

Learning Objectives

After studying this chapter, the students will be able to:

- ◆ define and calculate electric potential [At a point as the work done per unit positive charge in bringing a small test charge from infinity to the point. Use for the electric field due to a point charge]
- ◆ use the fact that the electric field at a point is equal to the negative of potential gradient at that point
- ◆ state how the concept of electric potential leads to the electric potential energy of two point charges and use $U = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r}$
- ◆ define and calculate capacitance [as applied to both isolated spherical conductors and to parallel plate capacitors]
- ◆ Derive and apply formulae for the combined capacitance of capacitors in series and in parallel
- ◆ use the capacitance formula for capacitors in series and in parallel
- ◆ determine the electric potential energy stored in a capacitor from the area under the potential charge graph [Use to solve problems related to physics]
- ◆ analyze graphs of the variation with time of potential difference, charge and current for a capacitor discharging through a resistor [use for the time constant for a capacitor discharging through a resistor] RC
- ◆ Use equations of the form $x = x_0 (\exp) -t/RC$ [where x could represent current, charge or potential difference for a capacitor discharging through a resistor]
- ◆ list the use of capacitors in various household appliances [such as in flash guns, refrigerators, electric fans, rectification circuits, etc.]

Electrostatics or static electricity refers to the phenomena arising from the stationary electric charges. These include forces exerted by charges on each other, electric field and electric potential produced by them and electrical energy stored in space and in various devices.

We have already studied about the electric field produced by a charge around it. Any other charge placed in this field experiences a force. Quantitatively, the electrostatic force can be found by applying coulomb's law $F_e = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r^2}$.

The direction of this force depends on the nature of charges whether positive or negative. In this chapter, we will study in detail the electric potential produced by a charge at any point in its field. In addition, we will see that electrical energy and charge can be stored in a widely used device known as a capacitor. We will also become acquainted with some important uses of capacitors.

16.1 ELECTRIC POTENTIAL DIFFERENCE

The electric potential difference is the work done per unit charge in moving a charge between two points, and is expressed as:

$$V = V_B - V_A = \frac{W_{AB}}{q_0} = \frac{\Delta U}{q_0} \quad \text{.....(16.1)}$$

The SI unit is the volt, where

$$1V = \frac{1 \text{ J}}{1 \text{ C}} \quad \text{.....(16.2)}$$

It can be converted into other units such as kilovolts or millivolts by simple scaling. The relationship between electric potential difference and the electric field:

$$\Delta V = E \cdot \Delta d \quad \text{.....(16.3)}$$

It is given by the fact that the electric field represents the rate of change of potential with distance, expressed as:

$$E = -\frac{\Delta V}{\Delta d} \quad \text{.....(16.4)}$$

Where the negative sign indicates that the field points from higher to lower potential. In the case of a uniform electric field, this relation simplifies to:

$$E = \frac{V}{d} \quad \text{.....(16.5)}$$

Showing that the potential difference between two points is directly proportional to the electric field strength and the distance between them; thus, a stronger electric field causes a more rapid decrease in potential, providing a clear physical link between field intensity and voltage variation in space.

Example 16.1 A 6 volts battery is connected to two parallel copper plates separated by a distance of 0.3 cm. Find the electric field intensity between them.

Solution

Potential difference between the plates $\Delta V = 6 \text{ V}$

Distance between the plates $= \Delta d = 0.3 \text{ cm} = 0.003 \text{ m}$

Using, $E = \frac{\Delta V}{\Delta d}$

Putting the values, $E = \frac{6 \text{ V}}{0.003 \text{ m}} = 2000 \text{ NC}^{-1}$

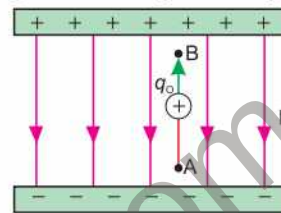


Fig. 16.1

For your information

Although we have assumed that the points at infinity are at zero potential, yet the Earth is assumed to be at zero potential practically. Therefore, absolute value of the electric potential at a point is measured with respect to the Earth.

16.2 ELECTRIC POTENTIAL

In order to give a concept of electric potential at a point in an electric field due to a point charge, we must have a reference to which we assign zero electric potential. This point

is usually taken at infinity.

If we take A to be at infinity and choose $V_A = 0$, the electric potential at B will be $V_B = W_{OB}/q_o$ or dropping the subscripts

$$V = \frac{W}{q_o} \dots\dots\dots(16.6)$$

which states that:

The electric potential at any point in an electric field is equal to work done in bringing a unit positive charge from infinity to that point keeping it in electrostatic equilibrium.

It is to be noted that potential at a point is still potential difference between the potential at that point and potential at infinity. Both potential and potential differences are scalar quantities because both W and q_o are scalars.

Let us derive an expression for the potential at a certain point in the field of a positive point charge q . This can be accomplished by bringing a unit positive charge from infinity to that point keeping the charge in equilibrium. The target can be achieved by using Eq.16.5 in the form $\Delta V = -E \Delta r$, provided electric intensity E remains constant. However in this case E varies inversely as square of distance from the point charge, it no more remains constant so we use basic principles to compute the electric potential at a point. The field is radial as shown in Fig. 16.2.

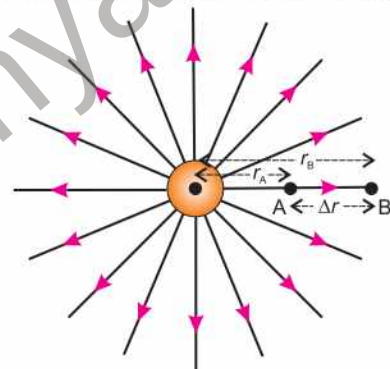


Fig. 16.2

Let us take two points A and B, infinitesimally close to each other, so that E remains almost constant between them. The distances of points A and B from q are r_A and r_B respectively and distance of midpoint of space interval between A and B is r from q . Then according to Fig. 16.2

$$r_B = r_A + \Delta r \dots\dots\dots(16.7)$$

$$\Delta r = r_B - r_A \dots\dots\dots(16.8)$$

As r represents midpoint of interval between A and B so

$$r = \frac{r_A + r_B}{2} \dots\dots\dots(16.9)$$

The magnitude of electric intensity at this point is,

$$E = \frac{1}{4\pi\epsilon_o} \frac{q}{r^2} \dots\dots\dots(16.10)$$

As the points A and B are very close then, as a first approximation, we can take the arithmetic mean to be equal to geometric mean which gives

$$\text{Therefore, } r^2 = r_A r_B \dots\dots\dots(16.11)$$

Thus, Eq. 16.10 can be written as

$$E = \frac{1}{4\pi\epsilon_0} \frac{q}{r_A r_B} \dots\dots\dots (16.12)$$

Now, if a unit positive charge is moved from B to A, the work done is equal to the potential difference between A and B,

$$V_A - V_B = -E(r_A - r_B)$$

$$V_A - V_B = E(r_B - r_A) \dots\dots\dots (16.13)$$

Substituting value of E from Eq. 16.12.

$$V_A - V_B = \frac{1}{4\pi\epsilon_0} \left(\frac{r_B - r_A}{r_A r_B} \right) \dots\dots\dots (16.14)$$

$$V_A - V_B = \frac{1}{4\pi\epsilon_0} \left(\frac{1}{r_A} - \frac{1}{r_B} \right) \dots\dots\dots (16.15)$$

To calculate absolute potential or potential at A, point B is assumed to be infinity point so that $V_B = 0$, and hence

$$\frac{1}{r_B} = \frac{1}{r_\infty} = \frac{1}{\infty} = 0$$

This gives,
$$V_A = \frac{1}{4\pi\epsilon_0} \frac{q}{r_A} \dots\dots\dots (16.16)$$

The general expression for electric potential V_r at a distance r from q is,

$$V_r = \frac{1}{4\pi\epsilon_0} \left(\frac{q}{r} \right) \dots\dots\dots (16.17)$$

The electric potential will be negative if the charge q is negative. However, if there are more than one charge at different locations, then each charge contributes to the total electric potential. At any point, the total electric potential is the algebraic sum of the individual potentials created by all the charges.

Example 16.2 Find the electric potential at a point 1.2 m from a charge of 5.0×10^{-8} C.

Solution $q = 5.0 \times 10^{-8}$ C, $r = 1.2$ m, $V = ?$

Using
$$V = \frac{1}{4\pi\epsilon_0} \frac{q}{r}$$

Putting the values
$$V = \frac{(9 \times 10^9 \text{ N m}^2 \text{C}^{-2}) (5.0 \times 10^{-8} \text{ C})}{1.2 \text{ m}}$$

$$V = 375 \text{ V}$$

Example 16.3 Two point charges $+8 \mu\text{C}$ and $-4 \mu\text{C}$ are placed 60 cm apart as shown in Fig. 16.3. Where is the electric potential zero on the line passing through the charges?

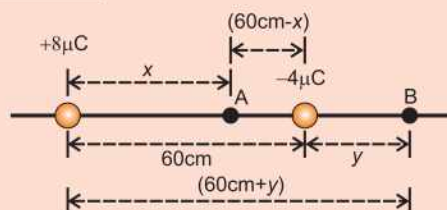


Fig. 16.3

Solution

The electric potential at any point will be zero where the potential due to positive charge will be exactly equal in magnitude to that due to negative charge. Since the magnitude of positive charge is greater than that of negative charge, so there will be two zero potential points. Both the points should be closer to the smaller negative charge. That is one point (A) between the two charges and the other point (B) outside the negative charge.

Let the point A lies at a distance x from the positive charge. Then using we have,

Let the point A lies at a distance x from the positive charge. Then using $V = \frac{1}{4\pi\epsilon_0} \frac{q}{r}$ we have,

$$\text{Electric potential at A due to positive charge} = \frac{1}{4\pi\epsilon_0} \left(\frac{8 \times 10^{-6} \text{ C}}{x} \right)$$

$$\text{Electric potential at A due to negative charge} = \frac{1}{4\pi\epsilon_0} \left(\frac{4 \times 10^{-6} \text{ C}}{60 \text{ cm} - x} \right)$$

As both the potentials balance each other, therefore

$$\frac{1}{4\pi\epsilon_0} \left(\frac{8 \times 10^{-6} \text{ C}}{x} \right) = \frac{1}{4\pi\epsilon_0} \left(\frac{4 \times 10^{-6} \text{ C}}{60 \text{ cm} - x} \right)$$

$$480 \text{ cm} - 8x = 4x$$

or

$$12x = 480 \text{ cm}$$

$$x = 40 \text{ cm}$$

$$\text{Electric potential at B due to positive charge} = \frac{1}{4\pi\epsilon_0} \left(\frac{4 \times 10^{-6} \text{ C}}{60 \text{ cm} - x} \right)$$

$$\text{Electric potential at B due to negative charge} = \frac{1}{4\pi\epsilon_0} \left(\frac{4 \times 10^{-6} \text{ C}}{y} \right)$$

Applying balance condition,

$$\frac{1}{4\pi\epsilon_0} \left(\frac{8 \times 10^{-6} \text{ C}}{x} \right) = \frac{1}{4\pi\epsilon_0} \left(\frac{4 \times 10^{-6} \text{ C}}{60 \text{ cm} - x} \right)$$

$$4(60 \text{ cm} + y) = 8y$$

$$240 \text{ cm} + 4y = 8y$$

$$4y = 240 \text{ cm}$$

$$y = \frac{240 \text{ cm}}{4} = 60 \text{ cm}$$

16.3 ELECTRIC POTENTIAL ENERGY

We have learnt in the previous section that a charge placed in an electric field possesses some electrical potential energy. If a charge q_o is placed at any point in the electric field due to a charge q and allowed to move it freely, it will be repelled away by the charge q . Equation (16.17) shows that the potential decreases with the increase of distance. Therefore, if a positive charge is allowed to move freely in an electric field, it will always accelerate from a point of higher potential to a point of lower potential. If the potential difference between these points be ΔV , the potential energy of the charge will decrease by $\Delta U = q_o \Delta V$. This decrease in potential energy of the charge will appear as its kinetic energy.

If m is the mass of the body carrying charge q_0 , then the body will reach the point at lower potential energy with velocity v . then

$$\frac{1}{2}mv^2 = q_0\Delta V \dots\dots\dots (16.18)$$

A negative charge allowed to move freely in an electric field moves from a point of lower potential to a point of higher potential.

The equation (16.18) suggests that the energy can also be expressed as the product of potential difference and charge. In atomic physics, we use one such unit of energy known as electron-volt (eV). This unit has already been defined in the previous class. It is the energy required by an electron which has been accelerated through a potential difference of 1 volt.

Hence, $1 \text{ eV} = \text{charge on an electron} \times 1 \text{ volt}$

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$

Electric Potential Energy of Two Point Charges

The concept of electric potential directly leads to the expression for electric potential energy of two point charges. Consider two points A and B distance r apart (Fig.16.4). Initially, there is no electric field at these points. Let us bring a charge Q from infinity to point A.

As there is no electric field at A, so the charge Q will not move against any electric intensity. In other words it will not face any opposition. Therefore, the work done to bring Q to point A is zero.

$$W_A = 0 \dots\dots\dots (16.19)$$

Once the charge Q has been placed at point A, an electric potential V is created by it at point B.

$$V = \frac{1}{4\pi\epsilon_0} \frac{Q}{r} \dots\dots\dots (16.20)$$

Now if a second charge q is brought from infinity to point B, work has to be done in moving it against the electric field. This work is,

$$W_B = q \times (\text{Electric potential})$$

$$W_B = qV \dots\dots\dots (16.21)$$

Putting the value of V in equation 16.21, we get

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

$$\text{or } W_B = \frac{1}{4\pi\epsilon_0} \frac{Qq}{r} \dots\dots\dots (16.22)$$

Total work done in placing the two charges at point A and B is,

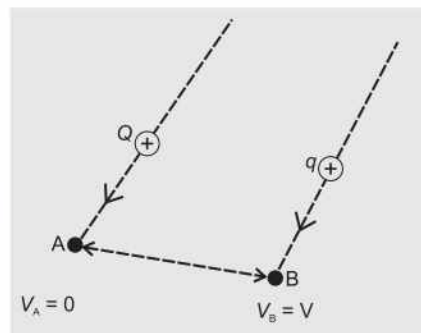


Fig. 16.5

$$W = W_A + W_B = 0 + \frac{1}{4\pi\epsilon_0} \frac{Qq}{r}$$

or

$$W = \frac{1}{4\pi\epsilon_0} \frac{Qq}{r} \dots\dots\dots(16.23)$$

Therefore, by definition, the work done in placing these two charges at points A and B is stored as electric potential energy (E_p) in the system which is given by

$$E_p = \frac{1}{4\pi\epsilon_0} \frac{Qq}{r} \dots\dots\dots(16.24)$$

Example 16.4 Two point charges are separated by a distance of 4.0 cm. If the charges are $8\ \mu\text{C}$ and $5\ \mu\text{C}$, what is the electric potential energy of the two charges?

Solution

Here,

Using the formula; $E_p = \frac{1}{4\pi\epsilon_0} \frac{Qq}{r}$

$$E_p = 9 \times 10^9 \text{ N m}^2 \text{ C}^{-2} \left[\frac{(8 \times 10^{-6} \text{ C})(5 \times 10^{-6} \text{ C})}{4 \times 10^{-2} \text{ m}} \right]$$

$$E_p = 9 \text{ Nm} = 9 \text{ J}$$

16.4 CAPACITORS

A capacitor is a device that can store electrical energy in the form of electric field. We will discuss here two types of such devices. (i) Isolated spherical conductors (ii) Parallel plate capacitors

Isolated Spherical Conductors

A spherical conductor placed in space such that it is far from other conductors or influence is known as an isolated spherical conductor. The ability of an isolated spherical conductor to store electric charge is called as capacitance. It is denoted by C .

The capacitance of an isolated spherical conductor is defined as the electric charge stored on the sphere per unit electric potential at its surface.

Mathematically, we can write as

$$C = \frac{Q}{V} \dots\dots\dots(16.25)$$

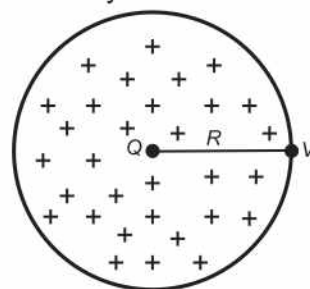


Fig. 16.5

Where Q is the amount of charge stored and V is the electric potential created at the surface of sphere due to charge Q (Fig. 16.5). The SI unit of capacitance C is farad (F).

For a spherical conductor, 1 farad is the capacitance of a sphere that stores 1 coulomb of charge when its electric potential is 1 volt, assuming it is isolated in free space.

$$1 \text{ farad} = \frac{1 \text{ coulomb}}{1 \text{ volt}}$$

The electric potential V at the surface of the sphere of radius R is given by

$$V = \frac{1}{4\pi\epsilon_0} \frac{Q}{R}$$

Substituting the value of V into eq. 16.25

$$C = \frac{Q}{\left(\frac{1}{4\pi\epsilon_0} \frac{Q}{R} \right)}$$

or $C = 4\pi\epsilon_0 R \dots\dots\dots (16.26)$

However, the capacitance of a spherical conductor in a medium of dielectric constant ϵ_r ,

is $C = 4\pi\epsilon_0 \epsilon_r R \dots\dots\dots (16.27)$

Equation (16.26) shows that the capacitance of a spherical conductor is independent of the charge or potential, it depends on the radius of the sphere and medium. The capacitance increases with increase in radius of the sphere. This means larger spheres store more charge at the same surface potential. The presence of a dielectric medium also increases the capacitance of the device.

16.5 PARALLEL PLATE CAPACITORS

A parallel plate, capacitor consists of two conductors placed near one another separated by vacuum, air or any other insulator, known as dielectric. Usually the conductors are in the form of parallel plates, and the capacitor is known as parallel plate capacitor. When the plates of such a capacitor are connected to a battery of voltage V (Fig. 16.6). It establishes a potential difference of V volts between the two plates and the

battery places a charge $+Q$ on the plate connected with its positive terminal and a charge $-Q$ on the other plate, connected to its negative terminal. Let Q be the magnitude of the charge on either of the plates. It is found that

$$Q \propto V \quad \text{or} \quad Q = CV \quad \text{or} \quad C = \frac{Q}{V} \dots\dots\dots (16.28)$$

The proportionality constant C is called the capacitance of the capacitor. As we shall see later, it depends upon the geometry of the plates and the medium between them. It is a measure of the ability of capacitor to store charge.

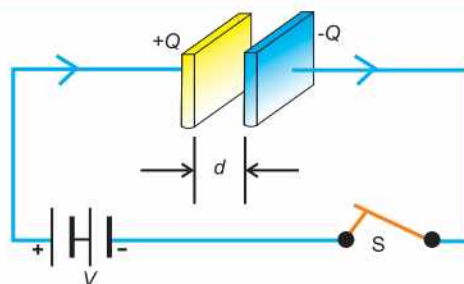


Fig. 16.6

The capacitance of a capacitor can be defined as the amount of charge on one plate necessary to raise the potential of that plate by one volt with respect to the other.

The SI unit of capacitance is coulomb per volt, which because of its frequent use, is commonly called farad (F), after the famous English scientist Michael Faraday.

"The capacitance of a capacitor is one farad if a charge of one coulomb, given to one of the plates of a parallel plate capacitor, produces a potential difference of one volt between them".

Capacitance of a Parallel Plate Capacitor

Consider a parallel plate capacitor consisting of two parallel metal plates, each of area A , separated by a distance d as shown in Fig.16.6. The distance d is small so that the electric field E between the plates is uniform and confined almost entirely in the region between the plates. Let initially the medium between the plates be air or vacuum. Then according to Eq.16.28

$$C_{\text{vac}} = \frac{Q}{V} \quad \dots\dots\dots (16.29)$$

where Q is the charge on the capacitor and V is the potential difference between the parallel plates. From Eq. (16.5), the magnitude E of electric intensity is related with the distance d as:

$$E = \frac{V}{d} \quad \dots\dots\dots (16.30)$$

As electric intensity between parallel plate capacitor (Gauss's law) is: $E = \frac{\sigma}{\epsilon_0}$
We can define surface charge density as:

$$\sigma = \frac{Q}{A} \quad \text{or} \quad Q = \sigma A$$

Thus,
$$E = \frac{Q}{A\epsilon_0} \quad \dots\dots\dots (16.31)$$

Therefore, from Eqs. (16.30) and (16.31)

$$\frac{V}{d} = \frac{Q}{A\epsilon_0} \quad \text{or} \quad \frac{Q}{V} = \frac{A\epsilon_0}{d}$$

It gives
$$C_{\text{vac}} = \frac{Q}{V} = \frac{A\epsilon_0}{d} \quad \dots\dots\dots (16.32)$$

If an insulating material, called dielectric, of relative permittivity ϵ_r is introduced between the plates, the capacitance of capacitor is enhanced by the factor ϵ_r . Capacitors commonly have some dielectric medium, thereby ϵ_r is also called as dielectric constant.

Following experiment gives the effect of insertion of dielectric between the plates of a capacitor.

Consider a charged capacitor whose plates are connected to a voltmeter (Fig. 16.7 a). The deflection of the meter is a measure of the potential difference between the plates. When a dielectric material is inserted between the plates, reading drops indicating a decrease in the potential difference between the plates (Fig. 16.7 b). From the definition, $C = Q/V$, since V decreases while Q remains constant, the value of C increases. Then Eq.16.32 becomes,

$$C_{\text{med}} = \frac{A\epsilon_0\epsilon_r}{d} \dots\dots\dots(16.33)$$

Eq.16.32 shows the dependence of a capacitor upon the area of plates, the separation between the plates and medium between them.

Dividing Eq.16.33 by Eq.16.32, we get expression for dielectric constant as:

$$\epsilon_r = \frac{C_{\text{med}}}{C_{\text{vac}}} \dots\dots\dots(16.34)$$

From Eq.16.34 dielectric co-efficient or dielectric constant is defined as

The ratio of the capacitance of a parallel plate capacitor with an insulating substance as medium between the plates to its capacitance with vacuum (or air) as medium between them.

The reason for decrease in potential difference between the plates of the capacitor is the polarization of the atoms of the dielectric medium. A dielectric is an insulator. It has no free electrons, i.e., all the electrons are bound to their respective positively charged nuclei. When such an atom is subjected to an electric field, its electrons are displaced slightly relative to the nucleus in a direction opposite to the field as shown in Fig. 16.7 (c). This phenomena is known as polarization of the dielectric and the distorted atom is said to be polarized.

When a slab of dielectric is placed between the two oppositely charged plates, its atoms get polarized due to the electric field in between the two plates as shown in Fig. 16.7 (d). As a result, charges appear on those surfaces of the dielectric slab which are in contact with the metal plates. The polarity of these charges is opposite to that of the charge on the adjacent plate. This affectively decreases the charge on the plates. Consequently, the electric intensity and potential difference between the

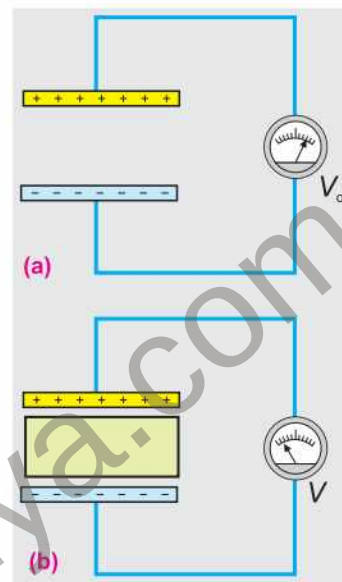


Fig. 16.7

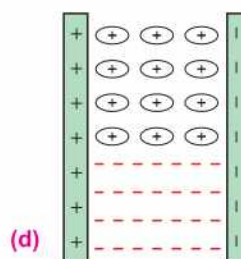
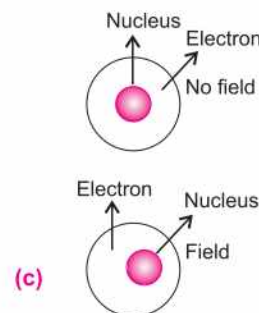


Fig. 16.7

plates decrease.

16.6 COMBINED CAPACITANCE OF CAPACITORS

When more than one capacitor are connected together in a circuit, it is known as combination of capacitors. It is done to obtain a desired capacitance. In this process, multiple connections of capacitors behave as a single equivalent capacitor. Usually it is named as combined capacitance. Two common types of combination are;

- (i) Parallel combination (ii) Series combination

Parallel Combination

In this method, the plates of one side of all the capacitors are connected to the negative terminal and plates of the other side to the positive terminal of the battery as shown in Fig. 16.8. The plates are charged by the battery. In this combination the potential difference V across the plates of each capacitor is the same. The charge on each will be different depending upon its capacitance. If Q_1 , Q_2 , and Q_3 are the charges on the capacitors C_1 , C_2 and C_3 respectively then the amount of charge Q on equivalent capacitor C_e would be the same as all the three capacitors hold together under the same potential difference V 16.8(b). So;

$$Q = Q_1 + Q_2 + Q_3$$

Putting $Q_1 = C_1 V$, $Q_2 = C_2 V$,
 $Q_3 = C_3 V$ and $Q = C_e V$,

we get $C_e V = C_1 V + C_2 V + C_3 V$

or $C_e = C_1 + C_2 + C_3 \dots \dots \dots (16.35)$

Thus

When capacitors are connected in parallel, their combined capacitance is equal to the sum of their individual capacitances.

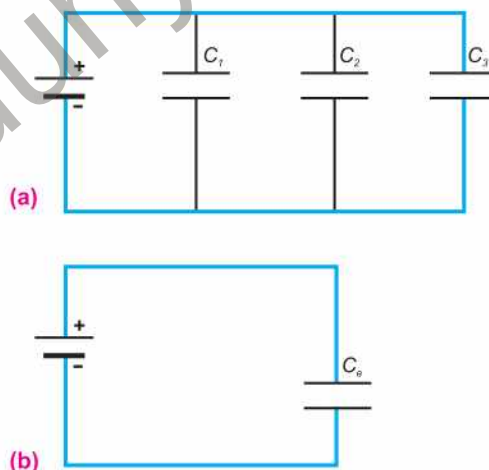


Fig. 16.8

Example 16.5 A capacitor of 80pF capacitance is charged to potential difference of 48 volts. Its plates are then connected in parallel to another capacitor. The potential difference across the combination is found to be 30 volts. What is the capacitance of the second capacitor?

Solution

Before connecting the capacitor C_1 to C_2 ; using formula $Q = CV$

Charge on $C_1 = Q_1 = C_1 V_1 = 80 \times 10^{-12} \text{F} \times 48 \text{V}$

or $Q_1 = 3840 \times 10^{-12} \text{C}$

After connecting C_2 in parallel to C_1 , $V_2 = 30 \text{V}$

Now charge on $C_1 = Q'_1 = C_1 V_2$

$$\begin{aligned}
 &= 80 \times 10^{-12} \text{ F} \times 30 \text{ V} \\
 &= 2400 \times 10^{-12} \text{ C}
 \end{aligned}$$

As total charge remains constant, so charge shifted to C_2 is

$$Q_2 = Q_1 - Q'_1 = 3840 \times 10^{-12} \text{ C} - 2400 \times 10^{-12} \text{ C}$$

$$Q_2 = 1440 \times 10^{-12} \text{ C}$$

To determine the capacitance C_2 of the second capacitor,

Using formula $C = \frac{Q}{V}$

We get $C_2 = \frac{Q_2}{V_2}$

or $C_2 = \frac{1440 \times 10^{-12} \text{ C}}{30 \text{ V}} = 48 \times 10^{-12} \text{ F} = 48 \text{ pF}$

Series Combination

The series combination is one after the other in a line. The circuit is shown in Fig. 16.9 (a). We can see that the second plate of capacitor C_1 is connected to the first plate of C_2 . Likewise, the second plate of C_2 is connected to the first plate of C_3 . The first plate of C_1 and the second plate of C_3 are connected to the battery.

The battery sends positive charge Q to the first plate of capacitor C_1 . As the second plate of C_1 is insulated from the first plate, so it cannot draw any charge from the battery. But the positive of the first plate induces an equal negative charge $-Q$ on the second plate. Since the first plate of capacitor C_2 is connected to the second plate of C_1 , therefore a charge $+Q$ appears on the first plate of C_2 . Similarly the capacitor C_3 is also charged. Thus each capacitor receives a charge of magnitude Q on each of its plates.

Fig.16.9(b) shows that the potential difference across the combination of three capacitors is equal to that of battery terminals (V). As C_1 , C_2 , and C_3 are connected in series, so potential difference across each of them will not be V . It will be different across each of them depending upon its capacitance. If V_1 , V_2 and V_3 are the values of potential difference across them, then

$$V = V_1 + V_2 + V_3 \dots \dots \dots (16.36)$$

If C_e is the capacitance of equivalent capacitor, the charge on it will also be equal to Q .

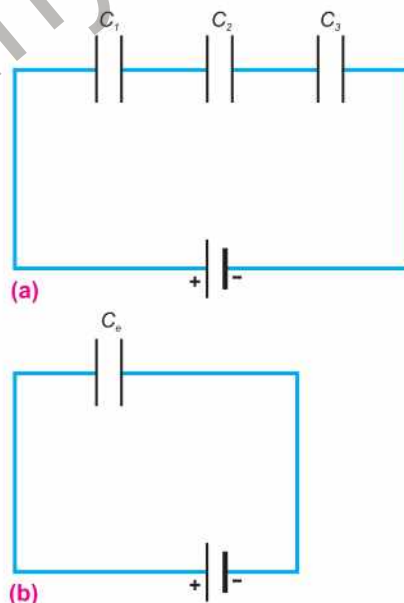


Fig. 16.9

Also the potential difference across C_e will be V which is the potential difference across the combination.

Using the formula $C = \frac{Q}{V}$ or $V = \frac{Q}{C}$ we have

$$V = \frac{Q}{C_e}, \quad V_1 = \frac{Q}{C_1}, \quad V_2 = \frac{Q}{C_2} \quad \text{and} \quad V_3 = \frac{Q}{C_3}$$

Putting these values in equation (16.36), we get

$$\frac{Q}{C_e} = \frac{Q}{C_1} + \frac{Q}{C_2} + \frac{Q}{C_3}$$

$$\text{or} \quad \frac{1}{C_e} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \dots\dots\dots(16.37)$$

Thus,

The reciprocal of equivalent capacitance is equal to the sum of the reciprocals of individual capacitances of the capacitors connected in series.

Example 16.6 Two capacitors of capacitances $12\mu\text{F}$ and $4\mu\text{F}$ are connected in series to a 80V battery.

- What is the total charge stored in the combination?
- What is the potential difference across each capacitor?

Solution

For series combination;

$$\frac{1}{C_e} = \frac{1}{C_1} + \frac{1}{C_2}$$

Putting the values of C_1 , and C_2 , we get

$$\begin{aligned} \frac{1}{C_e} &= \frac{1}{12 \times 10^{-6}\text{F}} + \frac{1}{4 \times 10^{-6}\text{F}} \\ &= \frac{1+3}{12 \times 10^{-6}\text{F}} = \frac{4}{12 \times 10^{-6}\text{F}} = \frac{1}{3 \times 10^{-6}\text{F}} \\ C_e &= 3 \times 10^{-6}\text{F} \end{aligned}$$

- Total charge on C_e will be given by the formula $Q = CV$,

$$\begin{aligned} \text{Therefore,} \quad Q &= C_e V = 3 \times 10^{-6}\text{F} \times 80\text{V} \\ Q &= 2.4 \times 10^{-4}\text{C} \end{aligned}$$

- In series combination charge on each capacitor will be the same Q . Therefore, potential difference across C_1 will be;

$$V_1 = \frac{Q}{C_1} = \frac{2.4 \times 10^{-4}\text{C}}{12 \times 10^{-6}\text{F}} = 20\text{V}$$

Potential difference across C_2 will be;

$$V_2 = \frac{Q}{C_2} = \frac{2.4 \times 10^{-4} \text{ C}}{4 \times 10^{-6} \text{ F}} = 60 \text{ V}$$

16.7 ENERGY STORED IN A CAPACITOR

A capacitor is a device to store charge. Alternatively, it is possible to think of a capacitor as a device for storing electrical energy. After all the charge on the plates possesses electrical potential energy which arises because work is to be done to deposit charge on the plates.

A good evidence of the energy stored in a charged capacitor is that of its discharging. If we connect the plates of charged capacitor by means of a thick wire, the charge flows from one plate to the other to neutralize the opposite charge on it. As a result, the wire becomes hot. Since heat is a form of energy, so the capacitor possessed energy when it was charged, and it was this energy which appeared as heat.

Let us determine the electric potential energy stored in a charged capacitor graphically. We have already studied that the charge Q on the plates increases with the increase in potential V between the plates of the capacitor, i.e.,

$$Q \propto V$$

Therefore if we draw a V vs Q graph, it will be a straight line passing through the origin as shown in Fig. 16.10. In fact, with each small increment of charge deposited during the charging process, the potential difference between the plates increases, and a larger amount of work is needed to bring up next increment of charge.

This problem can be resolved by dividing the area under the graph into very small increments of charge ΔQ each as shown in Fig. 16.10. The work required to move a small charge ΔQ through a potential difference V across the plates of capacitor is

$$\Delta W = (\Delta Q)(V_i) \dots \dots \dots (16.38)$$

This work done in depositing charge ΔQ on the plates is stored in the capacitor as increase in its electric potential energy. But $(\Delta Q)(V_i)$ is equal to the area of the rectangle shown red in the figure. Therefore total work done to charge the capacitor to a final value Q is equal to the sum of areas of all such rectangles under V vs Q graph. Fig. 16.10 shows that this sum is equal to the total area under the graph, i.e., area of the right angled triangle OAB.

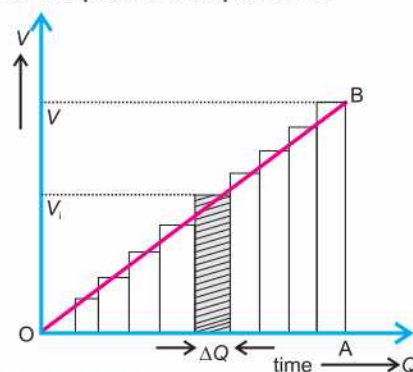


Fig. 16.15

$$\text{Area of triangle OAB} = \frac{1}{2} (\text{base}) (\text{height}) = \frac{1}{2} (OA) (AB)$$

If OA at this stage is equal to total charge Q and AB is equal to the final potential difference V then,

Area of the triangle $OAB = \frac{1}{2} QV$

Therefore, energy stored in a charged capacitor is

$$W = \frac{1}{2} QV \dots\dots\dots (16.39)$$

If we put the value of $Q = CV$ in eq. (16.39), we get

$$\text{Energy stored} = W = \frac{1}{2} (CV)V$$

$$\text{or} \quad W = \frac{1}{2} CV^2 \dots\dots\dots (16.40)$$

Therefore,

$$P.E = \frac{1}{2} CV^2$$

It is also possible to regard the energy as being stored in electric field between the plates, rather than the potential energy of the charges on the plates. Such a view point is useful when electric field strength between the plates instead of charges on the plates causing field is to be considered. This relation can be obtained by substituting $V = Ed$ and $C = \frac{A\epsilon_r\epsilon_0}{d}$ in Eq. (16.41).

$$\text{Energy} = \frac{1}{2} \left(\frac{A\epsilon_r\epsilon_0}{d} \right) (Ed)^2$$

As (Ad) is the volume between the plates, so

$$= \frac{1}{2} \epsilon_r\epsilon_0 E^2 \times (Ad)$$

This equation is valid for any electric field strength.

$$\text{Energy density} = \frac{\text{Energy}}{\text{Volume}} = \frac{1}{2} \epsilon_r\epsilon_0 E^2 \dots\dots\dots (16.42)$$

Example 16.7 Two capacitors of capacitances $4\mu\text{F}$ and $8\mu\text{F}$ are connected in series and charged by a 100V power supply. Find the total charge and energy stored in the system.

Solution

Equivalent capacitance C_e is given by;

$$C_e = \frac{8}{3} \times 10^{-6} \text{F}$$

Putting the values of C_1 and C_2 , we get

$$\text{and} \quad Q = C_e V = \left(\frac{8}{3} \times 10^{-6} \text{F} \right) \times 120\text{V}$$

$$Q = 3.2 \times 10^{-4} \text{C}$$

Energy stored in the system is given by

$$W = \frac{1}{2} QV$$

$$W = \frac{1}{2} (3.2 \times 10^{-4} \text{ C}) \times 120 \text{ V}$$

$$= 1.92 \times 10^{-2} \text{ J}$$

Example 16.8 A $16 \mu\text{F}$ capacitor is charged to a potential difference of 100 V . Determine the energy stored in it. If the potential difference is doubled by what factor does the energy increase?

Solution

Energy stored is given by;

$$W = \frac{1}{2} CV^2$$

Putting the values of C and V , we get

$$W = \frac{1}{2} (16 \times 10^{-6} \text{ F}) \times (100)^2$$

$$= 8 \times 10^{-2} \text{ J}$$

Since energy depends on V^2 , therefore if V^2 is doubled, the energy increases by a factor $(2)^2$, i.e., energy increases by 4 times.

16.8 CHARGING AND DISCHARGING A CAPACITOR

Many electric circuits consist of both capacitors and resistors. Fig.16.11 shows a resistor-capacitor circuit called R-C-circuit. When the switch S is set at terminal A , the R-C combination is connected to a battery of voltage V_0 which starts charging the capacitor through the resistor R .

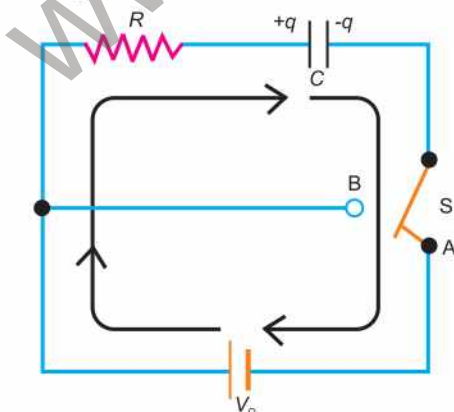


Fig. 16.11

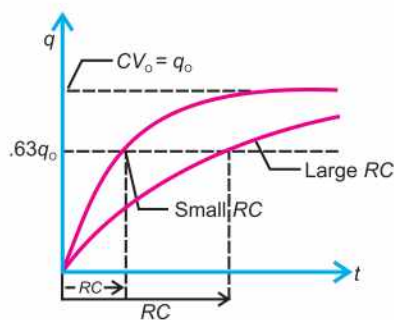


Fig. 16.12

The capacitor is not charged immediately, rather charges build up gradually to the equilibrium value of $q_0 = CV_0$. The growth of charge with time for different resistances is shown in Fig.16.12. According to this graph $q = 0$ at $t = 0$ and increases gradually with time till it reaches its equilibrium value $q_0 = CV_0$. The voltage V across capacitor at any instant can be obtained by dividing q by C , as $V = q/C$.

How fast or how slow the capacitor is charging or discharging, depends upon the product of the resistance R and the capacitance C used in the circuit. As the unit of product RC is that of time, so this product is known as time constant and is defined as the time required by the capacitor to deposit 0.63 times the equilibrium charge q_0 . The graphs of Fig.16.12 show that the charge reaches its equilibrium value sooner when the time constant is small.

Fig.16.13 (a) illustrates the **discharging** of a capacitor through a resistor. In this figure, the switch S is set at point B , so the charge $+q$ on the left plate can flow anti-clockwise through the resistance and neutralize the charge $-q$ on the right plate.

The graphs in Fig.16.13 (b) shows that discharging begins at $t = 0$ when $q = CV_0$ and decreases gradually to zero. Smaller values of time constant RC lead to a more rapid discharge.

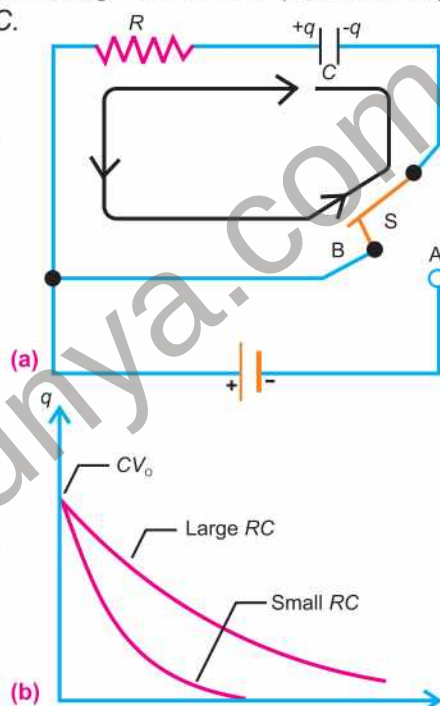


Fig. 16.13

Example 16.9 The time constant of a series RC circuit is $\tau = RC$. Verify that an ohm times farad is equivalent to second.

Solution: Ohm's law in terms of potential difference V , current/and resistance R can be written as,

Solution

$$V = IR$$

Putting $I = q/t$, this equation transforms into the equation,

$$V = \frac{q}{t} R \quad \text{or} \quad R = \frac{V \times t}{q}$$

According to equation $q = CV$, $C = q/V$

Multiplying this equation with above equation gives,

$$RC = \frac{V \times t}{q} \times \frac{q}{V} = \tau$$

Hence $1 \text{ ohm} \times 1 \text{ farad} = 1 \text{ second}$

Where ohm is the unit of resistance R .

14.9 EXPONENTIAL DECAY OF DISCHARGING CAPACITOR THROUGH RESISTOR

An RC circuit for the discharging capacitor through a resistor was shown in Fig. 16.13(a) in the previous section. A graph charge vs time for that is shown in Fig. 16.14. The charge (Q) decreases exponentially overtime (t). In general, exponential means increasing or decreasing very rapidly. It can also refer to a mathematical functions involving exponents where a variable appears as an exponent. We can write this function in the form,

$$f(x) = a^x$$

where a is a constant and x is the exponent (variable). The general exponential decay formula for a discharging capacitor in an RC circuit is of the form;

$$x = x_0 \left[\exp\left(\frac{-t}{RC}\right) \right] \dots\dots\dots (16.43)$$

or $x = x_0 e^{\frac{-t}{RC}}$

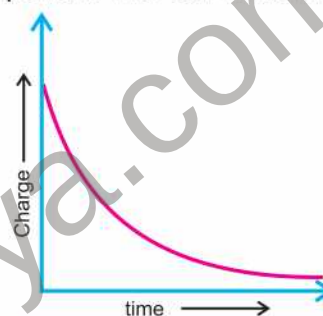


Fig. 16.14

where x = quantity (such as charge, voltage or current) at time t .

x_0 = initial value of the quantity at $t = 0$.

R = resistance in ohms (Ω).

C = capacitance in farads (F).

t = time in seconds.

RC = time constant (τ) which determines how quickly the capacitor discharges.

e = a mathematical constant called Euler's constant which is also used as of the natural logarithm ($\log_e$). Its value is approximately 2.718.

The negative exponent ($-t/RC$) in the formula indicates that the quantity decreases exponentially over time.

Using Eq.16.43, the decrease in charge, voltage and current at any time t , can be described by the following equations.

$$Q = Q_0 e^{-t/RC}, V = V_0 e^{-t/RC} \text{ and } I = I_0 e^{-t/RC}.$$

In the graph for the decrease in all the three quantities, they start with a steep slope (fast discharge) and gradually flattens out as the time progresses, indicating a slower discharge rate. This is shown in Fig. 16.15 by the charge decay graph.

The initial charge is Q_0 at $t = 0$ and it drops to Q after a time interval t . Now, if at another stage during the discharging of capacitor, let the charge be Q_0' . After

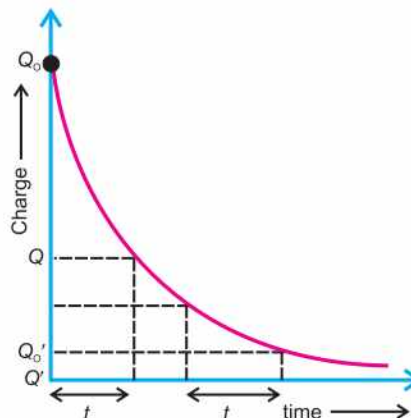


Fig. 16.15

the same interval of time t , it drops to Q' . We can see that the rate of decrease of charge in the beginning was $(Q_0 - Q)$, but as the process goes on, the rate of decrease of charge becomes $(Q' - Q')$ which is less than $(Q_0 - Q)$.

The decay of charge is very much similar to flow of water out of a tank through a narrow pipe. When the tank is full of water, its level and pressure is analogous to charge and voltage, and flow rate of water analogous to the current. In the beginning, the water level is high and it decreases rapidly and the flow of water through the pipe is fast. As the water level comes down, the rate of flow slows down. This flowing down is due to the decreasing pressure.

For your information

Exponential functions frequently and quantitatively describe a number of phenomena in physics, such as radioactive decay, in which the rate of change in a process or substance depends directly on its current value.

Role of Time Constant

The time constant $RC = \tau$ plays very important role in charging and discharge a capacitor through a resistance. Consider the exponential decay of the charge stored in a capacitor. It is given by the equation

$$Q = Q_0 e^{-t/RC}$$

If we put $t = RC$, we will get the quantity of charge remained after 1 time constant.

Therefore, $Q = Q_0 e^{-RC/RC} = Q_0 e^{-1} = Q_0 \times 1/e$

Substituting the value of e , we get

$$Q = Q_0 \times \frac{1}{2.718} = 0.37 Q_0$$

This gives the definition of time constant;

The time constant (τ) is the duration of time in which, the initial charge Q_0 drops to about $0.37 Q_0$.

This means that after one time constant, the charge drops to 37% of its initial value. Likewise the voltage and current also drops to the same extent. The exponential decay equation also shows that a smaller time constant ($\tau = RC$) means the circuit responds

faster, while a larger time constant means, it responds more slowly. This effect is shown in Fig. 16.16. Let us now determine $(t_{1/2})$ taken in terms of time constant (RC) during which the charge Q_0 drops to one half of its initial value. Putting the value of $Q = 1/2 Q_0$ in the exponential decay equation of the charge, we get

$$\frac{1}{2} Q_0 = Q_0 e^{-t_{1/2}/RC}$$

or

$$\frac{1}{2} = e^{-t_{1/2}/RC}$$

By definition of natural logarithm,

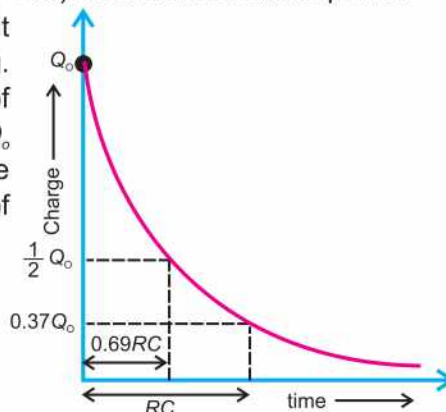


Fig. 16.16

$$\ln\left(\frac{1}{2}\right) = \frac{-t_{1/2}}{RC}$$

or $-(RC)\left[\ln\left(\frac{1}{2}\right)\right] = t_{1/2} \dots \dots \dots (16.44)$

Now $\ln\left(\frac{1}{2}\right) = \ln(1) - \ln(2)$
 $= 0 - \ln(2)$

From calculator, the value of $-\ln(2) = -0.69$

Putting the value of $\ln(1/2)$ in Eq. 4.45, we get

$$-RC(-0.69) = t_{1/2}$$

or $t_{1/2} = 0.69 RC \dots \dots \dots (16.45)$

we can show this in the graph of Fig. 4.17.

Example 16.10 In an RC circuit $R = 1\text{k}\Omega$, $C = 100\mu\text{F}$ and $V_o = 10\text{V}$. Determine the voltage across the capacitor after 0.2 s.

Solution

The constant $\tau = RC = 1000\Omega \times 100 \times 10^{-6}\text{F}$
 $= 0.1\text{ s}$

Voltage after 0.2 s = $V(t) = ?$

Using exponential decay equation for voltage,

$$V = V_o e^{\frac{-t}{RC}}$$

$$V = 10 \times e^{\frac{-0.2}{0.1}} = 10 \times e^{-2} = 10 \times \frac{1}{e^2}$$

or $V = 10 \times \frac{1}{(2.718)^2} = 1.35\text{V}$

16.10 USE OF CAPACITORS

Capacitors are used in various household appliances such as electric fans, water drawing motors, washing machines refrigerators, flashguns, computer keyboards, touchscreens etc. We will describe here a few of them with some detail.

Electric Fans and Electric Motors

A capacitor is connected to the starting of fan motor. When the power is turned ON the capacitor starts charging, i.e., it accumulates

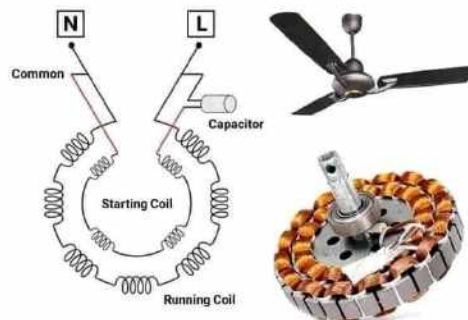


Fig. 16.17: Electric fan

charge. During the process of starting of fan motor, it provides additional power, helping the motor to overcome static friction and initial resistance due to inertia. In this way, it enables the fan motor to start and begin spinning quickly. The same role is played by the capacitor in motors used in washing machines, electric blenders, choppers, grinders, water drawing motors etc.

Refrigerators and Air Conditioners

The compressors of a refrigerator and an air conditioner typically use single phase motors, which can struggle to start on their own. The capacitors of high capacitance are used in them. Such a capacitor stores a big amount of electrical energy and releases it to the motor winding of the compressor. It acts like a “jump start” for the motor, providing a boost of power to get the motor rotating.

Once the motor reaches a certain speed, a relay disconnects the capacitor as it is no longer needed. Commonly, this capacitor is called as “start capacitor.” Most refrigerators and air conditioners also use a “run capacitor” which stays connected in the circuit to improve energy efficiency. However some older models may use “start capacitors” that only function during start up.

Capacitors in conjunction with resistors can form a time delay circuit. It is widely used in refrigerators, air conditioners and other devices to create delay in triggering the power supply. This is a precautionary measure to protect the devices from power fluctuation.

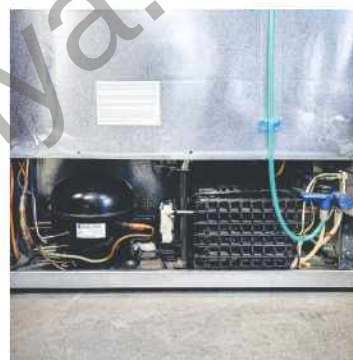


Fig. 16.18

Flashgun

In a flashgun, a capacitor stores and releases electrical energy to power the flash tube. A flash tube contains xenon gas in it. The capacitor accumulates charge from the battery of camera or some other device. When the shutter button is pressed the capacitor is connected to the flash tube. The rapid discharge of the capacitor provides the high current needed to ionize the xenon gas inside the tube, causing it to emit a burst of bright light.



Fig. 16.19

Rectification Circuits

Capacitors are widely used in the process of converting alternating current (AC) into direct current (DC). The process is called as rectification.

A typical full wave rectification circuit called “Bridge circuit” is shown in Fig. 16.15 (a,b). We will study half wave and full wave rectifiers in the next chapter.

There is a vast use of capacitors in the medical field. Capacitors store electrical energy needed to deliver a life-saving shock to heart, restoring a normal rhythm in case of cardiac arrest. Capacitors are also used in imaging machines (CT, MRI, X-Ray, Ultrasound etc.) helping to filter out noise, and improve image clarity. Similarly, capacitors filter out unwanted signals in EEG and ECG machines.

QUESTIONS

Multiple Choice Questions

Choose the correct answer:

- What is the work done on an electron by a potential difference of 100 volts?
(a) $1.6 \times 10^{-19} \text{ eV}$ (b) $1.6 \times 10^{-17} \text{ eV}$ (c) $6.25 \times 10^{-17} \text{ eV}$ (d) 100 eV
- A parallel plate capacitor of capacitance $50 \mu\text{F}$ is connected to a battery of 12 volts, the charge stored on each plate is:
(a) $60 \mu\text{C}$ (b) $4.2 \mu\text{C}$ (c) $6 \times 10^{-4} \text{ C}$ (d) $4 \times 10^{-4} \text{ C}$
- If a dielectric is inserted between the plates of a charged capacitor, the potential difference across the plates:
(a) increases (b) decreases (c) remains same (d) becomes zero
- The potential energy of a system of two charges $8 \mu\text{C}$ and $-8 \mu\text{C}$ separated by a distance 2 m is:
(a) $\frac{8 \times 10^{-6}}{\pi \epsilon_0} \text{ J}$ (b) $\frac{+16 \times 10^{-6}}{\pi \epsilon_0} \text{ J}$
(c) $\frac{-8 \times 10^{-6}}{\pi \epsilon_0} \text{ J}$ (d) $\frac{-16 \times 10^{-6}}{\pi \epsilon_0} \text{ J}$
- The electric potential at a point A is 50 V and at B is 80 V. If the electric field between the charges is uniform, what can be said about the motion of positive charge from A to B?
(a) No work is done
(b) Work is done by the electric field
(c) Work is done against the electric field
(d) None of the above statements is true
- The rate of charging or discharging the capacitor depends upon the product of resistance and:
(a) charge (b) potential difference (c) current (d) capacitance
- In a charged capacitor, the energy resides in:
(a) The positive plate (b) the negative plate
(c) both positive and negative plates (d) the electric field between the plates
- A capacitor of capacitance $1 \mu\text{F}$ is subjected to 4000 volts potential difference, the energy stored in it is:
(a) 8 J (b) 16 J (c) 32 J (d) 64 J

9. The electric potential energy of a point charge q at some point in an electric field is equal to: $\frac{1}{4\pi\epsilon_0} \frac{q^2}{r}$
- (a) $\frac{1}{4\pi\epsilon_0} \frac{q}{r}$ (b) $\frac{1}{4\pi\epsilon_0} \frac{q}{r^2}$ (c) qV (d) V^2
10. The time constant of a capacitor discharging through a resistor is the time in seconds in which the initial charge Q_0 drops to:
- (a) $0.25 Q_0$ (b) $0.37 Q_0$ (c) $0.50 Q_0$ (d) $0.69 Q_0$

Short Answer Questions

- 16.1 If the absolute potential at a point is zero, what can you say about the electric intensity at that point?
- 16.2 Is electron-volt a unit of potential difference or energy? Explain briefly.
- 16.3 Define capacitance. Give its units.
- 16.4 Define dielectric constant. Give its mathematical form.
- 16.5 How does the capacitance of a capacitor change if the separation between its plates is increased?
- 16.6 When will the energy stored in three capacitors be greater?
- (i) They are connected in series.
- (ii) They are connected in parallel.
- 16.7 What is time constant? Give its definition.

Constructed Response Questions

- 16.1 How is electric potential different from electric potential energy? Give an example to explain the difference.
- 16.2 How does the concept of electric potential help us understand the motion of charges in an electric field?
- 16.3 The electric field is negative gradient of electric potential. What does the negative sign indicate physically? Illustrate your answer with an example.
- 16.4 When a capacitor is charging, no actual charge flows across the gap between the plates. But the current is still said to be flowing. Explain it.
- 16.5 Two capacitors can be connected in parallel or in series. Explain how does total energy stored differ in two configurations.
- 16.6 A capacitor stores energy. Is this energy stored on the plates, in the dielectric or in the electric field? Explain how does a capacitor store energy?
- 16.7 Why does the capacitance increase on inserting a dielectric between the plates of a capacitor?

Comprehensive Questions

- 16.1 Derive an expression for the absolute electric potential at a point due to a point charge q .
- 16.2 What is a capacitor? Find the capacitance of a parallel plate capacitor. What is the role of a dielectric in the capacitor?
- 16.3 Derive formulae for parallel and series combinations of capacitors.
- 16.4 Determine the electric potential energy stored in a capacitor from the area under the potential-charge graph.
- 16.5 Explain the charging and discharging of a capacitor by drawing circuit diagrams and graphs between charge versus time. What is a time constant for a capacitor discharging through a resistor?
- 16.6 Describe some uses of capacitors in various household appliances.

Numerical Problems

- 16.1 A particle carrying a charge of $0.1 \mu\text{C}$ starts from rest in a uniform electric field of intensity 60 N C^{-1} . Find the kinetic energy acquired by the particle when it has moved 2 m . (Ans: $1.2 \times 10^{-3} \text{ J}$)
- 16.2 What should be the potential difference through which an electron falls to acquire a speed of $2 \times 10^6 \text{ m s}^{-1}$? (Ans: 11.4 V)
- 16.3 The potential difference between points A and B is $V_A - V_B = 84 \text{ V}$, while the potential difference between points C and B is $V_C - V_B = 24 \text{ V}$. What should be the work done on moving a $40 \mu\text{C}$ charge from C to A? (Ans: $2.4 \times 10^{-3} \text{ J}$)
- 16.4 A parallel plate capacitor has a capacitance of $6 \mu\text{F}$ when filled with a dielectric. The area of each plate is 1.2 m^2 and the separation between the plates is $9 \times 10^{-6} \text{ m}$. What is the dielectric constant? (Ans: 5.1)
- 16.5 A $15 \mu\text{F}$ capacitor is charged till the potential difference across its plates becomes 300 V . Find the energy stored in it. (Ans: 0.675 J)
- 16.6 Two capacitors of $2.0 \mu\text{F}$ and $8.0 \mu\text{F}$ capacitances are connected in series and a potential difference of 300 volts is applied. Find the charge and potential difference for each capacitor. (Ans: $Q_1 = Q_2 = 4.8 \times 10^{-4} \text{ C}$, $V_1 = 240 \text{ V}$, $V_2 = 60 \text{ V}$)
- 16.7 A capacitor has a capacitance of $3 \mu\text{F}$. It is charged by a battery. When the potential difference between the plates is 240 volts , how many electrons have been removed from one plate and placed on the other plate? (Ans: 3.0×10^{15})
- 16.8 Two positive point charges are held at two points 1.2 m apart. They are then moved towards each other so that their electric potential energy becomes double of its previous value. How much are they apart at their new positions? (Ans: 0.6 m)
- 16.9 A $100 \mu\text{F}$ capacitor is initially charged to 8 V . It is allowed to discharge through a 500Ω resistor. Find the voltage across the capacitor after 0.5 s . (Ans: $3.6 \times 10^{-4} \text{ V}$)