MODULE 3

ELECTRICITY AND MAGNETIC FIELD

CHARLES COULOMB

French physicist (1736–1806) *Coulomb's major contributions to science were in the areas of electrostatics and magnetism. During his lifetime, he also investigated the strengths of materials and determined the forces that affect objects on beams, thereby contributing to the field of structural mechanics. In the field of ergonomics, his research provided a fundamental understanding of the ways in which people and animals can best do work.*

3.1 INTRODUCTION

Lightning and thunder are two common phenomena in our hot and humid atmosphere in Nigeria. The laws of electricity and magnetism have a central role in the operation of devices such as radios, televisions, electric motors, computers, high-energy accelerators, and other electronic devices. A physicist, Benjamin Franklin demonstrated in 1752 that thunder clouds are charged with electricity. These charged clouds, when discharged in the atmosphere, give rise to a great spark, which is referred to as lightening. The amount of electric current during the discharge is about 20KA, lightning can occur in other situations, such as in a volcanic eruption. The electric discharge which gives rise to lightning also produces a great amount of heat. In a fraction of a second, temperature rises to about 15000^0C, the lightning develops in a small area which is about 20cm in width.

However, as a result of the heat produced in that small area the air molecules move fast and cause the intense sound which we call thunder. When the sound is reflected by clouds, hill or any other obstacle, we hear the roaring of clouds. A very important thing about electric charges is that the forces between them are very large and the force is known as electrostatic force or electric force. Electrostatic force is responsible for holding electrons to nuclei to form atoms and for holding the groups of the atoms together to form molecules, solids and liquids. The study of these static charges is known as electrostatic. Indeed, electrostatic was the first branch of electricity to be investigated and, for some time, it was regarded as a subject which had no practical value. However, it is now known to have practical industrial applications. Evidence in Chinese documents suggests that magnetism was observed as early as 2000 B.C. The ancient Greeks observed electric and magnetic phenomena possibly as early as 700 B.C. They found that a piece of amber, when rubbed, becomes electrified and attracts pieces of straw or feathers. The Greeks knew about magnetic forces from observations that the naturally occurring stone magnetite (Fe_3O_4) is attracted to iron. The word electric comes from elecktron, the Greek word for "amber." While the word magnetic comes from Magnesia, the name of the district of Greece where magnetite was first found. In 1600, the Englishman William Gilbert discovered that electrification is not limited to amber but rather is a general phenomenon. In the years following this discovery, scientists electrified a variety of objects. Experiments by Charles Coulomb in 1785 confirmed the inverse-square law for electric forces. It was not until the early part of the nineteenth century that scientists established that electricity and magnetism are related phenomena. In 1819, Hans Oersted discovered that a compass needle is deflected when placed near a circuit carrying an electric current. In 1831, Michael Faraday and, almost simultaneously, Joseph Henry showed that when a wire is moved near a magnet (or, equivalently, when a magnet is moved near a wire), an electric current is established in the wire. In 1873, James Clerk Maxwell used these observations and other experimental facts as a basis for formulating the laws of electromagnetism as we know them today. Electromagnetism is a name given to the combined study of electricity and magnetism. Around 1888, Heinrich Hertz verified Maxwell's predictions by producing electromagnetic waves in the laboratory. This achievement led to such practical developments as radio and television. Maxwell's contributions to the field of electromagnetism were especially significant because the laws he formulated are basic to all forms of electromagnetic phenomena. His work is as important as Newton's work on the laws of motion and the theory of gravitation.

3.2 ELECTROSTATICS

Study of Electricity in which electric charges are static i.e. not moving, is called electrostatics. A number of simple experiments demonstrate the existence of electric forces and charges. For example, we start with a PVC pipe and a paper towel. Initially there is no force between the two. However, after rubbing the paper on the PVC pipe, they are attracted to each other. If we rub the paper towel on two similar PVC pipes, we noticed that the two PVC pipes push each other apart ‘‘repulsion’’ **What kind of force is this, and what property of nature causes the force?** The force is certainly not gravity, and the source is not the objects mass as it is in Newtonian gravity. We call this the electrostatic (or electrical) interaction, and we call the property of nature that causes the force charge. It is quite different than the gravitational force, since the electrostatic force can be attractive or repulsive (whereas gravity is only attractive). Note that repulsion occurred between the two similar PVC pipes.

Whatever charge they had, they had the same charge. Thus, the experiments would imply that like charges repel.

What about attraction? Initially the PVC pipe and the paper did not attract or repel. However, after they were rubbed together then they attracted each other. We know that the PVC pipe acquired some charge, since two PVC pipes repel each other. The experiments would suggest that

initially the paper and pipe each had zero net charge, and after rubbing, some charge was transferred from the paper to the pipe. If the paper was initially neutral (0 net charge), then the paper might have negative (or the opposite) charge as the pipe. Thus, "opposite" charges attract.
To understand what is really going on, we need to understand what the materials are made of. We know that matter is made up of atoms. The atoms are comprised of a massive nucleus (protons and neutrons) surrounded by electrons.
Also, after rubbing a comb through your hair on a dry day, you will find that the comb attracts bits of paper. The attractive force is often strong enough to suspend the paper. The same effect occurs when certain materials are rubbed together, such as glass rubbed with silk or rubber with fur. Another simple experiment is to rub an inflated balloon with wool. The balloon then adheres to a wall, often for hours. When materials behave in this way, they are said to be ***electrified,*** or to have become electrically charged. You can easily electrify your body by vigorously rubbing your shoes on a wool rug. Evidence of the electric charge on your body can be detected by lightly touching (and startling) a friend. Under the right conditions, you will see a spark when you touch, and both of you will feel a slight tingle. (Experiments such as these work best on a dry day because an excessive amount of moisture in the air can cause any charge you build up to "leak" from your body to the Earth.)

3.3 ELECTRIC CHARGE

Electric charge is characteristic developed in particle of material due to which it exerts force on other such particles. It automatically accompanies the particle wherever it goes.

• Charge cannot exist without material carrying it

• It is possible to develop the charge by **rubbing two solids having friction.**

• Carrying the charges is called **electrification**.

• Electrification due to friction is called **frictional electricity**. Since these charges are not flowing it is also called static electricity.

There are two types of charges. +ve and –ve.

• Similar charges repel each other,

• Opposite charges attract each other.

• Benjamin Franklin made this nomenclature of charges being +ve and –ve for mathematical calculations because adding them together cancels each other.

• Any particle has vast amount of charges.

• The number of positive and negative charges are **equal**, hence **matter is basically neutral.**

• Inequality of charges give the material a **net** charge which is equal to the difference of the two type of charges.

3.4 ELECTROSTATIC INDUCTION

Phenomenon of polarization of charges in a body, when a charged body is present near it is called electrostatic induction. In this process bodies are charged without touching them, a charged object will induce a charge on a nearby conductor. In this example, a negatively charged rod pushes some of the negatively charged electrons to the far side of a nearby copper sphere because like charges repel each other. The positive charges that remain on the near side of the sphere are attracted to the rod.

If the sphere is grounded so that the electrons can escape altogether, the charge on the sphere will remain if the rod is removed.

3.5 CONDUCTORS, INSULATORS AND SEMICONDUCTORS

It is convenient to classify materials in terms of the ability of electrons to move through the material.

Insulator : electrical insulators are materials in which all electrons are bound to atoms and cannot move freely through the material. Examples; glass, pure water, plastic etc. Electrons can be forced to move across an insulator by applying strong force (called electric field.) Then this acts like a conductor.

Conductors : Electrons that are not bound to atoms and can move relatively freely through the material. Examples; metals, tap water, human body. Brass rod in our hand, if charged by rubbing the charge will move easily to earth, hence Brass is a conductor. The flow of this excess charge is called **discharging.**

When such materials are charged by rubbing, only the area rubbed becomes charged and the charged particles are unable to move to other regions of the material. In contrast, materials such as copper, aluminum, and silver are good electrical conductors. When such materials are charged in some small region, the charge readily distributes itself over the entire surface of the material. If you hold a copper rod in your hand and rub it with wool or fur, it will not attract a small piece of paper. This might suggest that a metal cannot be charged. However, if you attach a wooden handle to the rod and then hold it by that handle as you rub the rod, the rod will remain charged and attract the piece of paper. The explanation for this is as follows: without the insulating wood, the electric charges produced by rubbing readily move from the copper through your body, which is also a conductor, and into the Earth. The insulating wooden handle prevents the flow of charge into your hand.

Semiconductors: Semiconductors are a third class of materials, and their electrical properties are somewhere between those of insulators and those of conductors. Silicon and germanium are well-known examples of semiconductors commonly used in the fabrication of a variety of electronic chips used in computers, cellular telephones, and stereo systems. The electrical properties of semiconductors can be changed over many orders of magnitude by the addition of controlled amounts of certain atoms to the materials.

3.6 CHARGING OBJECTS BY INDUCTION

A charged object will induce a charge on a nearby conductor. In this example, a negatively charged rod pushes some of the negatively charged electrons to the far side of a nearby copper sphere because like charges repel each other. The positive charges that remain on the near side of the sphere are attracted to the rod. If the sphere is grounded so that the electrons can escape altogether, the charge on the sphere will remain if the rod is removed.

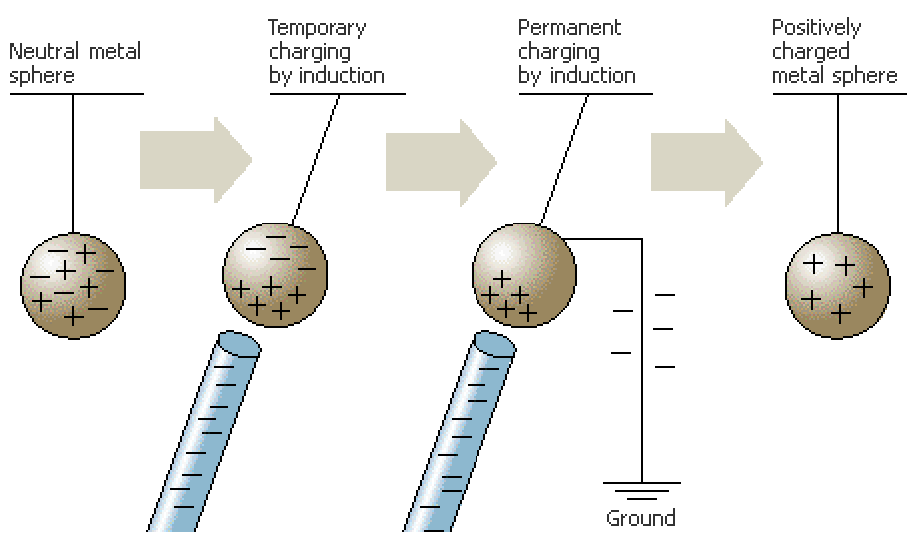


Figure 3.1 Charging a metallic object by conduction.

Figure 3.2 Rubbing a balloon against your hair on a dry day causes the balloon and your hair to become charged.

3.7 ELECTRIC FORCE - COULUMB'S LAW

Charles Coulomb (1736–1806) measured the magnitudes of the electric forces between charged objects using the torsion balance, which he invented (Fig. 3.3). Coulomb confirmed that the electric force between two small charged spheres is proportional to the inverse square of their separation distance *r*, that is, $F \alpha \frac{1}{r^2}$.

Coulumb's law in Electrostatics is the force of Interaction between two stationery point charges is directly proportional to the product of the charges, inversely proportional to the square of the distance between them and acts along the straight line joining the two charges.

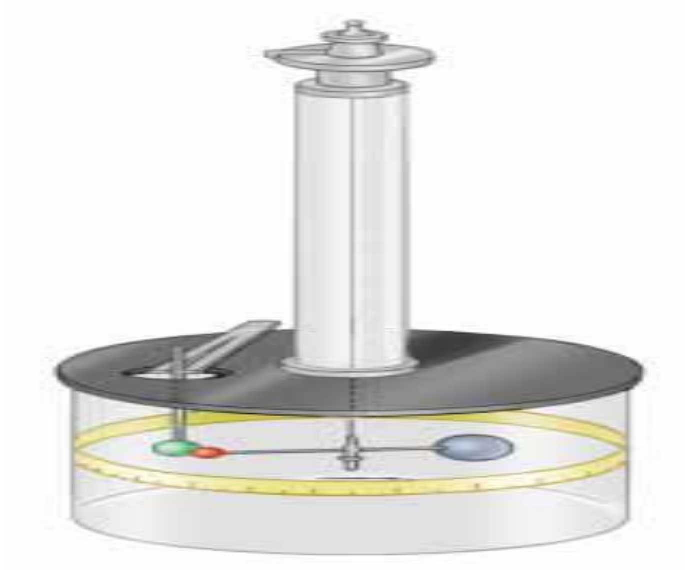


Figure 3.3 Coulomb's torsion balance, used to establish the inverse-square law for the electric force between two charges.

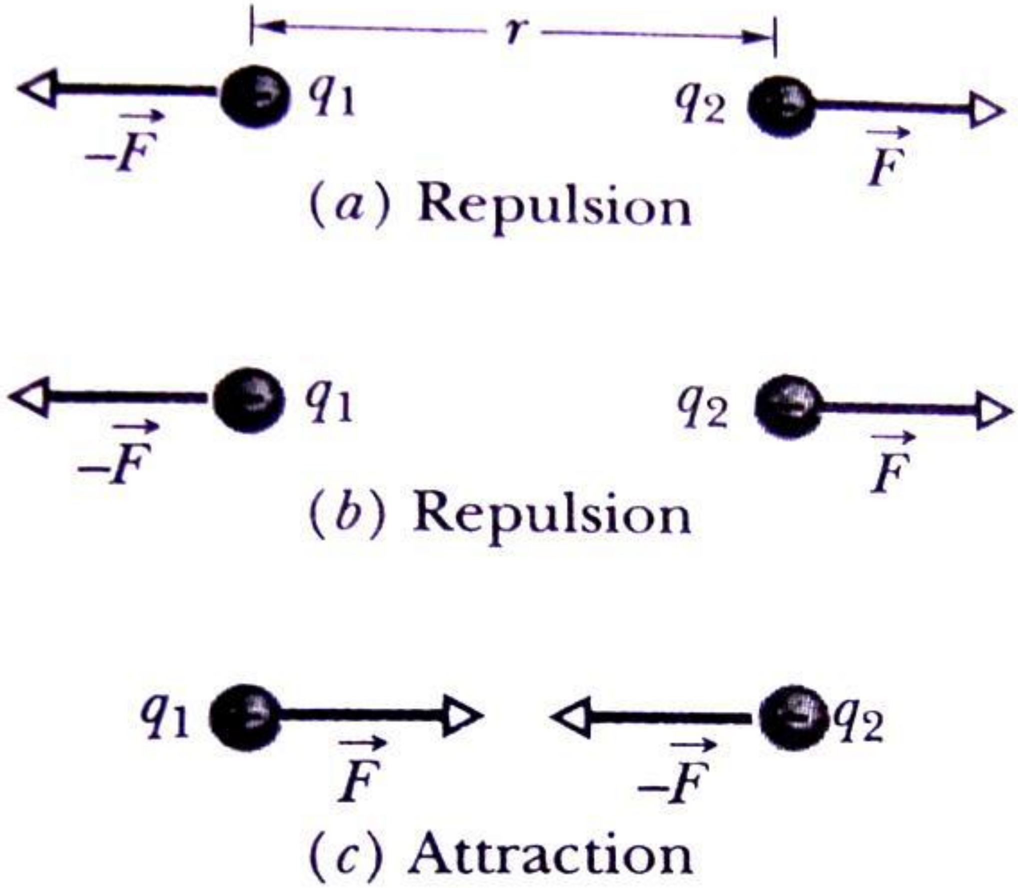
From Coulomb's experiments, we can generalize the following properties of the electric force between two stationary charged particles. The electric force

• is inversely proportional to the square of the separation r between the particles and directed along the line joining them;

• is proportional to the product of the charges $q1$ and $q2$ on the two particles;

• is attractive if the charges are of opposite sign and repulsive if the charges have the same sign;

• is a conservative force.



Two charged particles, separated by distance r, repel each other if their charges are (*a*) both positive and (*b*) both negative. (*c*) They attract each other if their charges are of opposite signs. In each of the three situations, the force acting on one particle is equal in magnitude to the force acting on the other particle but has the opposite direction.

If two charges $q_1$and q_2 are placed at distance r then,

$$F = K\frac{q_1 q_2}{r^2} \qquad 3.1$$

where *k* is a constant, *k* is called Coulomb's constant and its value is

$$K = \frac{1}{4\pi\varepsilon_0} \qquad 3.2$$

The value of the Coulomb constant depends on the choice of units. The SI unit of charge is the coulomb (C). The Coulomb constant *k* in SI units has the value

$$K = 8.9875 \text{ x } 10^{9} \text{ N.m}^2/\text{C}^2 \qquad 3.3$$

where the constant ε_0 is known as the permittivity of free space and has the value

$$\varepsilon_0 = 8.8542 \text{ x } 10^{-12} \text{ C}^2/\text{N.m}^2 \qquad 3.4$$

Particle	**Charge (C)**	**Mass (kg)**
Electron (e)	$-1.6021917 \text{ x } 10^{-19}$	$9.109\,5 \text{ x } 10^{-31}$
Proton (p)	$+1.6021917 \text{ x } 10^{-19}$	$1.672\,61 \text{ x } 10^{-27}$
Neutron (n)	0	$1.674\,92 \text{ x } 10^{-27}$

3.8 ELECTRIC FIELD

Is the environment created by an electric charge (source charge) in the space around it, such that if any other electric charges (test charges) is present in this space, it will come to know of its presence and exert a force on it. An electric field is a region where an electric charge experiences a force, just as a football field is an area where the game is played. If a very small, positive point charge q is place at any point in an electric field and it experiences a force F, then the field strength E (also called the E-field) at that point is defined by the equation.

$$F = qE \qquad 3.5$$

The magnitude of E is the force per unit charge and its direction is that of F (i.e the direction of the force which acts on a positive charge).

In order to measure the electric field in a given region, we introduce a test charge and measure the force on it. However, we should realize that the test charge q exerts forces on the charge that produce the field, so it may change the configuration of the charges. In principle, the test charge should be so small as to have no significant effect on the charge configuration that produces the field. Equation 3.5 shows that the electric field is measured in Newtons Coulomb^{-1} (NC^{-1}). Since F is a vector quantity, E will also be a vector. If q is positive, the electric field E has the same direction as the force acting on the charge. If q is negative, the direction of E is opposite to that of the force F. Let us consider the electric field of a point charge. We already know from coulomb's law that if we place a point charge q at a distance r from another point charges q_1 the force on q_2 will be.

$$F = \frac{1}{4\pi\varepsilon_0}\frac{qq_1}{r^2} \qquad 3.6$$

Since the electric field is force per unit charge, we divide the force in equation 3.6 by the charge q_1 to obtain the field due to q at the location of q_1.

That is

$$E = \frac{F}{q} \qquad = \qquad E = K\frac{q}{r^2} \qquad 3.7$$

Figure 3.3 This dramatic photograph captures a lightning bolt striking a tree near some rural homes. Lightning is associated with very strong electric fields in the atmosphere.

3.9 FIELD LINES

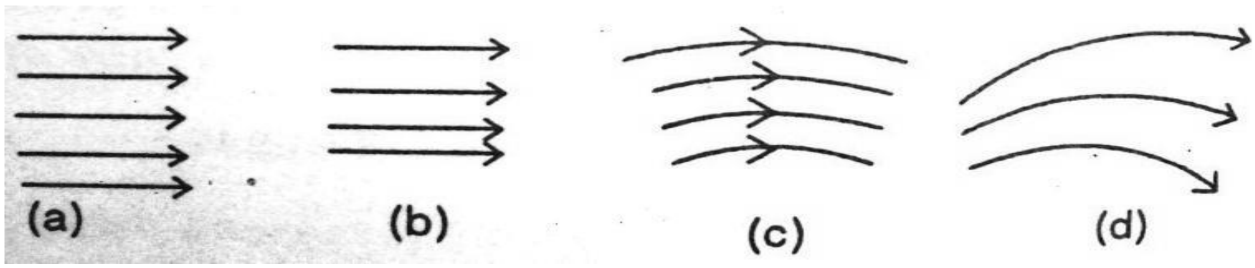
An electric field can be represented by electric field lines or lines of force. The lines are drawn so that

(a) The field line at a point (or the tangent to it if it is curved) gives the direction of E at the point. This is the direction in which a positive charge would accelerate.

(b) The number of lines per unit cross-section area is proportional to E.

3.10 PROPERTIES OF ELECTRIC LINES OF FORCE

1. Start from positive charge and end at negative.
2. Electric Lines of forces are **imaginary** but Electric field they represent is **real.**
3. The tangent drawn at any point on the line of force gives the direction of force acting on a positive charge at that point.
4. In SI system, the number of electric lines originating or terminating on charge q is q/ε_0 . That means lines associated with unit charge are $1/\boldsymbol{\varepsilon_0}$
5. Two lines of force never cross each other, because if they do so then at the point of intersection, intensity will have two directions which is absurd.
6. Electric Lines of force can never be a closed loop since they do not start and end at the same point. The lines are discontinuous, start from + and terminate at –.
7. The electric line of force does not pass through a conductor as electric field inside a conductor is zero.
8. Lines of force have tendency to contract longitudinally like a stretched string, producing attraction between opposite charges and edge effect.
9. Electric Lines of force start and end Normal to the surface of conductor.
10. Crowded lines represent strong field while distant lines represent weak field. Equidistant parallel lines represent uniform field. Non-straight or non- parallel represent non-uniform field. In the diagram a is uniform while b, c, and d are non-uniform fields.



FIELD LINES DUE TO SOME CHARGE CONFIGURATIONS

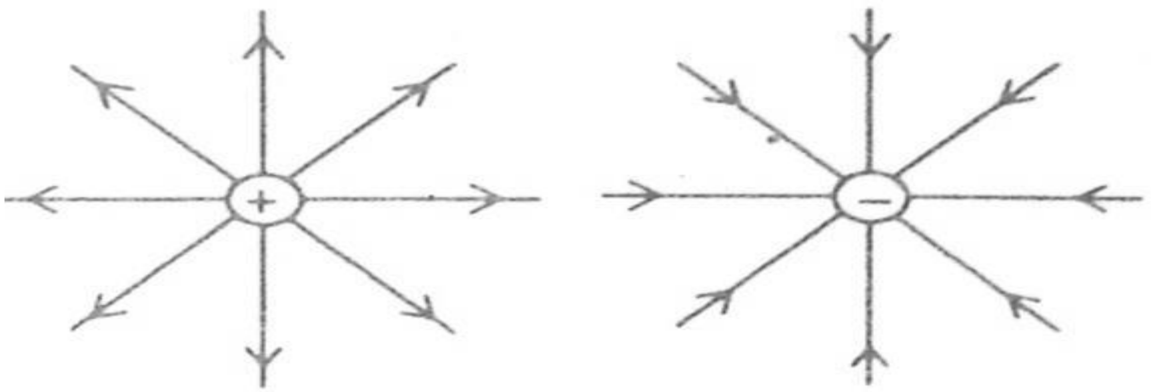


Figure 3.4 Single positive or negative charge.

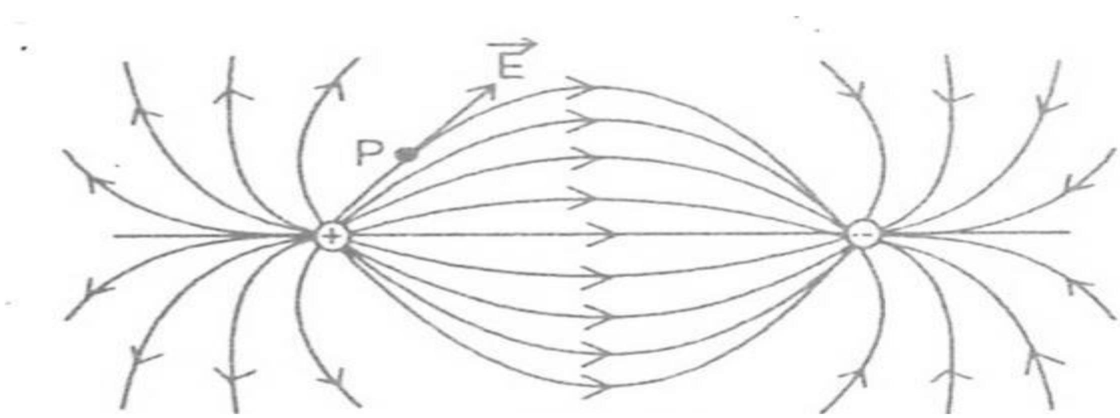


Figure 3.5 Two equal and opposite charges

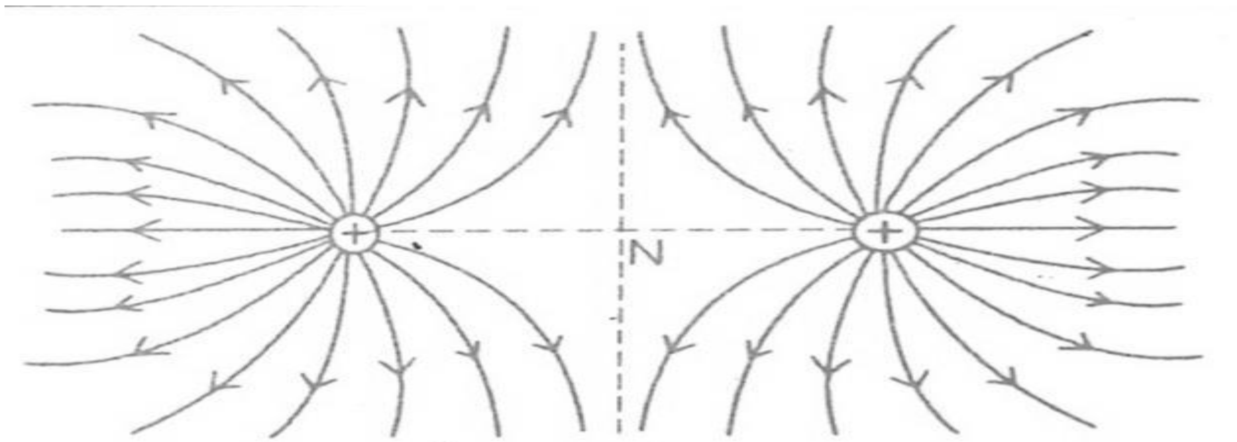


Figure 3.6 Lines of force due to two positive charges

3.11 SIMPLE ALTERNATING CURRENT CIRCUIT

Ac circuit analysis

Electricity is mostly generated, transmitted and distribute in alternating current (AC) for a number of reasons: electric machines are AC in nature; AC can be readily transformed to a high voltage so as to reduce the current and the size and cost of the transmission lines and cables; and it is easier to switch off.

Alternating current (AC) is the flow of electric charge that periodically reverses direction. If the source varies periodically, particularly sinusoidally, the circuit is known as an alternating current circuit. Examples include the commercial and residential power that serves so many of our needs. All DC based plugged in appliances and rechargeable battery based devices technically run on Alternating current as they all use some form of DC power derived from AC for either charging of their batteries or powering of the system. Thus Alternating current is the form via which power is delivered at the mains.

The Alternating circuit came into being in the 1980s when Tesla decided to solve the long range incapability of the Thomas Edison's DC generators. He sought a way of transferring electricity at a high voltage and then employs the use of transformers to step it either up or down as may be needed for distribution and was thus able to minimize power loss across a great distance which was the main problem of Direct Current at the time.

The Emf Generated by a Rotating Coil in a magnetic field has a graph similar to the one shown below. It is called an AC voltage because there is a reversal of polarity i.e., the voltage changes sign; AC voltages need not be sinusoidal. If the coil rotates with a frequency of *f* revolutions per second, then the emf has a frequency of *f* in hertz (cycles per second). The instantaneous voltage v that is generated has the form

$$v = v_0 \sin \omega t = v_0 \sin 2\pi f t \qquad 3.8$$

Where v is the voltage at time *t*, v_0 is the amplitude (maximum value) of the voltage in volts and $\omega = 2\pi f$ is the angular velocity in rad/s. The frequency *f* of the voltage to its period *T* by

$$T = \frac{1}{f} \qquad 3.9$$

Where *T* is in seconds.

For this simple resistance circuit, $I = \frac{V}{R}$, and so the AC current is

$$I = I_0 \sin 2\pi f t \qquad 3.10$$

where *I* is the current at time t, and $I_0 = \frac{V_0}{R}$ is the peak current.

Rotating source is not only source of AC voltages; electronic devices for generating AC voltages are very common. Alternating voltages produce alternating currents. An alternating current produced by a typical generator has graph much like that for the voltage shown in Fig. 3.8. Its instantaneous value is i and its amplitude is i_0. Often the current and voltage do not reach a maximum at the same time even though they both have the same frequency.

The generator determines the frequency of the current in any circuit connected to the generator. Because the output voltage of an ac generator varies sinusoidally with time, the voltage is positive during one half of the cycle and negative during the other half. Likewise, the current in any circuit driven by an ac generator is an alternating current that also varies sinusoidally with time. Commercial electric power plants in the United States use a frequency of 60 Hz, which corresponds to an angular frequency of 377 rad/s. The primary aim of this chapter can be summarized as follows: If an ac generator is connected to a series circuit containing resistors, inductors, and capacitors,

To simplify our analysis of circuits containing two or more elements, we use graphical constructions called *phasor diagrams.* In these constructions, alternating (sinusoidal) quantities, such as current and voltage, are represented by rotating vectors called phasors. The length of the phasor represents the amplitude (maximum value) of the quantity, and the projection of the phasor onto the vertical axis represents the instantaneous value of the quantity.

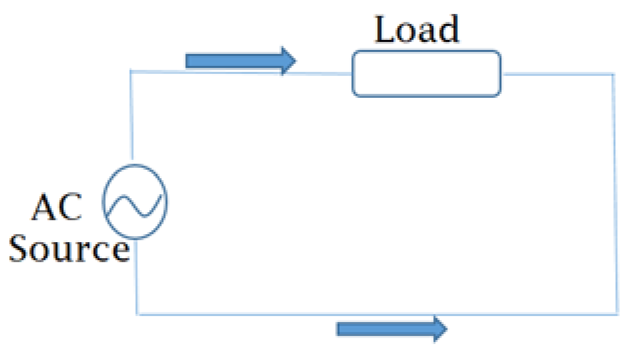


Figure 3.7 AC Current alternating at Intervals

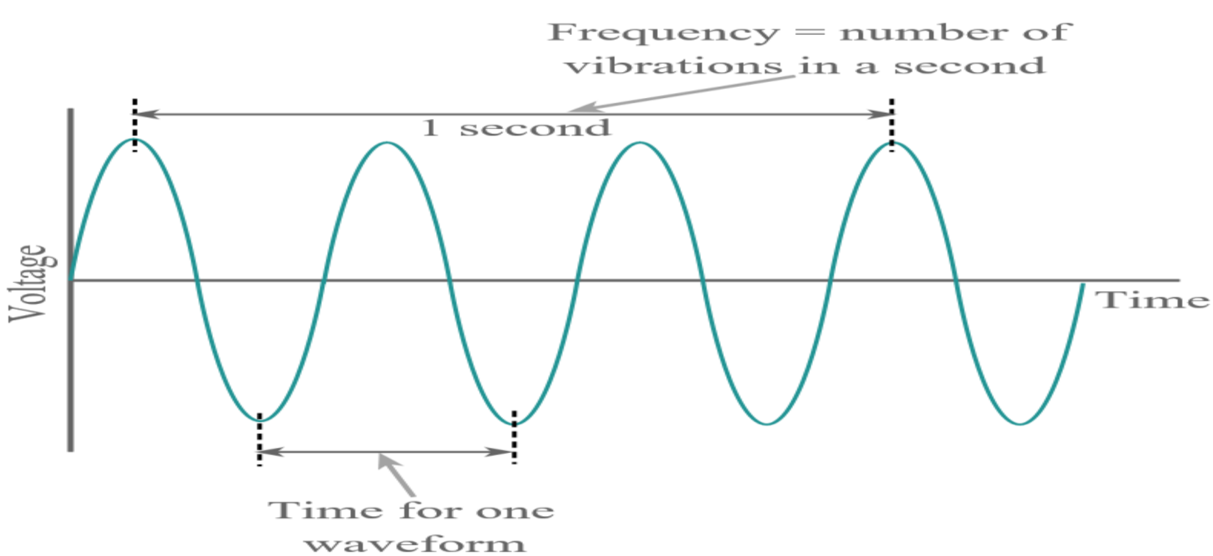


Figure 3.8

Current in the resistor alternates back and forth just like the driving voltage, since $I = \frac{V}{R}$. If the resistor is a fluorescent light bulb, for example, it brightens and dims 120 times per second as the current repeatedly goes through zero. A 120-Hz flicker is too rapid for your eyes to detect, but if you wave your hand back and forth between your face and a fluorescent light, you will see a stroboscopic effect evidencing AC. The fact that the light output fluctuates means that the power is fluctuating. The power supplied is $P=IV$. Using the expressions for I and V above, we see that the time dependence of power is $P = I_0 V_0 \sin^2 2\pi ft$, as shown in Figure 3.9

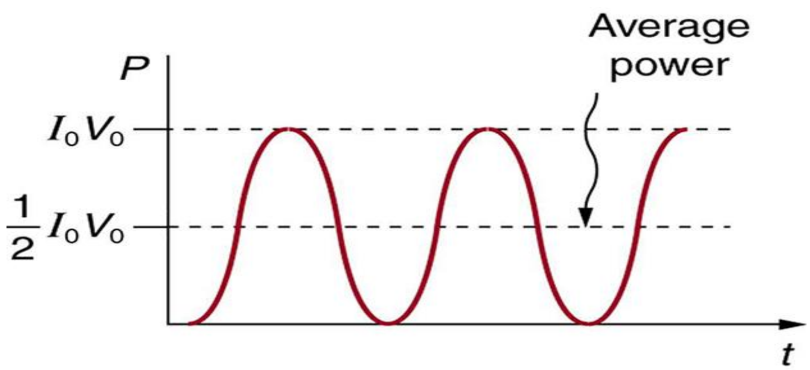


Figure 3.9 AC power as a function of time

Note read more on:

- Effective value or root mean square value of an AC.
- Alternating currents in resistors, capacitors and inductors
- The inductive reactance
- RLC circuit