Electrostatic induction

It is possible to obtain charges without any contact with another charge. They are known as induced charges and the phenomenon of producing induced charges is known as electrostatic induction. It is used in electrostatic machines like Van de Graaff generator and capacitors.

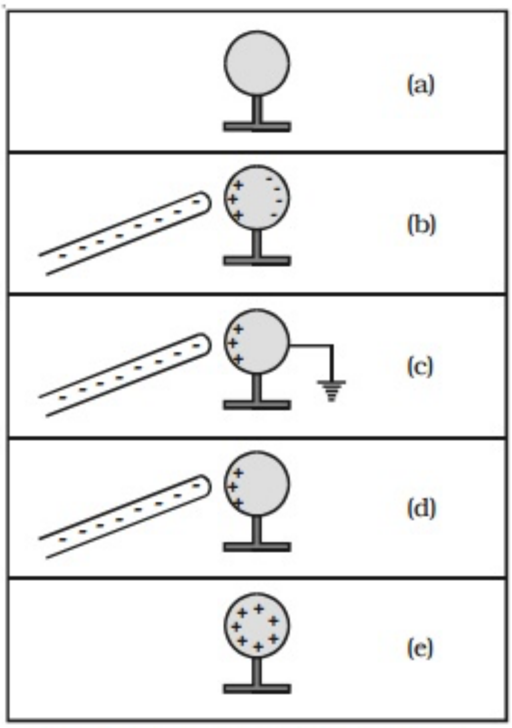


Fig 1.21 Electrostatic Induction

Fig 1.21 shows the steps involved in charging a metal sphere by induction.

a. There is an uncharged metallic sphere on an insulating stand.

b. When a negatively charged plastic rod is brought close to the sphere, the free electrons move away due to repulsion and start pilling up at the farther end. The near end becomes positively charged due to deficit of electrons. This process of charge distribution stops when the net force on the free electron inside the metal is zero (this process happens very fast).

c. When the sphere is grounded, the negative charge flows to the ground. The positive charge at the near end remains held due to attractive forces.

d. When the sphere is removed from the ground, the positive charge continues to be held at the near end.

e. When the plastic rod is removed, the positive charge spreads uniformly over the sphere.

1. Capacitance of a conductor

When a charge q is given to an isolated conductor, its potential will change. The change in potential depends on the size and shape of the conductor. The potential of a conductor changes by V, due to the charge q given to the conductor.

$q \propto V$ or $q = CV$

i.e. $C = q/V$

Here C is called as capacitance of the conductor.

The capacitance of a conductor is defined as the ratio of the charge given to the conductor to the potential developed in the conductor.

The unit of capacitance is farad. A conductor has a capacitance of one farad, if a charge of 1 coulomb given to it, rises its potential by 1 volt.

The practical units of capacitance are μF and pF.

Principle of a capacitor

Consider an insulated conductor (Plate A) with a positive charge 'q' having potential V (Fig 1.22a). The capacitance of A is $C = q/V$. When another insulated metal plate B is brought near A, negative charges are induced on the side of B near A. An equal amount of positive charge is induced on the other side of B (Fig 1.22b). The negative charge in B decreases the potential of A. The positive charge in B increases the potential of A. But the negative charge on B is nearer to A than the positive charge on B. So the net effect is that, the potential of A decreases. Thus the capacitance of A is increased.

If the plate B is earthed, positive charges get neutralized (Fig 1.22c). Then the potential of A decreases further. Thus the capacitance of A is considerably increased.

The capacitance depends on the geometry of the conductors and nature of the medium. A capacitor is a device for storing electric charges.

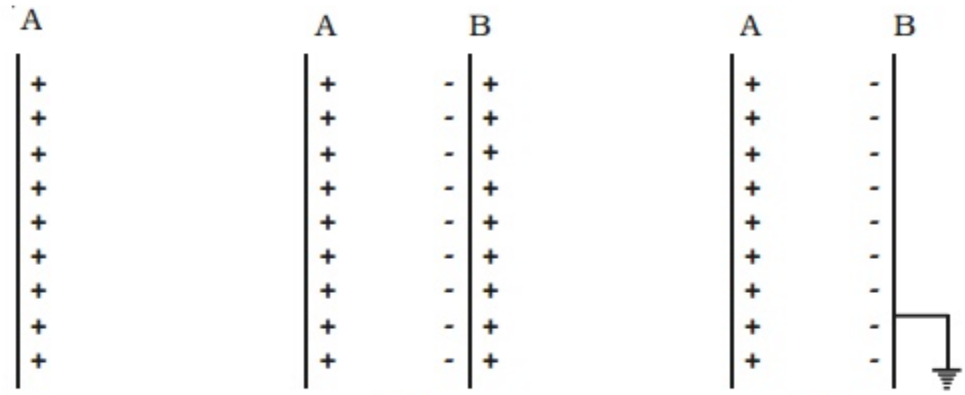


Fig 1.22 Principle of capacitor

2. Capacitance of a parallel plate capacitor

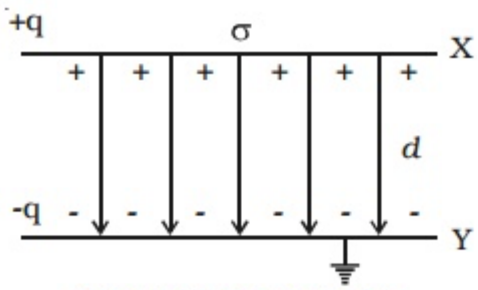


Fig 1.23 Parallel plate capacitor

The parallel plate capacitor consists of two parallel metal plates X and Y each of area A, separated by a distance d, having a surface charge density σ . The medium between the plates is air. A charge +q is given to the plate X. It induces a charge -q on the upper surface of earthed plate Y. When the plates are very close to each other, the field is confined to the region between them. The electric lines of force starting from plate X and ending at the plate Y are parallel to each other and perpendicular to the plates.

By the application of Gauss's law, electric field at a point between the two plates is,

$$E = \frac{\sigma}{\varepsilon_o}$$

Potential difference between the plates X and Y is

$$V = \int_d^0 -E\, dr = \int_d^0 -\frac{\sigma}{\varepsilon_o}\, dr = \frac{\sigma d}{\varepsilon_o}$$

The capacitance (C) of the parallel plate capacitor

$$C = \frac{q}{V} = \frac{\sigma A}{\sigma d/\varepsilon_o} = \frac{\varepsilon_o A}{d} \qquad [\text{since, } \sigma = \frac{q}{A}]$$

$$\therefore \quad C = \frac{\varepsilon_o A}{d}$$

The capacitance is directly proportional to the area (A) of the lates and inversely proportional to their distance of separation (d).

3. Dielectrics and polarisation

Dielectrics

A dielectric is an insulating material in which all the electrons are tightly bound to the nucleus of the atom. There are no free electrons to carry current. Ebonite, mica and oil are few examples of dielectrics. The electrons are not free to move under the influence of an external field.

Polarisation

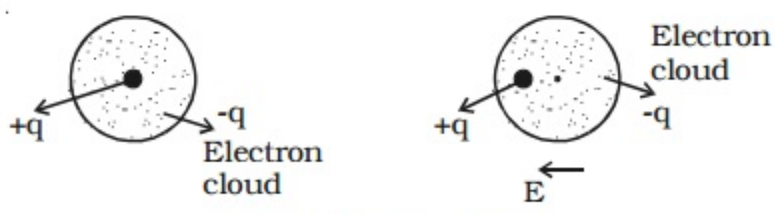
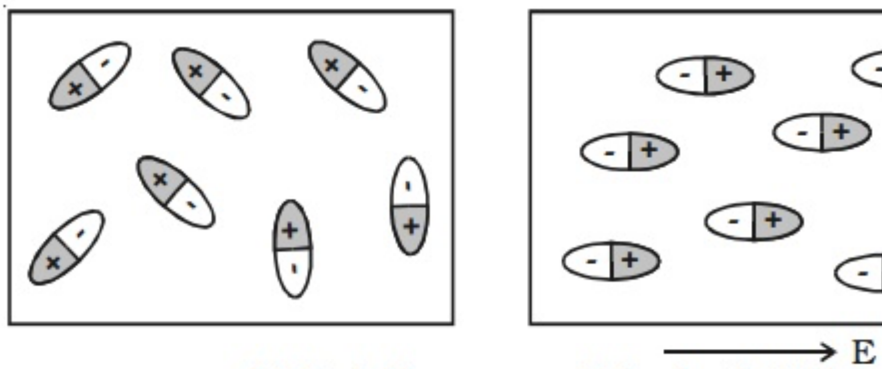


Fig 1.24 Induced dipole

A nonpolar molecule is one in which the centre of gravity of the positive charges (protons) coincide with the centre of gravity of the negative charges (electrons). Example: O_2, N_2, H_2. The nonpolar molecules do not have a permanent dipole moment.

If a non polar dielectric is placed in an electric field, the centre of charges get displaced. The molecules are then said to be polarised and are called induced dipoles. They acquire induced dipole moment p in the direction of electric field (Fig 1.24).

A polar molecule is one in which the centre of gravity of the positive charges is separated from the centre of gravity of the negative charges by a finite distance. Examples : N_2O, H_2O, HCl, NH_3. They have a permanent dipole moment. In the absence of an external field, the dipole moments of polar molecules orient themselves in random directions. Hence no net dipole moment is observed in the dielectric. When an electric field is applied, the dipoles orient themselves in the direction of electric field. Hence a net dipole moment is produced (Fig 1.25).



(a) No field (b) In electric field

Fig1.25 Polar molecules

The alignment of the dipole moments of the permanent or induced dipoles in the direction of applied electric field is called polarisation or electric polarisation.

The magnitude of the induced dipole moment p is directly proportional to the external electric field E.

$p \propto E$ or $p = \alpha E$, where α is the constant of proportionality and is called molecular polarisability.

4. Polarisation of dielectric material

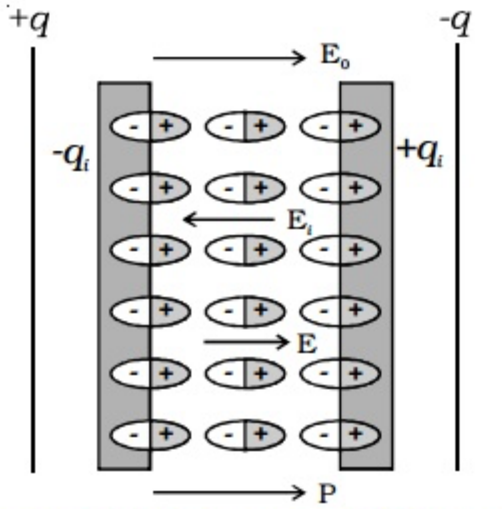


Fig1.26 Polarisation of dielectric material

Consider a parallel plate capacitor with +q and -q charges. Let E_o be the electric field between the plates in air. If a dielectric slab is introduced in the space between them, the dielectric slab gets polarised. Suppose $+q_i$ and $-q_i$ be the induced surface charges on the face of dielectric opposite to the plates of capacitor (Fig 1.26). These induced charges produce their own field E_i which opposes the electric field E_o. So, the resultant field, $E < Eo$. But the direction of E is in the direction of Eo.

? $E = E_o + (-E_i)$

(? E_i is opposite to the direction of E_o)

5. Capacitance of a parallel plate capacitor with a dielectric medium.

Consider a parallel plate capacitor having two conducting plates X and Y each of area A, separated by a distance d apart. X is given a positive charge so that the surface charge density on it is ? and Y is earthed.

Let a dielectric slab of thick-ness t and relative permittivity $?_r$ be introduced between the plates (Fig.1.27).

Thickness of dielectric slab = t

Thickness of air gap = (d-t) Electric field at any point in the air between the plates,

$$E = \frac{\sigma}{\varepsilon_o}$$

Electric field at any point, in

he dielectric slab $E' = \frac{\sigma}{\varepsilon_r \varepsilon_o}$

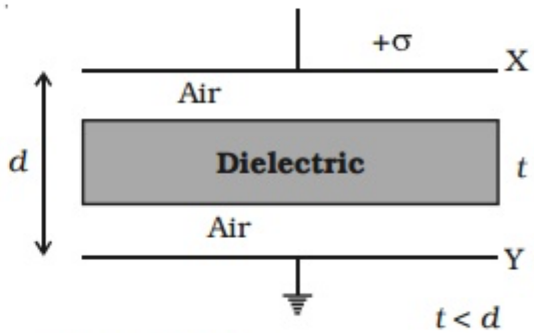


Fig 1.27 Dielectric in capacitor

The total potential difference between the plates, is the work done in crossing unit positive charge from one plate to another in the field E over a distance (d-t) and in the field E' over a distance t, then

$$V = E\,(d-t) + E'\,t$$

$$= \frac{\sigma}{\varepsilon_o}(d-t) + \frac{\sigma t}{\varepsilon_o \varepsilon_r}$$

$$= \frac{\sigma}{\varepsilon_o}\left[(d-t) + \frac{t}{\varepsilon_r}\right]$$

The charge on the plate X, $q = \sigma A$

Hence the capacitance of the capacitor is,

$$C = \frac{q}{V} = \frac{\sigma A}{\frac{\sigma}{\varepsilon_o}\left[(d-t) + \frac{t}{\varepsilon_r}\right]} = \frac{\varepsilon_o A}{(d-t) + \frac{t}{\varepsilon_r}}$$

Effect of dielectric

In capacitors, the region between the two plates is filled with dielectric like mica or oil.

The capacitance of the air filled capacitor, $C = \frac{\varepsilon_o A}{d}$

The capacitance of the dielectric filled capacitor, $C' = \frac{\varepsilon_r \varepsilon_o A}{d}$

$$\therefore \quad \frac{C'}{C} = \varepsilon_r \text{ or } C' = \varepsilon_r C$$

since, $\varepsilon_r > 1$ for any dielectric medium other than air, the capacitance increases, when dielectric is placed.

6. Applications of capacitors.

(i) They are used in the ignition system of automobile engines to eliminate sparking.

(ii) They are used to reduce voltage fluctuations in power supplies and to increase the efficiency of power transmission.

(iii) Capacitors are used to generate electromagnetic oscillations and in tuning the radio circuits.

7. Capacitors in series and parallel

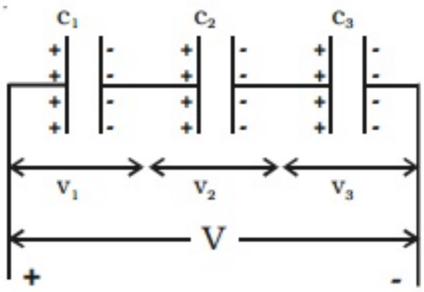
(i) Capacitors in series

Consider three capacitors of capacitance C_1, C_2 and C_3 connected in series (Fig 1.28). Let V be the potential difference applied across the series combination. Each capacitor carries the same amount of charge q. Let V_1, V_2, V_3 be the potential difference across the capacitors C_1, C_2, C_3 respectively. Thus $V = V_1 + V_2 + V_3$

The potential difference across each capacitor is,

$$V_1 = \frac{q}{C_1}; V_2 = \frac{q}{C_2}; V_3 = \frac{q}{C_3}$$

$$V = \frac{q}{C_1} + \frac{q}{C_2} + \frac{q}{C_3} = q\left[\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}\right]$$



If Cs, be the effective capacitance of the series combination, it should acquire a charge q when a voltage V is applied across it.

i.e. $$V = \frac{q}{C_S}$$

$$\frac{q}{C_s} = \frac{q}{C_1} + \frac{q}{C_2} + \frac{q}{C_3}$$

$$\therefore \quad \frac{1}{C_s} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

when a number of capacitors are connected in series, the reciprocal of the effective capacitance is equal to the sum of reciprocal of the capacitance of the individual capacitors.

(ii) Capacitors in parallel

Consider three capacitors of capacitances C_1, C_2 and C_3 connected in parallel (Fig.1.29). Let this parallel combination be connected to a potential difference V. The potential difference across each capacitor is the same. The charges on the three capacitors are,

$$q_1 = C_1V,\ q_2 = C_2 V,\ q_3 = C_3V.$$

The total charge in the system of capacitors is

$$q = q_1 + q_2 + q_3$$
$$q = C_1V + C_2V + C_3V$$

But $q = C_p.V$ where C_p is the effective capacitance of the system

$$\therefore \quad C_pV = V (C_1 + C_2 + C_3)$$
$$\therefore \quad C_p = C_1 + C_2 + C_3$$

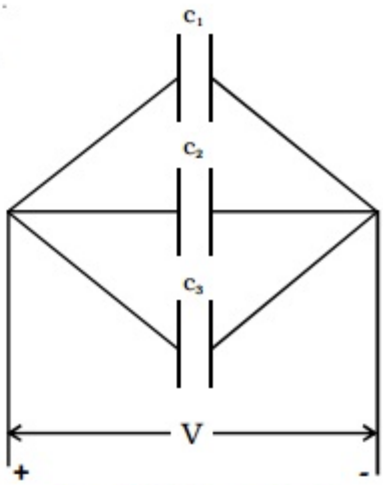


Fig 1.29 Capacitors in parallel

Hence the effective capacitance of the capacitors connected in parallel is the sum of the capacitances of the individual capacitors.

8. Energy stored in a capacitor

The capacitor is a charge storage device. Work has to be done to store the charges in a capacitor. This work done is stored as electrostatic potential energy in the capacitor.

Let q be the charge and V be the potential difference between the plates of the capacitor. If dq is the additional charge given to the plate, then work done is, dw = Vdq

$$dw = \frac{q}{C}\,dq \qquad \left(\because V = \frac{q}{C}\right)$$

Total work done to charge a capacitor is

$$w = \int dw = \int_0^q \frac{q}{C}\,dq = \frac{1}{2}\frac{q^2}{C}$$

This work done is stored as electrostatic potential energy (U) in the capacitor.

$$U = \frac{1}{2}\frac{q^2}{C} = \frac{1}{2}CV^2 \qquad (\because q = CV)$$

This energy is recovered if the capacitor is allowed to discharge.

9. Distribution of charges on a conductor and action of points

Let us consider two conducting spheres A and B of radii r_1 and r_2 respectively connected to each other by a conducting wire (Fig 1.30). Let r_1 be greater than r_2. A charge given to the system is distributed as q_1 and q_2 on the surface of the spheres A and B.

Let ?1, ?2 be the charge densities on the sphere A and B.

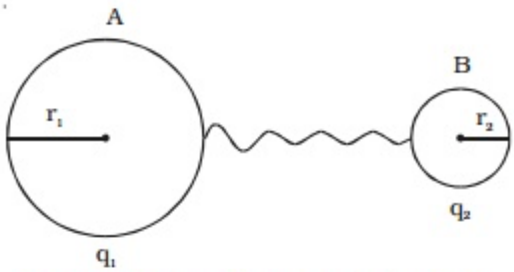


Fig 1.30 Distribution of charges

The potential at A,

$$V_1 = \frac{q_1}{4\pi\varepsilon_o r_1}$$

The potential at B, $V_2 = \dfrac{q_2}{4\pi\varepsilon_o r_2}$

Since they are connected, their potentials are equal

$$\frac{q_1}{4\pi\varepsilon_o r_1} = \frac{q_2}{4\pi\varepsilon_o r_2} \qquad \left[\because q_1 = 4\pi r_1^2\sigma_1 \text{ and } q_2 = 4\pi r_2^2\sigma_2\right]$$

$$\sigma_1 r_1 = \sigma_2 r_2$$

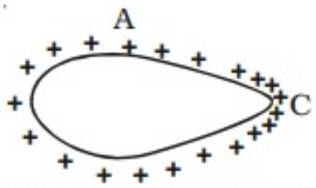


Fig 1.31 Action of point

i.e., σr is a constant. From the above equation it is seen that, smaller the radius, larger is the charge density.

In case of conductor, shaped as in Fig.1.31 the distribution is not uniform. The charges accumulate to a maximum at the pointed end where the curvature is maximum or the radius is minimum. It is found experimentally that a charged conductor with sharp points on its surface, loses its charge rapidly.

The reason is that the air molecules which come in contact with the sharp points become ionized. The positive ions are repelled and the negative ions are attracted by the sharp points and the charge in them is therefore reduced.

Thus, the leakage of electric charges from the sharp points on the charged conductor is known as action of points or corona discharge. This principle is made use of in the electrostatic machines for collecting charges and in lightning arresters (conductors).

Principle of a capacitor and Energy stored in a capacitor

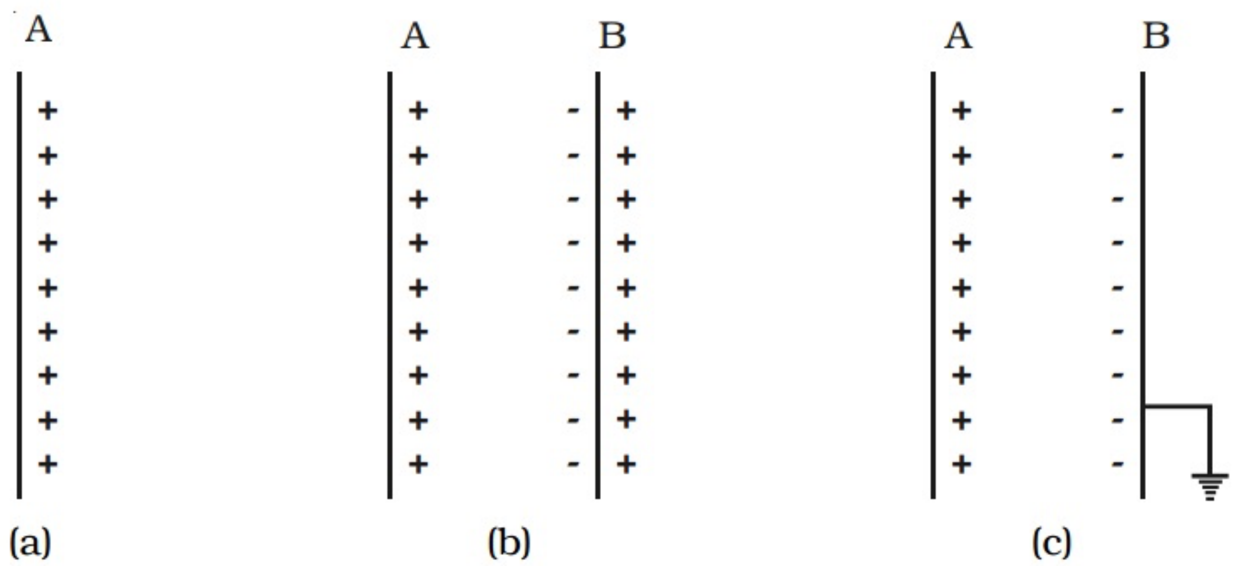


Fig Principle of capacitor

Capacitance of a conductor

When a charge q is given to an isolated conductor, its potential will change. The change in potential depends on the size and shape of the conductor. The potential of a conductor changes by V, due to the charge q given to the conductor.

$q \propto V$ or $q = CV$

i.e. $C = q/V$

Here C is called as capacitance of the conductor.

The capacitance of a conductor is defined as the ratio of the charge given to the conductor to the potential developed in the conductor.

The unit of capacitance is farad. A conductor has a capacitance of one farad, if a charge of 1 coulomb given to it, rises its potential by 1 volt.

The practical units of capacitance are µF and pF.

Principle of a capacitor

Consider an insulated conductor (Plate A) with a positive charge 'q' having potential V (Fig 1.22a). The capacitance of A is C = q/V. When another insulated metal plate B is brought near A, negative charges are induced on the side of B near A. An equal amount of positive charge is induced on the other side of B (Fig 1.22b). The negative charge in B decreases the potential of A. The positive charge in B increases the potential of A. But the negative charge on B is nearer to A than the positive charge on B. So the net effect is that, the potential of A decreases. Thus the capacitance of A is increased.

If the plate B is earthed, positive charges get neutralized (Fig 1.22c). Then the potential of A decreases further. Thus the capacitance of A is considerably increased.

The capacitance depends on the geometry of the conductors and nature of the medium. A capacitor is a device for storing electric charges.

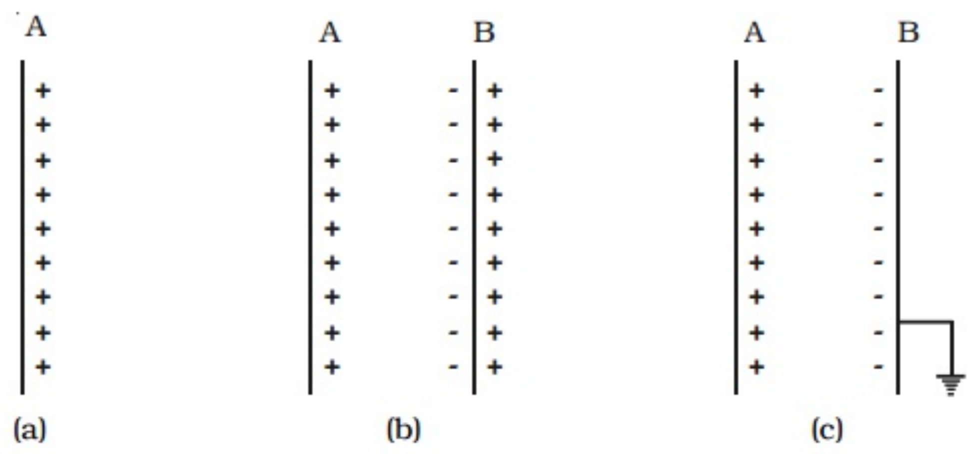


Fig 1.22 Principle of capacitor

Energy stored in a capacitor

The capacitor is a charge storage device. Work has to be done to store the charges in a capacitor. This work done is stored as electrostatic potential energy in the capacitor.

Let q be the charge and V be the potential difference between the plates of the capacitor. If dq is the additional charge given to the plate, then work done is, dw = Vdq

$$dw = \frac{q}{C}\,dq \qquad \left(\because V = \frac{q}{C}\right)$$

Total work done to charge a capacitor is

$$w = \int dw = \int_0^q \frac{q}{C}\,dq = \frac{1}{2}\frac{q^2}{C}$$

This work done is stored as electrostatic potential energy (U) in the capacitor.

$$U = \frac{1}{2}\frac{q^2}{C} = \frac{1}{2}CV^2 \qquad (\because\ q = CV)$$

This energy is recovered if the capacitor is allowed to discharge.

Lightning conductor -Van de Graaff Generator- working principle and construction

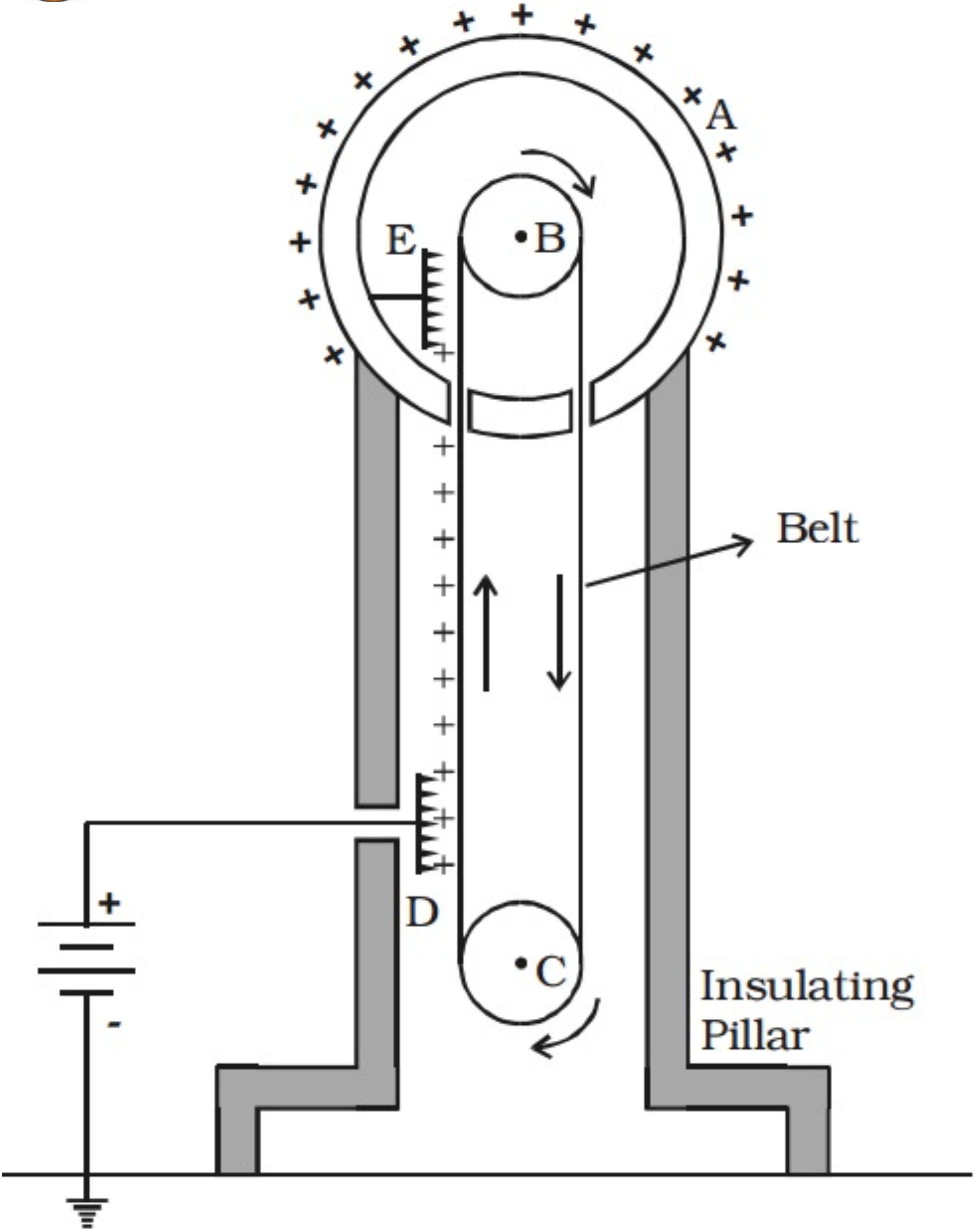


Fig 1 Van de Graaff Generator

This is a simple device used to protect tall buildings from the lightning. It consists of a long thick copper rod passing through the building to ground. The lower end of the rod is connected to a copper plate buried deeply into the ground. A metal plate with number of spikes is connected to the top end of the copper rod and kept at the top of the building.

Lightning conductor - working principle and construction

Lightning conductor

This is a simple device used to protect tall buildings from the lightning.

It consists of a long thick copper rod passing through the building to ground. The lower end of the rod is connected to a copper plate buried deeply into the ground. A metal plate with number of spikes is connected to the top end of the copper rod and kept at the top of the building.

When a negatively charged cloud passes over the building, positive charge will be induced on the pointed conductor. The positively charged sharp points will ionize the air in the vicinity. This will partly neutralize the negative charge of the cloud, thereby lowering the potential of the cloud. The negative charges that are attracted to the conductor travels down to the earth. Thereby preventing the lightning stroke from the damage of the building.

Van de Graaff Generator

In 1929, Robert J. Van de Graaff designed an electrostatic machine which produces large electrostatic potential difference of the order of 10^7 V.

The working of Van de Graaff generator is based on the principle of electrostatic induction and action of points.

A hollow metallic sphere A is mounted on insulating pillars as shown in the diagram A pulley B is mounted at the centre of the sphere and another pulley C is mounted near the bottom. A belt made of silk moves over the pulleys. The pulley C is driven continuously by an electric motor. Two comb?shaped conductors D and E having number of needles, are mounted near the pulleys. The comb D is maintained at a positive potential of the order of 10^4 volt by a power supply. The upper comb E is connected to the inner side of the hollow metal sphere.

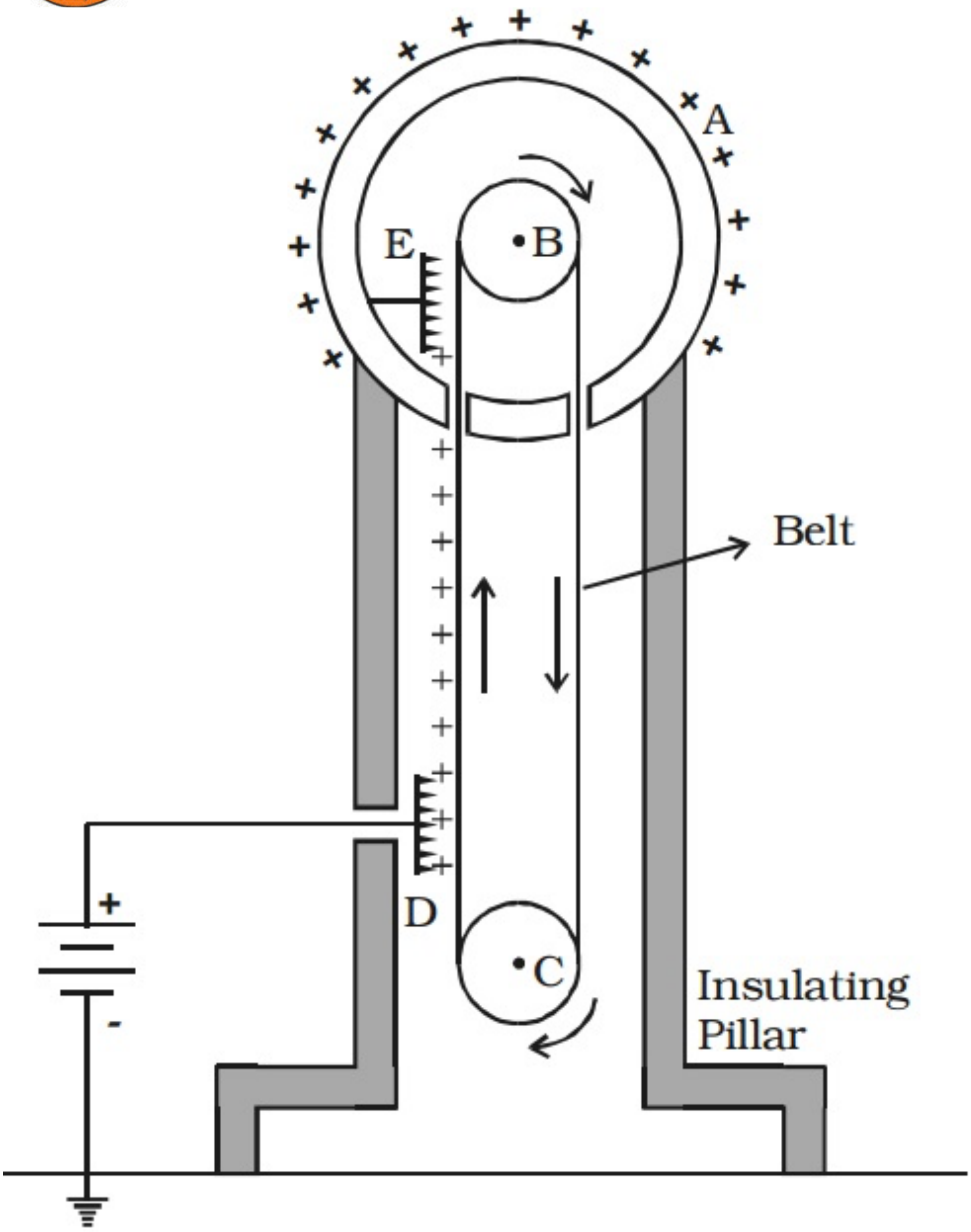


Fig 1 Van de Graaff Generator

Because of the high electric field near the comb D, the air gets ionised due to action of points, the negative charges in air move towards the needles and positive charges are repelled on towards the belt. These positive charges stick to the belt, moves up and reaches near the comb E.

As a result of electrostatic induction, the comb E acquires negative charge and the sphere acquires positive charge. The acquired positive charge is distributed on the outer surface of the sphere. The high electric field at the comb E ionises the air. Hence, negative charges are repelled to the belt, neutralises the positive charge on the belt before the belt passes over the pulley. Hence the descending belt will be left uncharged.

Thus the machine, continuously transfers the positive charge to the sphere. As a result, the potential of the sphere keeps increasing till it attains a limiting value (maximum). After this stage no more charge can be placed on the sphere, it starts leaking to the surrounding due to ionisation of the air.

The leakage of charge from the sphere can be reduced by enclosing it in a gas filled steel chamber at a very high pressure.

The high voltage produced in this generator can be used to accelerate positive ions (protons, deuterons) for the purpose of nuclear disintegration.