi\epsilon_0} \left(\frac{q_{net}}{r} \right)$$

At distance r due to continuous charge distribution

$$V = \frac{1}{4\pi\epsilon_0} \int \frac{dq}{r}$$

8. Electric potential in a dipole at any point p , at distance r from the centre of dipole, making angle θ from the dipole axis

$$V_p = \frac{1}{4\pi\epsilon_0} \left(\frac{p \cos \theta}{r^2} \right)$$

- When $\theta = 0^\circ$, (axial position of dipole)

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$$V_p = \frac{1}{4\pi\epsilon_0} \left(\frac{p}{r^2} \right)$$

- When $\theta = 90^\circ$, (at the equatorial point),

$$V = 0$$

9. Electric potential in case of hollow spherical conductor,

Inside the hollow spherical conductor ($r < R$) where R is the radius of conductor and q is the charge distributed on the surface of conductor

$$V_{inside} = V_{surface} = \frac{1}{4\pi\epsilon_0} \left(\frac{q}{R} \right)$$

Outside at any point at distance r from the centre of the spherical shell

$$V_r = \frac{1}{4\pi\epsilon_0} \left(\frac{q}{r} \right)$$

10. Electric potential in case of two metallic hollow concentric shells:

If the inner shell A has radius R_1 and charge distributed is q_1 and has outer shell B has radius R_2 and charge distributed is q_2 , then potential V_A and V_B are given as

$$V_A = \frac{1}{4\pi\epsilon_0} \left(\frac{q_1}{R_1} + \frac{q_2}{R_2} \right)$$

$$V_B = \frac{1}{4\pi\epsilon_0} \left(\frac{q_1}{R_2} + \frac{q_2}{R_2} \right)$$

Thus, potential difference

$$V_A - V_B = \frac{1}{4\pi\epsilon_0} q \left(\frac{1}{R_1} - \frac{1}{R_2} \right)$$

11. Capacitance C: SI Unit: Farad (F)

Capacitance of a capacitor of charge q and V the potential difference

$$C = \frac{q}{V}$$

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A metallic spherical conductor of radius R and charge q on its surface

$$C = 4\pi\epsilon_0 R$$

Of a two concentric metallic hollow spherical conductor of inner and outer shell having radii R_1 and R_2 and charges on inner and outer surface q and $-q$ respectively

$$C = 4\pi\epsilon_0 \frac{R_1 R_2}{R_2 - R_1}$$

Of a two co-axial metallic hollow cylindrical conductor placed in free space of inner and outer shell having radii R_1 and R_2 and charge on inner outer surface of sphere is q and charge on outer surface of shell B is $-q$

$$C = \frac{2\pi\epsilon_0 L}{\ln \frac{R_2}{R_1}}$$

12. Parallel Plate Capacitor

Capacitance C when gap is completely filled with dielectric slab

$$C = \frac{\epsilon_0 K A}{d}$$

Capacitance C of n similar plates of equal separation (d) and same plate area (A) connected alternatively

$$C = (n - 1) \frac{\epsilon_0 A}{d}$$

Capacitance C of a parallel plate capacitor when a dielectric slab is partially filled in the gap

$$C = \frac{\epsilon_0 A}{d - t + \frac{t}{K}}$$

Special cases:

- If more than one dielectric slabs of different thickness and different constants are placed between the parallel plates capacitor, then

$$C = \frac{\epsilon_0 A}{(d - t_1 - t_2 - \dots) + (\frac{t_1}{K_1} + \frac{t_2}{K_2} + \dots)}$$

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- If a conductor is completely filled in the gap, then $t = d$ and $K = \infty$, then

$$C = \infty$$

- If the conductor is partially filled with thickness t and same area, then

$$C = \frac{\epsilon_0 A}{d - t}$$

- The capacitance will be infinity if one of the plates is earthed..

13. Energy stored in capacitor is given by

$$U = \frac{1}{2} CV^2 = \frac{1}{2} qV = \frac{1}{2} \frac{q^2}{C}$$

14. Energy density

- The energy per unit volume is called the energy density (u).

$$u = \frac{U}{Volume}$$

- Energy density of air capacitor

$$u = \frac{1}{2} \epsilon_0 E^2$$

- Energy density in a dielectric medium (dielectric constant K)

$$u = \frac{1}{2} (\epsilon_0 K E^2)$$

15. Electric field intensity on the $-q$ plate due to positive charge in case of two parallel plates

$$E = \frac{q}{2A\epsilon_0}$$

16. Force of attraction with which both parallel plates (charge q and $-q$ and area A with separation d) attract each other

$$F = \frac{q^2}{2A\epsilon_0}$$

17. Electric field intensity (E) in the dielectric (dielectric constant K) inserted between parallel plates

$$E = \frac{\sigma}{\epsilon} = E_0 - E_i$$

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18. In free space between the plates, External electric field (E_0)

$$E_0 = \frac{\sigma}{\epsilon_0}$$

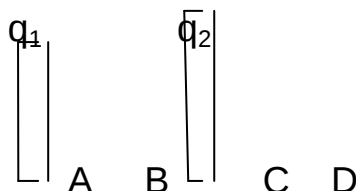
19. Dielectric Constant K

$$K = \frac{E_0}{E} \text{ or, } K = \frac{E_0}{E_0 - E_i}$$

20. Relation between induced charge, charge on plates and dielectric constant K

$$q_i = q \left(1 - \frac{1}{K} \right)$$

21. If the charge on plate 1 is q_1 and on plate 2 is q_2 then charge at each **point** (inner & outer surface of plate-1 and plate-2 respectively are



- Charge on point A and D

$$q_A = q_D = \frac{q_1 + q_2}{2}$$

Where q_1 is

$$q_1 = \text{Charge at point A} + \text{Charge at point B}$$

And q_2 is

$$q_2 = \text{Charge at point C} + \text{Charge at point D}$$

- Charge at point B

$$q_B = \frac{q_1 - q_2}{2}$$

- Charge at point C

$$q_C = - \left(\frac{q_1 - q_2}{2} \right)$$

22. **Charge redistribution:**

When two conductors of charge q_1 and q_2 on its surfaces and having capacitances as C_1 and C_2 with radii as R_1 and R_2 , are connected by

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a conducting wire, then charges on conductors after joining the wire are in the ratio of their capacities as given-

$$q'_1 = C_1 V' \text{ and } q'_2 = C_2 V'$$

Where

$$V_{com} = \text{Common potential} = \frac{q_1 + q_2}{C_1 + C_2}$$

Since,

$$C \propto R \text{ So, } q'_1 = (q_1 + q_2) \left(\frac{R_1}{R_1 + R_2} \right)$$

23. Loss of energy during redistribution of charge

$$\Delta U = U_i - U_f = \frac{C_1 C_2}{2(C_1 + C_2)} ((V_1 - V_2)^2)$$

Where,

$$U_i = \frac{1}{2} \left(\frac{q_1^2}{C_1} \right) + \frac{1}{2} \left(\frac{q_2^2}{C_2} \right) \text{ and } U_f = \frac{1}{2} \left[\frac{(q_1 + q_2)^2}{C_1 + C_2} \right]$$

24. Capacitors Combination

If C_1, C_2 capacitors are connected in

- Series (same charge in each capacitor)

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \dots \dots \dots$$

- Parallel (same potential difference across each capacitor)

$$C = C_1 + C_2 + \dots \dots \dots$$

25. Relation between Electrical susceptibility and Polarisation

Polarisation is defined as dipole moment per unit volume and its magnitude is referred to as polarisation density.

Electrical susceptibility is given by

$$\chi = \frac{\vec{p}}{\epsilon_0 \vec{E}}$$

26. Relation between dielectric constant (K) and electrical susceptibility (χ)

$$K = 1 + \chi$$

27. Polarisation density (P)

$$P = \frac{q_i t}{At} = \frac{\text{dipole moment in the slab}}{\text{volume}} = \frac{q_i}{A} = \sigma_i$$

Where A is the area of dielectric slab, t the thickness of slab, q_i the induced charge in the dielectric slab.

28. Effect of dielectric on various parameters

Effect of dielectric

Initially No dielectric and Supply is Connected

Let q_0 , V_0 , C_0 , E_0 and U_0 be the charge, potential difference, capacitance, electric field

Intensity and potential energy stored respectively before dielectric slab is inserted.

Then,

$$V_0 = \frac{q_0}{C_0} \text{ and } V_0 = E_0 d \text{ and } U_0 = \frac{1}{2} C_0 V_0^2$$

Finally

(i) When supply is disconnected and dielectric slab is inserted:

- Charge (remains same)

$$q = q_0$$

The charge on capacitor plate remains q_0 as battery has been disconnected before the insertion of dielectric slab.

- Electric field (decreased by K times)

$$E = \frac{E_0}{K}$$

- Potential difference (decreased by K times)

$$V = \frac{V_0}{K}$$

- Capacitance (increased by K times)

$$C = C_0 K$$

- Potential energy stored (decreased by K times)

$$U = \frac{1}{2} C V^2 = \frac{U_0}{K}$$

Finally

(ii) When battery remains connected across the capacitor

- Potential difference (remains same)

$$V = V_0$$

- Electric field intensity (remains same)

$$E = E_0$$

- Capacitance (increased by K times)

$$C = C_0 K$$

- Charge (increased by K times)

$$q = K q_0$$

- Potential energy stored:

$$U = K U_0$$