AIR PUBLICATION 1093
Issued May, 1937

CHAPTER I.—ELECTRICITY

MATTER

1. Before commencing the study of electromagnetic phenomena, it is necessary to acquire at least a rudimentary knowledge of the constitution of matter.

Matter may be defined as anything which occupies space and is acted upon by gravitational forces. The amount of matter contained in a body is called its mass, and the amount of matter in unit volume the density, so that the density of a homogeneous body, that is, one which is of the same nature throughout, is its mass divided by its volume. There are three states in which matter may exist—solid, liquid and gaseous. A solid is a body which tends to retain its shape, that is, it will support a stress (or force) tending to shear it. Liquids and gases are both classed as fluids. A liquid takes the shape of the vessel which holds it, and unless acted upon by other than gravitational forces, tends to maintain a level surface, while a gas takes the shape, and occupies the whole volume, of its containing vessel.

2. With a few exceptions, any substance may exist in either of the three states, according to the temperature and pressure to which it is subjected. Thus at normal atmospheric pressure water is a liquid between temperatures of 0° C. and 100° C. It becomes a solid (ice), at temperatures below 0° C., and a gas (steam), at temperatures above 100° C. These temperatures are called the " melting point of ice " and the " boiling point of water " respectively. An increase of pressure lowers the melting point and raises the boiling point.

Molecules

3. (i) If a homogeneous body is divided into two portions, each of these has chemical and physical properties similar to those possessed by the original substance, for example, the density is unaltered. It is not possible, however, to proceed with such sub-division indefinitely, a stage being ultimately reached at which further sub-division completely changes the properties of the substance. The smallest particle into which a given material will divide, while retaining the properties of that particular material, is called its molecule. Further sub-division of the molecule is possible, but its constituents do not exhibit the same properties as the original material.

(ii) In all states of matter, the molecules are in continuous rapid motion, that is, they possess kinetic energy. In a solid, the molecules are crowded closely together, so that, although the motion is rapid, it consists of an oscillation about a mean position. The closeness of their packing results in large attractive forces between the molecules, the phenomenon being known as cohesion, and it is this cohesion which gives the solid its rigidity and enables it to withstand shearing stress. In a liquid the molecules are less closely packed, and cohesion between molecules is insufficient to prevent their movement from point to point in the material, while in a gas, there is little or no cohesive force, and consequently the molecules are free to move in all directions. The gas therefore expands and fills the whole volume of the containing vessel, the amplitude and velocity of the molecular movement depending upon the temperature of the body. The absolute zero of temperature is that at which all the molecules would be at rest, or possess no kinetic energy. The higher the temperature, the greater are the amplitude and velocity of the molecular movement, so that in solids and liquids, an increase of temperature results in an increase of linear dimensions. In the case of an enclosed gas, however, the dimensions are fixed by the containing vessel, and an increase of temperature is accompanied by an increase of pressure upon the walls of the container.

Atoms

4. Molecules are capable of sub-division, but the resulting particles are no longer molecules. They are called atoms, and have properties different from the molecules of which they formed a part, except in certain substances of which the molecule consists of only one atom. An atom is the smallest portion of matter which can enter into chemical combination, or which is obtainable by chemical separation.

Elements and Compounds

5. The term element is used to denote a substance whose molecule is composed entirely of the same kind of atom, e.g. the molecule of hydrogen consists entirely of hydrogen atoms. Hydrogen is therefore an element. The complete series of elements which enter into the constitution of the universe is believed to number ninety-two, but a few of these have yet to be discovered or isolated. This belief is based upon the regularity of grouping of the known elements, and the existence of a few gaps in the regular series obtained by arranging elements in order according to the number of protons contained in the nucleus. Each element is allotted a chemical symbol, e.g. hydrogen H, oxygen O, etc. Molecules formed from atoms of different kinds are called chemical compounds, thus two atoms of hydrogen (H_2) combine with one atom of oxygen (O) to form water (H_2O). The result of such a chemical reaction is frequently exhibited in the form of a chemical equation as follows :—

$$H_2 + O = H_2O$$

Again, one atom of sodium (Na) combines with one atom of Chlorine (Cl) to form common salt or sodium chloride (Na Cl).

Atoms were for a long time thought to be absolutely indivisible—the bricks from which the whole universe was constructed. Modern research, however, has shewn that, small as an atom is, it consists of infinitely smaller particles called electrons and protons, which are so widely separated that the bulk of the atom is mainly made up of empty space.

Electrons

6. (i) An electron is an elementary particle of negative electricity. The word " is " has been used in an endeavour to emphasise that the electron has no existence whatever apart from the charge of electricity with which it is identified. This charge is generally denoted by " *e* ", and is extremely small compared with the practical unit of quantity of electricity. An electron possesses none of the ordinary properties of matter, and all electrons have identical properties irrespective of the kind of matter from which they have been derived, or with which they are associated. They have been measured and weighed by ingenious and often laborious methods, so that the radius of the electron is known to be of the order of 10^{-13} cm., and its mass 9×10^{-28} gram ; this is $\frac{1}{1850}$th of the mass of the lightest known atom, that of hydrogen. The radius of a hydrogen atom is of the order of 10^{-8} cm., about 100,000 times that of the electron. An idea of the relative magnitudes of the electron and the atom may be gained by considering a hydrogen atom magnified to the size of an ocean liner. The electron contained in it would then approximate in dimensions to the head of a pin.

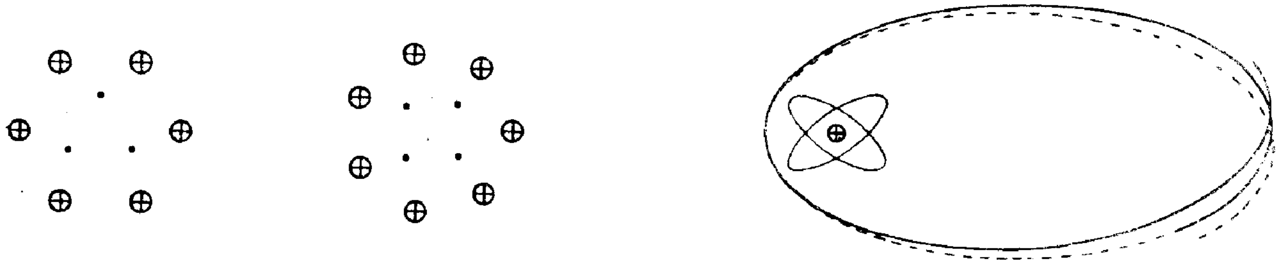
(ii) Owing to their electric charge, all electrons exercise upon each other a repulsive force, which is enormous compared with their size. If two electrons were placed 1 cm. apart, the force exerted between them would be, in round figures, $\frac{1}{2{\cdot}5 \times 10^{24}}$ of a pound. In case this may seem utterly insignificant, let us suppose that by some means it is possible to compress a large number of electrons into a sphere weighing one gram, or roughly $\frac{1}{450}$ of a pound. Two such spheres, placed 1 centimetre apart would repel each other with a force amounting to many millions of tons.

Protons

7. A proton is an elementary particle of positive electricity, and carries a charge equal to that of one electron. The force exerted between a proton and an electron is one of attraction, while two protons or two electrons mutually repel each other, giving rise to the first Law of Electrostatics, which may be stated in this way :—" Like charges repel and unlike charges attract each other." The mass of a proton is very much greater than that of an electron, being $1{\cdot}63 \times 10^{-24}$ gram. To all intents and purposes, therefore, the mass of an atom is entirely due to that of its protons, the contribution of the electrons being absolutely negligible.

8. It is now generally accepted as a working hypothesis in electrical theory that every atom consists of a central core, or nucleus, about which one or more electrons rotate in regular orbits. The nucleus invariably contains one or more protons, together with a number of electrons, the nucleus as a whole possessing a positive charge, that is, it always contains fewer electrons than protons. In a normal atom, this positive nuclear charge is neutralised by the outer or rotating electrons. The atom thus resembles a miniature solar system, having for a sun the central nucleus, and the orbitary electrons as planets. This analogy is somewhat faulty, however, inasmuch as in the atom, the orbits of the planetary electrons are not co-planar, as is the case in our solar system. The planetary electrons are, in ordinary circumstances, retained in their orbits by the central attraction of the positively charged nucleus.

9. It has already been stated that there are believed to be ninety-two different kinds of atoms, or different elements. These atoms differ only in the number of their constituent protons and electrons. The hydrogen atom is the lightest known, having one proton only in its nucleus, and one planetary electron. The helium atom possesses four times the mass of the hydrogen atom, and is known to possess two planetary electrons. Its nucleus must therefore consist of four protons and two electrons, the latter being bound within the nucleus in some manner not yet understood. Lithium is an example of a substance having two kinds of atoms, one having six protons in the nucleus, and the other seven, so that the construction of each kind is as shewn diagrammatically in fig. 1. On the left, the constituents of the two kinds of nuclei are shewn, protons being denoted by circles carrying a cross or positive sign, and electrons by dots. The three planetary electrons necessary to render the atom electrically neutral are believed to occupy three orbits, the two inner being circular and the outer elliptical in shape. The latter orbit may precess about the nucleus as shewn by the dotted continuation of the orbit. It must be emphasised that both kinds of lithium atoms, when entering into chemical reactions, behave identically, because both have three planetary electrons. Substances which have two forms, with different nuclear construction but the same number of planetary electrons, are called isotopic materials, each kind being called an isotope of that particular substance.



Constituents of nucleus

Orbits of planetary electrons

FIG. 1, CHAP. I.—Lithium atom.

10. From the foregoing explanation it is seen that the masses of the different kinds of atoms should increase in direct proportion to the number of protons in the nucleus, and this is found to be the case. Thus the helium atom is four times as heavy as a hydrogen atom. Some lithium atoms are six and some seven times as heavy, and so on. The atomic weight of a substance is the ratio of the mass of its atom to that of the hydrogen atom. Modern research has also revealed that under certain conditions two other elementary particles may exist, namely the positive electron or positron, having a mass equal to that of the negative electron, but carrying opposite charge, and the neutron, which has a mass equal to that of a proton but is devoid of all electrical properties. Little is known about these particles owing to the rarity of their appearance, but it appears to be firmly established that they rarely if ever enter into electrical processes, and for this reason it is unnecessary to consider their properties in connection with electrical theory.

Electrification

11. In certain circumstances, one or more of the planetary electrons can be detached from an atom, and is then called a free electron. Sooner or later, a free electron generally attaches itself to another atom, possibly displacing another electron in the process, which then in turn becomes free. The atom from which the electron is dislodged does not change its nature, which, as we have seen, depends essentially upon the construction of its nucleus. Atoms which have lost an electron by any means are called positive ions, and those which have gained more than their normal complement are called negative ions. The process by which atoms are caused to acquire either a surplus or deficit of electrons is called ionisation. Energy must be expended on the atom in order to detach an electron from it. If a glass rod is rubbed with a piece of silk (both being carefully dried before the experiment) it will be found that both the glass and the silk possess the property of attracting light bodies, such as dry bran or pith. The rod and silk are said to be electrified or charged, the glass positively, and the silk negatively. Actually, the glass rod has parted with some of the electrons from its superficial atoms, and these have been acquired by the silk. The results of this experiment may be summarised by stating that a positive charge is caused by a deficit of electrons in the constituent molecules of a body, and a negative charge by a surplus of electrons. Also, whenever a positive charge exists at any point, there is an equal negative charge elsewhere. That branch of the subject dealing with the phenomena associated with charged bodies is called electrostatics, the study of which will be resumed after a consideration of the action of electrons in motion.

ELECTRIC CURRENT, E.M.F. AND P.D.

12. An electric current may be defined as any movement of electrons, other than in their normal orbits within the atoms. Electric currents may be divided into three classes, depending upon the atomic or molecular mechanism by which the electronic movement takes place. They are

(i) Conduction currents.
(ii) Convection currents.
(iii) Displacement currents.

Conduction Currents

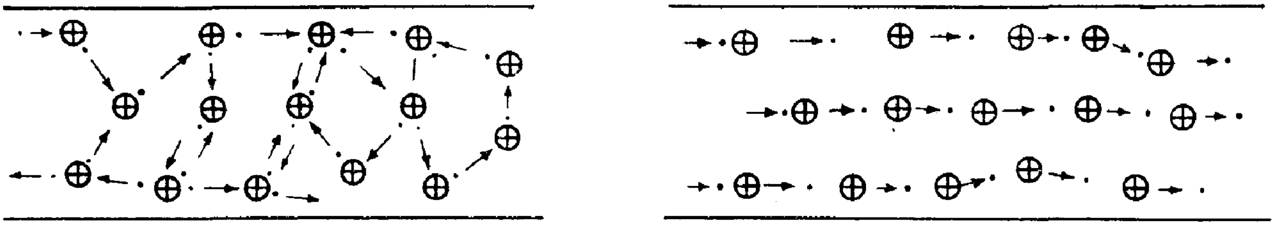
13. (i) A conductor of electricity is a substance in which spontaneous ionisation takes place. Such substances usually have a large number of planetary electrons—copper, for instance, has twenty-nine—and the electrons in the outer orbits, while being attracted by their own nucleus, are also under the influence of adjacent nuclei to almost the same extent. It is therefore natural to suppose that these outer electrons are attached to one particular nucleus only by comparatively feeble bonds, and as an atom vibrates, one of its outer electrons is frequently more strongly attracted by a neighbouring nucleus than by the one about which it is nominally rotating. This electron migrates to the adjacent atom, which then momentarily possesses a surplus electron. This state of the atom, however, is unstable, and in a very short space of time one of the surplus electrons is ejected, not necessarily the intruder.

(ii) A constant transference of electrons from atom to atom is thus taking place, and at any given instant a great many free electrons are in transit from one atom to another. This migration of electrons is quite irregular, and if it were possible to count the electrons passing through any given plane in the conductor over a period of time, it would be found that just as many passed in one direction as in the opposite, so that there is no average flow in any particular direction. In certain circumstances, however, such an average flow along the conductor can be established. The flow then constitutes a conduction current. Fig. 2 is an attempt to describe an electron current pictorially, and in this figure, the direction in which each electron is moving is indicated by a small arrow.

(iii) It cannot be too strongly emphasised that, in a material carrying a conduction current, only the electrons have an average movement in one direction. The nuclei of the atoms maintain their mean relative positions with reference to each other, forming a kind of lattice, or ladder, through which the electrons move, dislodging others as they pause momentarily at each atom. The actual velocity of the electrons along the conductor is very small, probably of the order of 1 centimetre per second. Pure metals are good conductors, silver being the best, and copper ranking second. Alloys, such as brass, are inferior to the pure metals in conducting property, but are still classed as good conductors.

Convection Currents

14. (i) An electrolyte is a conductor in which both positive and negative ions are free to move, and is therefore usually a liquid. Electrolytes consist of chemical compounds in solution, and in practice the term electrolyte is generally given to a solution of such a compound in water. As a concrete example, consider an aqueous solution of common salt (Na Cl). The sodium atom (Na) has eleven planetary electrons arranged in three rings, the outer ring containing only one electron, while the chlorine atom (Cl) has seventeen electrons in three rings, the outer ring containing seven electrons. Now the latter arrangement is known to be somewhat unstable chemically, and a chlorine atom tends always to acquire an eighth electron on the outer orbit. When Na and Cl atoms are brought into chemical combination the sodium atom gives up its outer electron to the chlorine atom, the former becoming a positive, and the latter a negative ion, the molecule NaCl as a whole remaining electrically neutral. In the solid salt, the atoms thus united are held together by the electrical attraction between the ions. On entering into solution, however, this bond appears to be weakened, and the ions wander about between the water molecules. The name " ion " was given to these charged particles on this account, ion being the Greek word for wanderer.



No current flowing Current flowing

FIG. 2, CHAP. I.—Conduction current.

(ii) Recombination continually occurs between the sodium and chlorine atoms, but at any given moment there are always very large numbers of free ions, an equal number of each kind being of course always in existence. If a large positive charge were introduced into one end of the vessel containing the electrolyte, and an equal negative charge into the other, a momentary electric current would be established in the electrolyte. This current would consist of negatively charged chlorine atoms moving towards the positive charge, and positively charged sodium atoms moving towards the negative charge. It is called a convection current, because it is carried by actual particles of matter, and not by electrons alone. Under certain conditions convection currents also take place in gases. The " anode current " of a thermionic valve is generally regarded as an example, although in this case free electrons play the greater part in the conduction. Nevertheless, even in the best attainable vacuum, ionised gas molecules must be present to some extent and so the term convection current is justifiable.

Displacement currents

15. In some materials, the electrons appear to be very firmly bound to their positive nuclei. Spontaneous ionisation does not occur in such substances except in a very minor degree, and they are therefore poor conductors of electricity. If ionisation never occurred at all, the substance would be an absolute non-conductor or perfect insulant. No such substance is known, and consequently there is no material which possesses perfect insulating properties. Dry air is probably the best insulant, while glass, ebonite, india-rubber, sulphur and oil are all used as

insulators, that is, to isolate a charged body or to confine an electric current to a given conductor. Although in a good insulant the number of free electrons is negligibly small, the electrons attached to atoms are acted upon by the proximity of electric charges. Let us suppose it is possible to hold a single atom of sulphur (which is an insulating material) rigidly by its nucleus, while bringing near to it a positive charge. The electrons will be attracted by the charge, and will attempt to unite with it, resulting in a displacement of the orbit of each electron, e.g. it may become elliptical and eccentric instead of circular and concentric with the nucleus. (Fig. 3.) The same effect occurs if instead of a single atom we have a body composed of insulating material. The proximity of an electric charge causes the electrons to be strained from their normal orbits, towards a positive or away from a negative charge. During the very small space of time in which this motion is taking place, it constitutes a displacement current.

Insulator in unstrained condition

Insulator in state of electric strain

FIG. 3, CHAP. I.—Displacement current.

Constant and varying currents

16. In addition to the classification of currents according to the physical conditions under which the electronic or ionic movements take place—conduction, convection or displacement—currents are also divided into different kinds according to their variation with time. They are as follows :—

(i) *Direct current* (or D.C.).—An electric current flowing in one direction only and sensibly free from pulsation.

(ii) *Pulsating current.*—An electric current which undergoes regular recurring variations in magnitude. Both these types are referred to as unidirectional currents.

(iii) *Alternating current* (or A.C.).—An electric current which alternately reverses its direction in a circuit in a periodic manner, the frequency being independent of the constants of the circuit.

(iv) *Oscillating (or oscillatory) current.*—An electric current which alternately reverses its direction in a circuit in a periodic manner, the frequency being dependent solely on the constants of the system.

Direct currents are produced by chemical means, or by dynamo-electric machinery fitted with commutating devices or rectifying systems, while pulsating currents are found, to give only one example, in the anode circuits of thermionic valves. There is usually a slight pulsation in direct currents which are produced by rotating machinery. A pulsating current can be considered as the sum of a direct current and a series of alternating currents of different frequencies. The magnitude of an electric current of any form may be measured by means of some form of amperemeter, more shortly and commonly called an ammeter. Various types of ammeter are described in Chapter III.

Production of E.M.F.

17. If in an electrical circuit, energy of any other kind is converted into electrical energy, an electromotive force or E.M.F., is said to exist in that circuit. There are four ways of producing an E.M.F.

(i) *Chemical*, by the immersion of two dissimilar conducting substances in an electrolyte, chemical energy being transformed into electrical energy. The production of E.M.F. by this method will be dealt with in the section on primary cells.

(ii) *Thermo-electric*, by the heating of the junction between two dissimilar metals, heat energy being transformed into electrical energy. This principle is used in the service in the construction of some types of thermal ammeters which are dealt with in Chapter III.

(iii) *Frictional*, by using mechanical energy to cause friction, for example by rubbing an insulated metal cylinder with a metallic rubber, which may consist of leather coated with an amalgam of zinc and mercury. This method is of no importance as a practical method of producing an E.M.F.

It is probable that all the above methods are manifestations of one principle, i.e. that a small E.M.F. is developed whenever two dissimilar substances are in contact.

(iv) *Electromagnetic.*—The potential energy stored in a magnetic field may be combined with some kinetic energy, such as that of a moving conductor, in such a manner that some of the kinetic energy is transformed into electrical energy. This is the most practical method of obtaining electrical energy and is used in all dynamo-electric machinery.

Difference of potential

18. If between two points in an electrical circuit it is possible to convert electrical energy into any other form, a difference of potential is said to exist between the two points. The conception of difference of potential (or P.D.) is one of the most useful in practical electrical engineering. It is a matter of everyday observation that, under the action of gravitational forces, a body will fall from a high level to a lower one, losing potential energy in its passage, but acquiring kinetic energy. If the surface of the earth were perfectly smooth, without mountains or valleys, the body would possess no potential energy when lying at any point on the surface. In speaking of this aspect of gravitation, the word energy is often omitted, and the body is said to fall from a point of high potential to a point of lower potential. The word " potential " is thus synonymous with " level," and if two points are at different levels there is said to be a difference of potential between them.

Translating this notion into electrical terminology, the earth is regarded as having zero potential, and any point may then be described as " above earth potential " or " possessing positive potential with respect to earth," if the passage of a positive charge from that point to earth converts electrical energy into some other form. This can easily be visualised as the repulsion of a positive charge from the point of positive potential, resulting in mechanical movement of the charge. If the passage of a positive charge from the earth to a given point is accompanied by a conversion of electrical energy into some other form, the point is said to be below earth potential, or " possessing negative potential with respect to earth". Instruments designed for the measurement of P.D. are known as voltmeters ; several types are described in Chapter III. A hydraulic analogy of P.D. is shewn in fig. 4, in which the pump may be regarded as a device converting mechanical energy into hydraulic energy, while the difference of pressure between different points on the output pipe is shewn by the difference of water level in the stand pipes. In the corresponding electrical circuit the electric battery may be regarded as a device for converting chemical into electrical energy. A difference of electrical potential exists between any two points in the circuit, owing to the resistance of the latter to the flow of electric current, and this is shewn by the difference in reading of the voltmeters. If there is a break in the electric circuit no current can flow, and there is no P.D. between any two points in the wire. This corresponds to the pipe in the water circuit being stopped up, under which conditions no water can flow, and no difference of level exists between individual stand pipes. The hydraulic analogy will be found of great assistance later, when considering the action of an electrical condenser in a circuit containing a source of alternating E.M.F.

Direction of current

19. If conduction currents only had to be considered the most natural method of defining the direction of current would be that in which the free electrons moved. We have seen, however, that a convection current consists of ions flowing in both directions, and it must be borne in mind that the chemical effects of the electric current in electrolytes were almost the first electrical phenomena to be thoroughly investigated. In this early work it was assumed that the direction of current was that of the average flow of positive ions, and this convention is still used. Thus it is considered that an electric current flows from a point of high potential to a point of lower potential, in conformity with the gravitational analogy given in the preceding section. In a complete electric circuit the current is assumed to flow in the external circuit from the positive to the negative terminals of the source of E.M.F., but through the source of E.M.F. from negative to positive terminals. When for any reason it is necessary to refer specifically to the direction of movement of the electrons, the term " electron current " will be used.

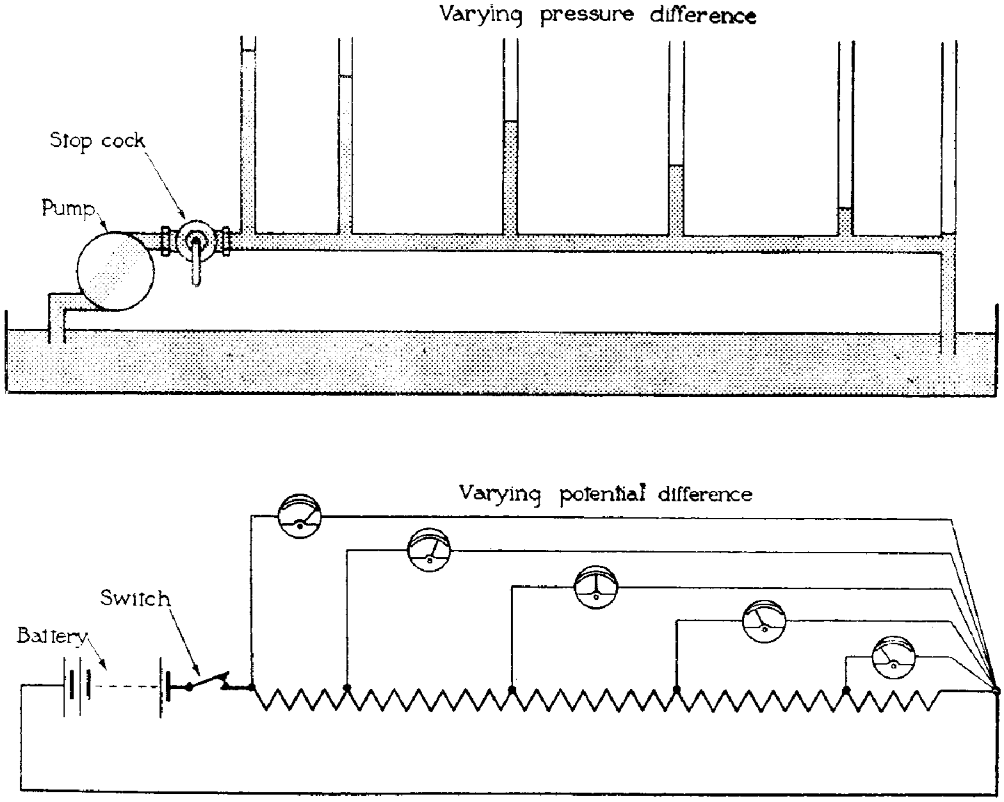


FIG. 4, CHAP. I.—Hydraulic analogue of P.D.

Effects of an electric current

20. When an electric current is flowing the following effects may be observed.

(i) *Heating effect.*—It has already been stated that every conversion of energy from one form to another necessitates the degradation of some portion into heat. In an electric conductor, the passage of a current results in the heating of the conductor and consequently, by radiation and convection, its immediate surroundings.

(ii) *Magnetic effect.*—The movement of an electron is always accompanied by the production of a magnetic field, and this effect is of the greatest importance in electrical work. The relation between electricity and magnetism is discussed more fully in succeeding chapters.

(iii) *Chemical effect.*—This has already been mentioned in connection with convection currents. If a current is passed through the solution of a metallic salt, pure metal is deposited upon one of the electrodes by which the current is led through the solution and gas is evolved at the other. This process is known as electrolysis.

Either of the above effects can be used to measure the rate of flow of electricity, that is, the magnitude of an electric current. The first two are commonly employed in indicating instruments, i.e. those provided with a pointer and scale graduated in units of current.

Practical electrical units

21. The deposition of metals by electrolysis lends itself admirably to the standardisation of "quantity of electricity". The practical standard of quantity is the coulomb, which is equal to $6{\cdot}29 \times 10^{18}$ electrons. This unit was established before the actual charge of an electron was discovered. In an electrolyte consisting of a 10 per cent aqueous solution of nitrate of silver, the passage of one coulomb invariably deposits ·0011800 gram of silver at one electrode, which is called the cathode. Now mass is a physical quantity which can be determined with very great accuracy, and the coulomb can be standardised with equal precision. The practical unit of current is a rate of flow of one coulomb of electricity per second. This unit is called the ampere. The international ampere is defined as the unvarying electric current which, when passing through a 10 per cent solution of nitrate of silver in water, deposits silver at a rate of ·0011800 gram per second.

The word "unvarying" is important. If the current is perfectly steady, the relationship between the ampere and the coulomb can be written algebraically

$$Q = I \times t$$

where Q = quantity of electricity in coulombs.
I = current in amperes.
t = time during which current flows.

22. The practical unit of E.M.F. is the volt. The E.M.F. in a circuit is one volt if the amount of energy converted into the electrical form is one joule per coulomb of electricity passing. The symbol for E.M.F. is E. The relation between the energy converted W, the E.M.F. E and the quantity Q can be expressed by the equation

$$E = \frac{W}{Q}$$

The idea of energy conversion also enters into the conception of potential difference, and the volt is therefore also used as the practical unit of P.D.

If between two points in a circuit, one joule of electrical energy is converted into some other form, for each coulomb which passes from one point to the other, then the P.D. between them is one volt, i.e.

$$V = \frac{W}{Q}$$

The units of E.M.F. and P.D. having been derived, it will be observed that although we speak of electromotive force, the latter is not analogous to force in mechanics, and therefore the pump in fig. 4 is not described as "forcing water round the circuit", but as "converting mechanical into hydraulic energy". Nevertheless, the number of quarts of water moved corresponds to the quantity of electricity, and a flow of I quarts per second to a current of I coulombs per second or I amperes.

Production of E.M.F. by chemical action

23. The existence of an electric current in a circuit signifies that energy in some other form is being converted into electrical energy. When chemical reactions take place energy is liberated—a most impressive example being furnished by the explosion which accompanies chemical action between the constituents of nitro-glycerine. One device by which chemical energy can be partly transformed into electrical energy is known as a primary cell.

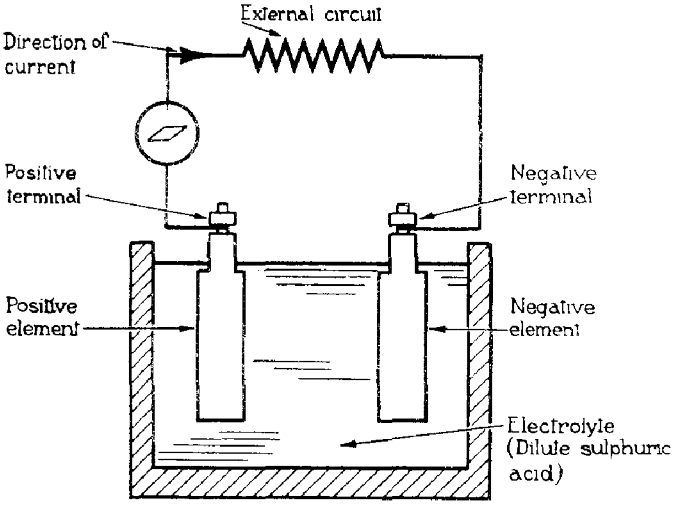


FIG. 5, CHAP. I.—Simple cell.

The simple primary cell consists of two plates, of zinc and copper respectively, immersed in a suitable electrolyte, e.g. dilute sulphuric acid. If these plates are connected externally by a conducting wire, a complete electric circuit is formed and an electric current will be established. This current is due to the electromotive force of the cell, and is accompanied by the liberation of hydrogen at the copper plate. This effect is known as polarisation. It is an undesirable phenomenon, inasmuch as it increases the resistance of the circuit, and also reduces the E.M.F. obtainable. Polarisation can be much reduced, but not entirely prevented, by supplying oxygen to the copper plate in such a way that it may combine with the hydrogen to form water. The copper plate, with the terminal attached thereto, is known as the positive element of the cell, and the zinc plate, together with its terminal, as the negative element.

24. The electrolyte used in a primary cell is not necessarily dilute sulphuric acid. Cells of the leclanche type make use of a solution of sal-ammoniac (ammonium chloride, NH_4Cl), the positive element being a carbon rod, and the negative element a zinc plate or rod. Possibly the simplest form of cell using a depolarising agent is the air depolariser cell. In this type, the positive element is in the form of a massive, thick-walled cylinder of porous carbon, while the electrolyte is a sal-ammoniac solution. The hydrogen liberated at the carbon electrode combines with oxygen occluded in the pores of the carbon, forming water. The oxygen so used is replaced by a supply from the air outside the cell by atmospheric pressure. This type of cell is not suitable for heavy currents, but it has been used in the service for intermittent supply of about ·2 ampere for the filament current of a portable receiver.

The leclanche cell proper (fig. 6) makes use of the same chemical agents as the above, but in addition chemical depolarisation is resorted to, the depolariser being manganese dioxide, which is mixed with crushed carbon and packed round the positive element, the whole being contained in a porous pot of unglazed earthenware. Chemical action between the zinc and the electrolyte results in the formation of zinc chloride, ammonia gas, and hydrogen. The ammonia gas is given off at the zinc electrode, while the hydrogen passes to the positive element, where it is oxydised by association with the manganese dioxide, forming water. This depolarisation takes place very slowly, and the leclanche cell is only suitable for small currents or for intermittent use. The E.M.F. of a leclanche cell (or of an A.D. cell) is about 1·4 volt.

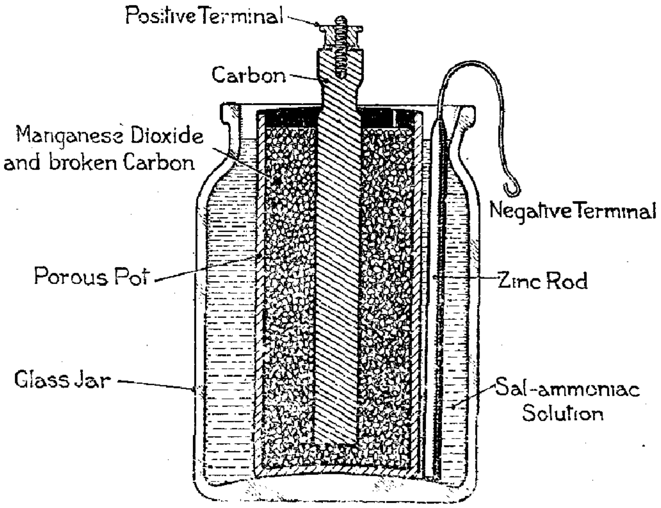


FIG. 6, CHAP. I.—Leclanche cell.

25. Dry cells are invariably of the leclanche type, but the electrolyte is in the form of a moist paste instead of a liquid solution. This paste tends to dry up with age even if the cell is unused. Batteries of dry or inert cells are used for H.T. and grid bias supplies to most service radio receivers. A typical construction is shown in fig. 7. Inert cells are leclanche type cells and are similar in construction to dry cells, but are supplied with the sal-ammoniac in crystal form, needing the addition of water before the electrolyte is formed. They are therefore quite inactive until prepared for use, and therefore compare favourably with dry cells as regards shelf life, i.e. their depreciation under conditions of storage.

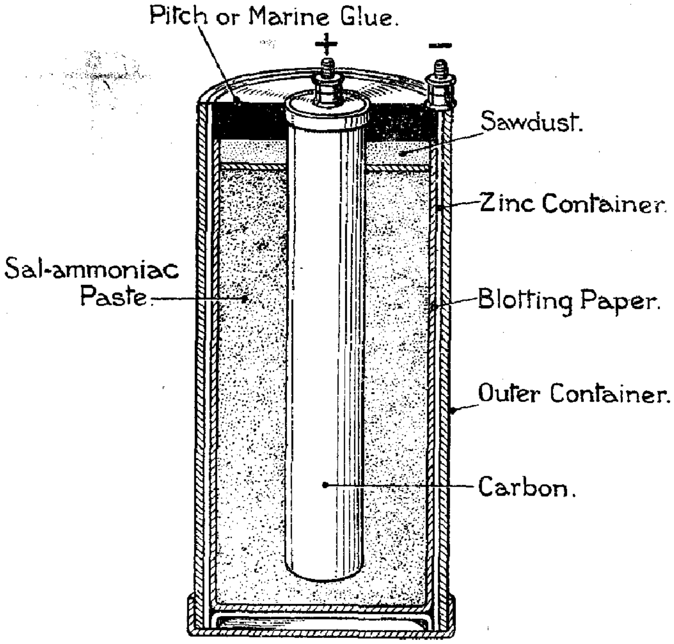


FIG. 7, CHAP. I.—Dry cell.

In a secondary cell, electrical energy is supplied and converted into chemical energy, and is available for re-conversion, into electrical energy when a suitable circuit is connected to the cell. An outline of the theory of this type of cell is contained in Air Publication 1095.

OHM'S LAW

26. Having standardised the units of current, E.M.F. and P.D., it is desirable to ascertain how these two quantities are related. To illustrate this relationship, let us take a definite conductor, say one mile of insulated electric lighting cable, and measure the current which flows when various values of E.M.F. are applied to its ends. It is assumed that the temperature of the conductor will remain constant throughout the experiment. The results may be exhibited in graphical form, the value of the current being plotted as ordinate against applied E.M.F. as abscissa, as in fig. 8. Such a graph is called the characteristic curve of the conductor, although

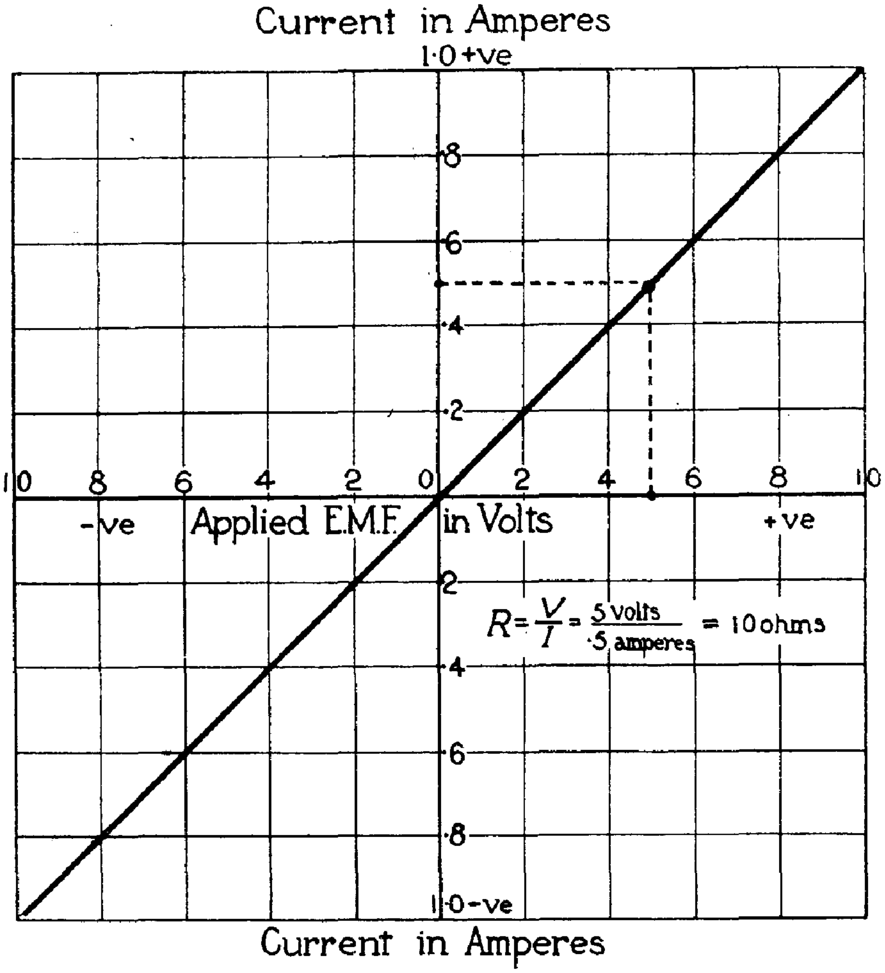


FIG. 8, CHAP. I.—Characteristic curve of conductor.

in point of fact it is a straight line through the origin of the graph. The significance of this straightness is that the current is directly proportional to the E.M.F. Expressed algebraically, $I \propto E$, or $I = G E$, G being a constant of proportion. Any conducting substance, or combination of conducting substances, which exhibits this linear relationship between current and voltage, is said to obey Ohm's law. Ohm's law is applicable either to a portion of the circuit where V is the P.D. between the two ends of that portion, or to a whole circuit. In the former case, the current is proportional to the terminal P.D., V, so that $I = G V$.

The constant G depends upon the material and dimensions of the conductor. It is known as its conductance, and is a measure of the number of free electrons (or of positive and negative ions) existing in the material. It is frequently more convenient to speak of the opposition of a conductor to the flow of an electric current, which is called its resistance, and is denoted by the symbol R. The conductance and the resistance stand in reciprocal relationship, so that $R = \frac{1}{G}$. The unit of resistance is the ohm, while the unit of conductance is the siemens ; an older name for the latter unit is the mho. We have seen that the coulomb, and therefore the ampere, is capable of very exact standardisation by measurement of mass and time. The ohm can also be established by measurements of length and mass, and the international ohm is defined as follows:—

The international ohm is the resistance at 0° C. of a column of mercury 106·300 cms. high and 1 sq. mm. in cross section, its mass being 14·4521 grams.

27. The volt, being based theoretically upon the capability of a charge to do work, does not lead itself to standardisation by direct measurement. It is therefore established by means of Ohm's law, from the standards of current and resistance. In order to do this it is convenient to state the law in the form $V = IR$, leading to a definition of the international volt :—

The international volt is the P.D. existing between the ends of a conductor whose resistance is one international ohm, when a current of one international ampere is flowing in the conductor.

Ohm's law can only be applied to steady currents, and even then does not hold for every possible kind of conducting material. The manner in which Ohm's law is modified when dealing with varying currents is dealt with in Chapter V. Conductors which do not obey Ohm's law even for steady currents are frequently called non-ohmic conductors. There are two important classes of these.

(i) Certain combinations of metallic oxides, metallic sulphides, and metals, in contact with each other, generally referred to as crystal rectifiers.

(ii) Ionised gases carrying convection currents.

These non-ohmic conductors have important properties which will be referred to in later chapters. In particular, the second class will be dealt with at some length in Chapter VIII. In future, whenever a conductor is referred to, it will be assumed to obey Ohm's law, unless the contrary is explicitly stated.

Resistance

28. The resistance of a conductor depends upon its material, its dimensions, and its temperature. The nature of the material determines the number of free electrons, while the temperature determines the amplitude of vibration of the molecules, and therefore the degree to which free electrons are attracted by neighbouring atoms. The longer the conductor, the more certain it is that any free electron will be recaptured by an atom, while the greater the area, the more free electrons will exist in any cross section at all times. These considerations indicate, and experiment proves, that the resistance R of a conductor to an unvarying current can be expressed by the equation

$$R = \frac{l\varrho}{A}$$

where l is the length of the conductor, A its cross-sectional area, and ϱ is a constant for any particular material. The resistance thus calculated is usually referred to as the " D.C. resistance ". It will be seen later that this formula must be modified if the current is varying rapidly.

Specific resistance

29. The constant ϱ is called the specific resistance of the material and may be defined either in British or metric units, depending upon the system used for the length l and cross-section A of the material. If l is in inches and A in square inches, the specific resistance is the resistance

of a sample of the material in the form of a cube each side of which is one inch in length. This standard size and shape is referred to as the "inch cube" (not the cubic inch which may have any shape whatever). If l and A are given in centimetres and square centimetres respectively the specific resistance is that of a similar sample in the form of a cube of 1 centimetre side. The resistance is measured between two opposite faces of the cube, and in either system it is convenient to refer to the specific resistance in microhms per unit cube rather than in ohms; it is also necessary to state the temperature at which the specific resistance was determined. The specific resistance of a number of common materials is given in Table I, Appendix A. The specific resistance of silver is lower than that of any other substance (1·557 microhms per centimetre cube at 15° C.) while annealed copper is a close second (1·66 microhms per centimetre cube at 15° C.).

In calculating the resistance of round wires it is convenient to state the specific resistance in ohms per mil-foot, that is the resistance of a wire one foot long and one mil (·001 inch) in diameter. The unit of area is then the circular mil, the area of a circle of diameter d mils being d^2 circular mils. This artifice avoids the introduction of the multiplier $\frac{\pi}{4}$ which would otherwise enter into the calculation of the area. To illustrate the use of the various methods the resistance of one mile of pure copper wire 0·1 inch in diameter and of uniform circular cross-section, may be calculated.

(i) Given $\varrho = 1{\cdot}66$ microhm per centimetre cube. Both length and area must be expressed in centimetre units.

$$\begin{aligned}
\text{Area} &= \frac{\pi d^2}{4}\ \text{in.}^2 \\
&= \frac{\pi d^2}{4}\ \text{in.}^2 \times \frac{(2{\cdot}54\ \text{centimetres})^2}{1\ \text{in.}^2} \\
&= \frac{\pi}{4} \times (0{\cdot}1)^2 \times 6{\cdot}45\ \text{cm}^2 \\
&= {\cdot}7854 \times {\cdot}0645 \\
&= {\cdot}05\ \text{cm}^2 \\
\text{length} &= 1\ \text{mile} \times \frac{5{,}280\ \text{feet}}{1\ \text{mile}} \times \frac{30{\cdot}5\ \text{cm}}{1\ \text{foot}} \\
&= 5{,}280 \times 30{\cdot}5\ \text{cms} \\
&= 161{,}200\ \text{centimetres} \\
R &= \frac{l\,\varrho}{A} \\
&= \frac{161{,}200}{{\cdot}05} \times \frac{1{\cdot}66}{10^6} \\
&= 5{\cdot}37\ \text{ohms}
\end{aligned}$$

(ii) Given

$$\begin{aligned}
\varrho &= {\cdot}654\ \text{microhms per inch cube} \\
\text{area} &= \frac{\pi d^2}{4} = {\cdot}7854 \times {\cdot}01\ \text{in.}^2 \\
\text{length} &= 5{,}280 \times 12\ \text{inches} \\
R &= \frac{5{,}280 \times 12 \times {\cdot}654}{{\cdot}7854 \times {\cdot}01 \times 10^6} \\
&= 5{\cdot}37\ \text{ohms}
\end{aligned}$$

(iii) Given

$$\begin{aligned}
\varrho &= 10{\cdot}18 \text{ ohms per mil-foot} \\
d &= 0{\cdot}1 \text{ inch} = 100 \text{ mils} \\
A = d^2 &= 10^4 \text{ circular mils} \\
l &= 5{,}280 \text{ feet} \\
R &= \frac{5{,}280 \times 10{\cdot}18}{10^4} \\
&= 5{\cdot}375 \text{ ohms}
\end{aligned}$$

Note the comparative simplicity of the third method.

Temperature coefficient

30. The effect of an increase of temperature is to increase the specific resistance of all pure metals. For all practical purposes the increase is directly proportional to the rise in temperature. If ϱ_1 is the specific resistance at temperature t_1 and ϱ_2 the specific resistance at temperature t_2

$$\varrho_2 = \varrho_1 \left\{1 + \alpha\,(t_2 - t_1)\right\}$$

$t_2 - t_1$ being the increase in temperature.

The constant α is called the temperature coefficient of the material and is given in Appendix A for a standard temperature of 15° C. = 59° F.

Example :—

If the conductor previously considered is heated by the passage of current to 30° C., what is its resistance ?

The specific resistance at 15° C. is $\varrho_1 = 1{\cdot}66$ microhms per cm. cube, and the temperature coefficient ·0041.

$$\begin{aligned}
\text{Temperature rise} &= 15^\circ \text{ C.} \\
\varrho_2 &= \varrho_1\,(1 + \alpha \times 15) \\
&= \varrho_1\,(1 + 0{\cdot}06) \\
\frac{\varrho_2}{\varrho_1} &= 1{\cdot}06 \\
\therefore R_2 &= 1{\cdot}06\,R_1 = 5{\cdot}7 \text{ ohms.}
\end{aligned}$$

The temperature coefficients of alloys are very much smaller than those of pure metals while certain substances, notably carbon, have negative coefficients, that is, the resistance decreases with temperature.

ELECTRIC CIRCUIT CALCULATIONS

Kirchoff's Laws

31. These important laws are simply extensions of the idea contained in Ohm's law, and are as follows :—

First law.—At any junction of resistance the sum of the currents flowing to the junction is equal to the sum of the currents flowing away from it. This may be more shortly expressed by the statement " at any point in a circuit, the algebraic sum of the currents in zero," or more briefly still by $\Sigma I = 0$.

Second law.—In any closed circuit, the algebraic sum of the E.M.F.'s is equal to the algebraic sum of the P.D.'s. As $V = IR$, this may be written $E = \Sigma IR$, where the symbol Σ means " the algebraic sum of all such quantities as . . . ."

Circuit diagrams

32. In making diagrams of connections in electrical engineering it is necessary to employ symbols to denote the various machines and devices used. The connecting wires are shown by

lines and the points where they make electrical contact with the machine may be indicated in the diagram. In selecting and devising these symbols stress has been laid on the following points :—

Each symbol should be, as far as possible :—

(i) Self explanatory.
(ii) Easy to draw.
(iii) In general use.
(iv) Exclusive to one particular machine or device.

These symbols will be introduced to the reader by the text, as and when found desirable.

Up to the present, we have only encountered two appliances which bear standard symbols, viz. chemical sources of E.M.F. and resistances, the appropriate symbols being embodied in fig. 4.

Conductors in series

33. Conductors are said to be in series when they are connected end to end, in such a manner that the same current flows through each. Each conductor must have resistance, and the circuit diagram of a number of resistive conductors in series with a primary battery is shewn in fig. 9. It must be remembered that the battery itself has resistance, although it is not customary to draw any separate symbol to shew this, but the resistance in ohms may be written beside the battery symbol. An expression for the total resistance of this circuit, containing resistances R_1, R_2, R_3, will now be derived. Since there is no accumulation of electricity at any point, the same current flows through each resistance in accordance with Kirchoff's first law. Let this total current be I amps. Then by Ohm's law, the E.M.F. in the circuit is given by

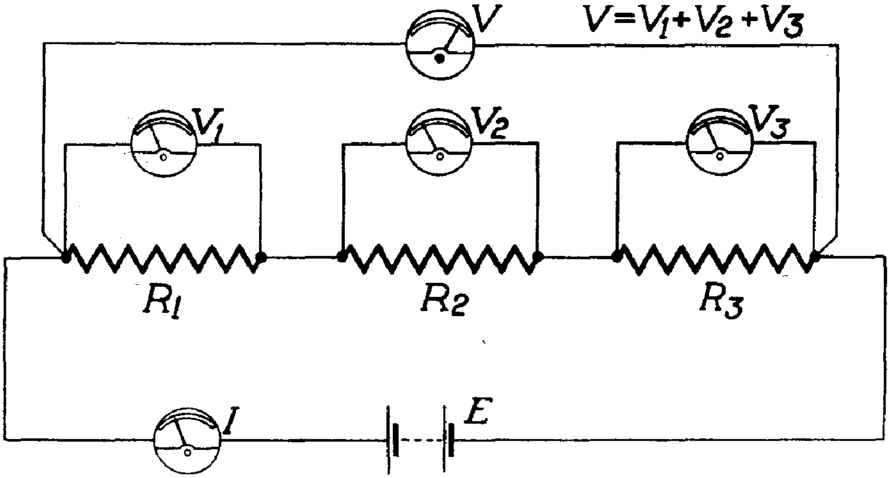


FIG. 9, CHAP. I.—Conductors in series.

$$E = IR \qquad (a)$$

where R is the total resistance.

Now consider the P.D.'s between different points in the circuit

$$\text{Across } R_1 \text{ the P.D. is } IR_1 = V_1$$
$$\text{Across } R_2 \text{ the P.D. is } IR_2 = V_2$$
$$\text{Across } R_3 \text{ the P.D. is } IR_3 = V_3$$

By Kirchoff's second law, $E = V_1 + V_2 + V_3$,

or $E = I\,(R_1 + R_2 + R_3) \qquad (b)$

Comparing expressions (a) and (b), it is seen that both can be true only if

$$R = R_1 + R_2 + R_3$$

Hence the " rule for resistance in series " :—

The total resistance of a number of conductors in series is equal to the sum of their individual resistances.

Conductors in parallel

34. Conductors are said to be in parallel when they have a common P.D. between their ends, as in the diagram, fig. 10. The current in each conductor will not be equal, unless the resistance of each conductor is the same.

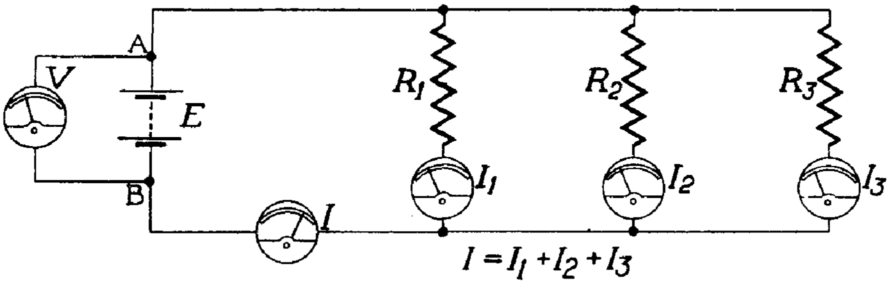


FIG. 10, CHAP. I.—Conductors in parallel.

Referring to the diagram, let the resistances of the three conductors be R_1, R_2, R_3, and the corresponding currents through them be I_1, I_2, I_3. By Kirchoff's first law, the current I, flowing to the point B is equal to $I_1 + I_2 + I_3$, and the latter also combine to form a current I flowing away from the point A.

That is $I = I_1 + I_2 + I_3$.

The P.D. (V) between the points A and B is equal to I_1R_1 or to I_2R_2 or to I_3R_3.

That is

$$I_1 = \frac{V}{R_1}$$

$$I_2 = \frac{V}{R_2}$$

$$I_3 = \frac{V}{R_3}.$$

$$I_1 + I_2 + I_3 = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$

$$I = V\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)$$

but by Ohm's law $I = \frac{V}{R}$

where R is the joint resistance of the three resistances in parallel.

$$\therefore \frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

and $$R = 1 \div \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)$$

Note that R is less than either R_1, R_2, or R_3 alone. The " rule for resistances in parallel " is :—The sum of the reciprocals of the individual resistances is equal to the reciprocal of the joint resistance.

Series parallel circuits

35. When a circuit consists of combinations of conductors in series and in parallel, the procedure is to first attack all parallel combinations, reducing each to a single equivalent resistance. The various equivalent resistances can then be treated as series resistances, as in the following example :—

In the circuit given in fig. 11 find

(i) the total resistance of the circuit,
(ii) the current given by the battery,
(iii) the P.D. at the terminals of the battery. N.B. this must not be confused with the E.M.F. of the battery which is 10 volts,
(iv) the current I_3, in the 3 ohm wire of branch A.

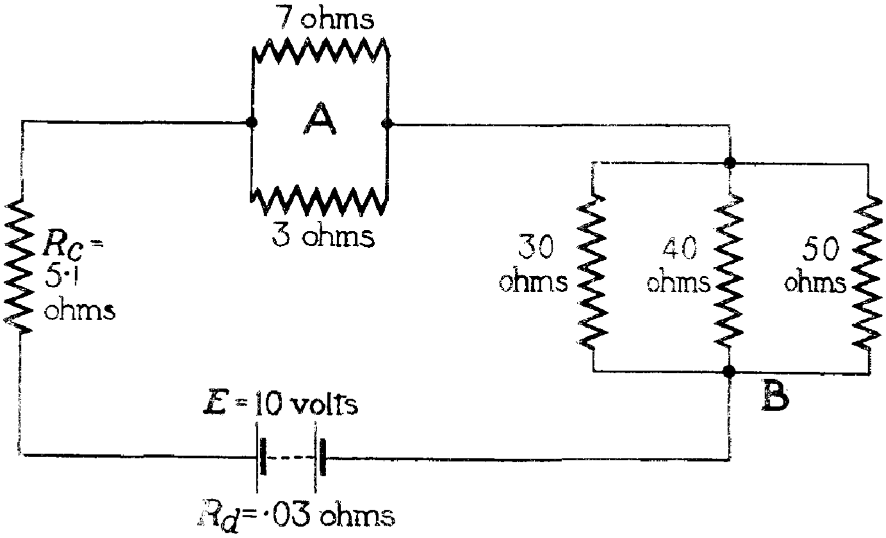


FIG. 11, CHAP. I.—Conductors in series and parallel.

(i) The method of attack is as follows. First resolve the parallel element A into an equivalent single resistance R_a.

$$\frac{1}{R_a} = \frac{1}{7} + \frac{1}{3} = \frac{3+7}{21} = \frac{10}{21}$$

$$R_a = 2\cdot 1 \text{ ohms.}$$

Next resolve the parallel element B in a similar manner.

$$\begin{aligned}\frac{1}{R_b} &= \frac{1}{30} + \frac{1}{40} + \frac{1}{50}\\ &= \frac{20 + 15 + 12}{600}\\ &= \frac{47}{600}\end{aligned}$$

$$R_b = \frac{600}{47} = 12\cdot 77 \text{ ohms}$$

The total resistance R is $R_a + R_b + R_c + R_d$

or $5\cdot 1 + 2\cdot 1 + 12\cdot 77 + \cdot 03 = 20$ ohms

(ii) The current given by the battery is $\frac{E}{R} = \frac{10}{20}$ or $0\cdot 5$ ampere.

(iii) The P.D. at the terminals of the battery is equal to the product of current and resistance in the external circuit, or $I \times (R_a + R_b + R_c)$. This is $0\cdot 5 \times 19\cdot 97$ or $9\cdot 985$ volts. In some examples it may be more convenient to find the terminal P.D. by remembering that it is equal to the E.M.F. minus the "IR drop" in the battery itself. The latter quantity is ·03 × 0·5 = ·015 and the terminal P.D. is 20 − ·015 = 9·985 volts.

(iv) The current in the 3-ohm wire may be found by either of two methods.

(*a*) Find the P.D. V_a between the ends of the loop A. This is IR_a, and $I = 0{\cdot}5$, $R_a = 2{\cdot}1$ ∴ $V_a = 1{\cdot}05$ volts.

The current in the 3-ohm wire is then $\frac{V_a}{3}$ or 0·35 ampere.

This may be checked by finding the current in the 7-ohm wire. This is $\frac{V_a}{7}$ or 0·15 ampere. The sum of these currents is 0·5 ampere, the total current flowing.

(*b*) The current in parallel paths divides in inverse ratio to the resistance of each path. In the parallel element A, the 3-ohm wire carries $\left(\frac{7}{3+7}\right)$ths and the 7-ohm wire $\left(\frac{3}{3+7}\right)$ths of the total current. Hence $I_3 = \frac{7}{10}$ of $0{\cdot}5 = {\cdot}35$ ampere as already calculated by method (*a*).

As a further example of the manner in which current divides between different parallel paths find the currents in each of the resistances forming the parallel element B, using the second method of calculation.

Let the 30 ohms resistance be R_1 and its current $I_1 = \frac{V_b}{R_1}$

Let the 40 ohms resistance be R_2 and its current $I_2 = \frac{V_b}{R_2}$

Let the 50 ohms resistance be R_3 and its current $I_3 = \frac{V_b}{R_3}$

the P.D. between the ends of the branch being V_b. The total current I is

$$\frac{V_b}{R_b} = V\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)$$

$$\frac{I_1}{I} = \frac{\frac{V_b}{R_1}}{V_b\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)} = \frac{\frac{1}{R_1}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

and therefore $I_1 = \dfrac{\frac{1}{R_1}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} \times I$

$$= \frac{\frac{1}{30}}{\frac{1}{30} + \frac{1}{40} + \frac{1}{50}} \times 0{\cdot}5$$

$$= \frac{\frac{20}{600}}{\frac{20 + 15 + 12}{600}} \times 0{\cdot}5$$

$$= \frac{20}{47} \times 0{\cdot}5$$

$$= \frac{10}{47} \text{ amperes.}$$

By the same reasoning $I_2 = \frac{15}{94}$ amperes and $I_3 = \frac{12}{94}$ amperes.

Networks

36. In some circumstances the solution of a problem is facilitated by the direct application of Kirchoff's laws. An example of this type of circuit is the distribution network shewn in fig. 12

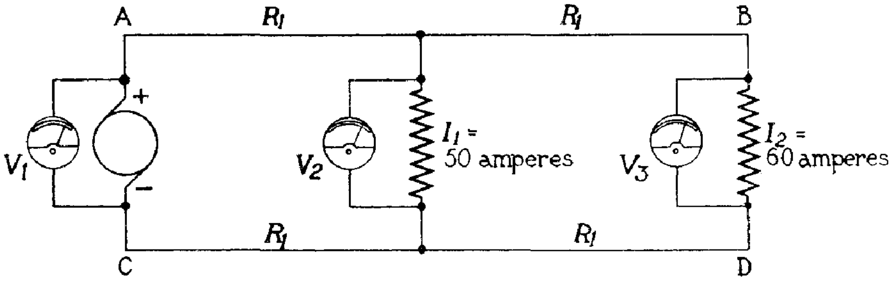


FIG. 12, CHAP. I.—Distribution network.

in which I_1 and I_2 represent two concentrated " loads " supplied from the power mains AB, CD. The P.D. at the terminals of the generator (V_1) being given it is often necessary to calculate the P.D. at the terminals of each load. The method of solving this problem is as follows.

$V_2 = V_1$ — (the " IR drop " in the leads between V_1 and V_2) $= V_1 - 2R_1 (I_1 + I_2)$.
As all the quantities on the right-hand side are known, V_2 can be determined.

As an example take $V_1 = 220$ volts, $I_1 = 50$ amperes $I_2 = 60$ amperes, $R_1 = \cdot 01$ ohm.

Then
$$\begin{aligned} V_2 &= 220 - \cdot 02 \times 110 \\ &= 220 - 2\cdot 2 \\ V_2 &= \underline{217\cdot 8 \text{ volts.}} \end{aligned}$$

Also
$$\begin{aligned} V_3 &= V_2 - 2R_1 I_2 \\ &= 217\cdot 8 - \cdot 02 \times 60 \\ &= 217\cdot 8 - 1\cdot 2 \\ &= \underline{216\cdot 6 \text{ volts.}} \end{aligned}$$

It will be noticed that the P.D. across the load farthest from the feeding point is 3·4 volts below the P.D. at the generator end of the line. If a second generator of the same terminal P.D. were connected to the points BD the IR drop in the leads would be reduced. The distribution of the current would then be as in fig. 13 in which the actual currents supplied by each generator

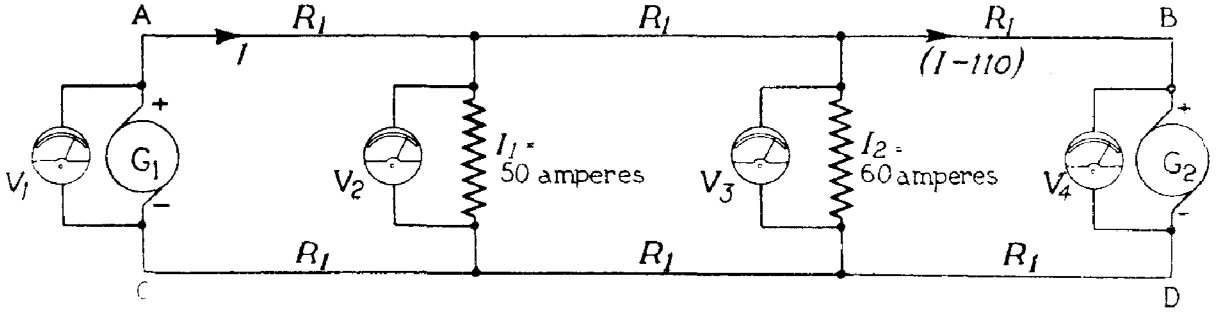


FIG. 13, CHAP. I.—Distribution network with two generators.

are unknown. It is assumed that a current I is flowing into the upper line from the terminal A, and a current (I — the total load current) is flowing out of the upper line into the generator G_2 at the terminal B. In the solution we shall find that the quantity (I—total load current) is a negative quantity, signifying that a current is actually flowing into the upper line from the generator G_2. The following equations can be set up from the data

$$V_2 = V_1 - 2R_1 I$$

$$V_3 = V_2 - 2R_1\,(I - 50)$$

$$V_4 = V_3 - 2R_1\,(I - 110)$$

i.e. $$V_4 = V_2 - 2R_1\,(I - 50) - 2R_1\,(I - 110)$$

or $$V_4 = V_1 - 2R_1\,I - 2R_1\,(I - 50) - 2R_1\,(I - 110).$$

$$V_4 = V_1 - 2R_1\,I - 2R_1\,I + 100R_1 - 2R_1\,I + 220R_1.$$

but $$V_4 = V_1$$

$$\therefore\ 0 = -\,3\,(2R_1\,I) + 320R_1.$$

$$6I = 320$$

$$I = \frac{320}{6} = 53\frac{1}{3}\ \text{amperes.}$$

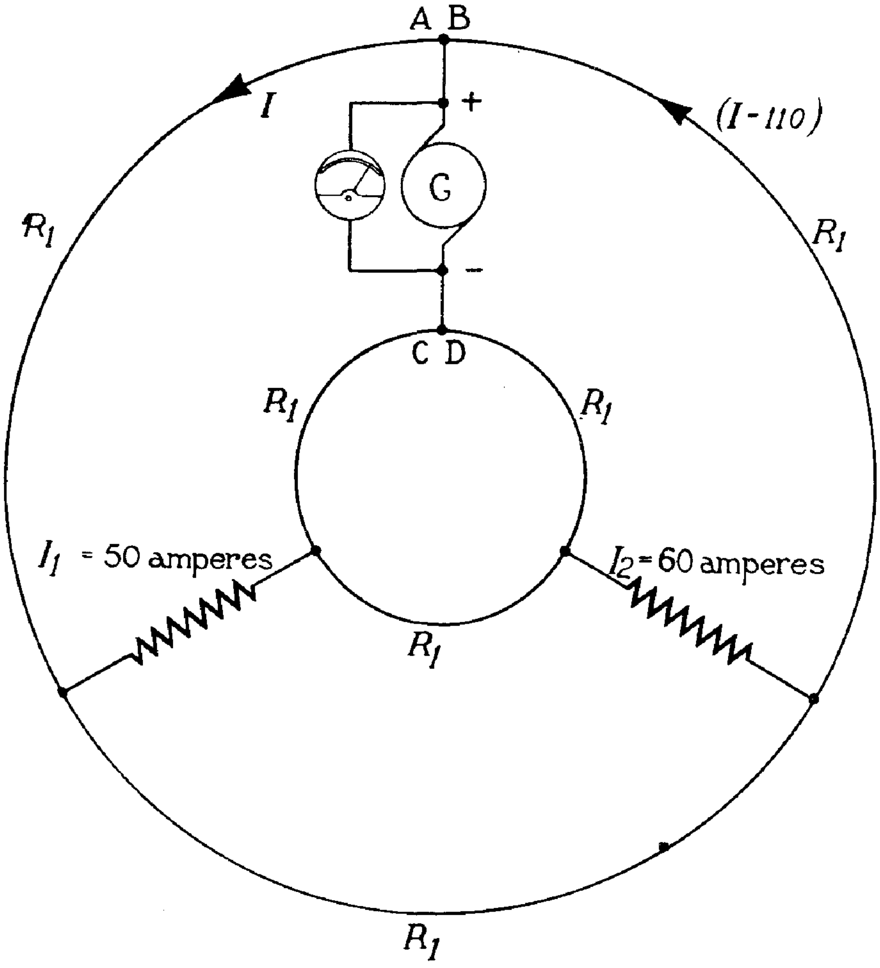


FIG. 14 CHAP. I.—Ring main system of distribution.

The current flowing into the generator G_2 at B is $(53\frac{1}{3} - 110) = -56\frac{2}{3}$ amperes, i.e. a current of $56\frac{2}{3}$ amperes flows into the upper line at this point.

The P.D's V_2 and V_3 can now be found, for

$$\begin{aligned} V_2 &= V_1 - 2R_1I \\ &= 220 - \cdot 02 \times 53\frac{1}{3} \\ &= 220 - \frac{3\cdot 2}{3} \\ &= 220 - 1\cdot 066 \\ &= \underline{218\cdot 933 \text{ volts.}} \end{aligned}$$

$$\begin{aligned} V_3 &= V_2 - 2R_1\,(I - 50) \\ &= 218\cdot 933 - \cdot 02 \times 3\frac{1}{3} \\ &= 218\cdot 933 - \cdot 066 \\ &= \underline{218\cdot 867 \text{ volts.}} \end{aligned}$$

It is seen from the above that by feeding from both ends of the line the P.D. across the load is maintained at a value more nearly at the generator terminals. This principle is applied in the ring main system in which each supply main is closed upon itself, so that the points A and B are coincident, as also are C and D. A single generator then feeds the network, current flowing in either direction round the ring according to the distribution of the load (fig. 14).

Maxwell's rule

37. This is an application of Kirchoff's laws, which is often of considerable assistance in solving network problems. Consider the circuit in fig. 15 in which it is required to find the P.D. at the terminals of the resistance R, to which current is being supplied by the two batteries of E.M.F. E_1 and E_2 respectively. The rule is as follows. In every closed " mesh " of a network, consider a current to flow in clockwise direction, apply Kirchoff's law $E = \Sigma IR$ to each mesh of the network, and solve the simultaneous equations thus obtained. In the diagram, the current x is assumed to circulate in a clockwise direction in the mesh A G F D, while the current y is assumed to circulate in a clockwise direction in the mesh G B C F. The fact that this current is contrary to the polarity of the E.M.F. E_2 is immaterial. If y is found to be a positive quantity this will signify that the E.M.F. E_1 is sufficient to force a current to flow in the direction assumed, while if E_2 is supplying current to the resistance R, y will be found to have a negative value, i.e. its direction is opposite to that postulated in the equations.

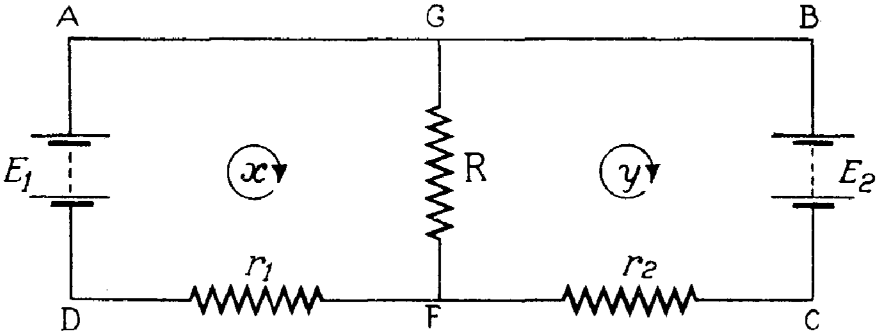


FIG. 15, CHAP. I.—Example of Maxwell's Rule.

The current through the resistance R will be $x - y$, and its terminal P.D. $R(x-y)$.

Forming the equations from the data, we have

$$E_1 = r_1x + Rx - Ry$$

because both x and y flow through R and the IR drop caused by the current y must be taken into account.

Similarly

$$-E_2 = r_2y + Ry - Rx$$

E_2 is given a negative sign because it is acting in the opposite direction to that assumed to be positive, i.e. against the current y.

These equations may be arranged thus :—

$$(r_1 + R)\,x - Ry = E_1 \quad \ldots \quad (a)$$

$$-Rx + (r_2 + R)\,y = -E_2 \quad \ldots \quad (b)$$

$$R\,(r_1 + R)\,x - R^2y = RE_1 \quad \ldots \quad (c)$$

$$-R\,(r_1 + R)\,x + (r_1 + R)\,(r_2 + R)\,y = -(r_1 + R)\,E_2 \quad \ldots \quad (d)$$

Equation (c) is obtained from equation (a) by multiplying all terms by R, while equation (d) is obtained from equation (b) by multiplying all terms by $(r_1 + R)$. Adding (c) and (d)

$$\{(r_1 + R)\,(r_2 + R) - R^2\}\,y = RE_1 - (r_1 + R)\,E_2$$

$$y = \frac{RE_1 - (r_1 + R)\,E_2}{r_1r_2 + r_1R + r_2R} \quad \ldots \quad (e)$$

Instead of eliminating y from the equations, we may eliminate x; if equation (a) is multiplied by $(r_2 + R)$ and equation (b) by R, we obtain

$$(r_2 + R)\,(r_1 + R)\,x - R\,(r_2 + R)\,y = E_1\,(r_2 + R) \quad \ldots \quad (f)$$

$$-R^2x + R\,(r_2 + R)\,y = -E_2R \quad \ldots \quad (g)$$

Adding these equations,

$$\{(r_2 + R)\,(r_1 + R) - R^2\}\,x = (r_2 + R)\,E_1 - RE_2$$

$$\text{or } x = \frac{(r_2 + R)\,E_1 - RE_2}{r_1r_2 + r_1R + r_2R} \quad \ldots \quad (h)$$

The current through the resistance R is $x - y$

$$\text{or } \frac{r_2E_1 + RE_1 - RE_2 - RE_1 + r_1E_2 + RE_2}{r_1r_2 + r_1R + r_2R}$$

$$= \frac{r_2E_1 + r_1E_2}{r_1r_2 + r_1R + r_2R} \quad \ldots \quad (i)$$

and the P.D. between the points G and F is

$$R\,\frac{r_2E_1 + r_1E_2}{r_1r_2 + r_1R + r_2R} \quad \ldots \quad (j)$$

As an example, suppose that $E_1 = 12$ volts, $r_1 = \cdot 1$ ohm, $E_2 = 6$ volts, $r_2 = 1$ ohm, while $R = 5$ ohms.

The P.D. at G.F. is then

$$5\,\frac{1 \times 12 + \cdot 1 \times 6}{1 \times \cdot 1 + \cdot 1 \times 5 + 1 \times 5}$$

$$= 5\,\frac{12 \cdot 6}{\cdot 1 + \cdot 5 + 5}$$

$$= \underline{11 \cdot 25 \text{ volts.}}$$

The direction in which this P.D. is acting is such that a current y will flow in a clockwise direction in opposition to the E.M.F. E_2. Its magnitude will be $\frac{11 \cdot 25 - E_2}{r_2} = 5 \cdot 25$ amperes; this may be verified by direct calculation using equation (e) above.

Now calculate the P.D. if the resistance $r_1 = 1$ ohm and $r_2 = \cdot 1$ ohm. This is given by

$$5 \frac{\cdot 1 \times 12 + 1 \times 6}{5 \cdot 6} = \frac{7 \cdot 2 \times 5}{5 \cdot 6} = \underline{6 \cdot 43 \text{ volts.}}$$

This example shews that in certain conditions when cells or batteries are connected in parallel, it is possible for one cell or battery to force a reverse current through the other. Referring to equation (e) it is seen that the current y will be zero if $RE_1 = (r_1 + R)\, E_2$.

If E_1, E_2 and r_1 are fixed, and R is varied, y will be zero if $R = \frac{r_1 E_2}{E_1 - E_2}$.

If E_1, E_2 and r_1, r_2 have the values given, y becomes zero if R is equal to r_1, or 1 ohm. If R is greater than this, as in the above example, y is a positive quantity, signifying that the assumed direction of current is the correct one, or that the voltage E_1 is forcing a " reverse current " through the other battery E_2. This might of course have been anticipated from the difference in the respective values of E_1 and E_2, but it is not obvious, without calculation, that if R has a value less than $\frac{r_1 E_2}{E_1 - E_2}$ (i.e. less than 1 ohm in the given example) both batteries will contribute to a flow of current through the resistance R.

Although of course two batteries of unequal E.M.F. are never deliberately connected in the above manner the principle has an important application. If one of the sources of E.M.F. in fig. 15 is a secondary battery and the other a shunt-wound generator (*see* Chapter IV), the E.M.F. of the generator and battery being nominally the same, the battery is said to be " floating." So long as the equality of E.M.F. is maintained, the generator and battery will each contribute an equal current which will flow in the load circuit R, and the battery tends to discharge, that is, its E.M.F. falls as the energy stored in chemical form is converted into electrical energy. When the battery E.M.F. falls below the P.D. at the load terminals, the generator supplies a charging current to the battery restoring its E.M.F. to its normal value, while if for any reason the generator voltage fails, the battery maintains the desired current through the load resistance R. Some device is obviously required to disconnect the generator from the load in case of complete failure of its E.M.F., and this is provided by an automatic electromagnetic cutout. The operation of such devices is dealt with in A.P.1095, Electrical Equipment Manual.

Wheatstone bridge

38. A type of network which is frequently used in electrical measurements is shown in its simplest form in fig. 16, the arrangement being known as Wheatstone bridge. In the diagram, R_1 and R_2 are known resistances of fixed value, R_3 is an adjustable resistance whose value is accurately known, and R_4 is a resistance of unknown value. The object of the bridge is to measure the resistance of R_4. In order to achieve this, a current-indicating instrument such as the simple galvanometer described in the following chapter is connected to the points A and B while a battery and switch are connected to points C and D. The resistances R_1, R_2, R_3, R_4 are called the arms of the bridge while the connections between A and B, and between C and D are referred to as the diagonals of the bridge. First, assume the galvanometer circuit to be broken by the key K_2. On pressing the key K_1, a current will be established through the two parallel paths $R_1 + R_3$ and $R_2 + R_4$, and the current in these two branches may be denoted by I_1 and I_2 respectively. The P.D. between the ends of R_1, i.e. between A and C, will be I_1, R_1, while the P.D. between B and C will be $I_2\, R_2$. If these two differences of potential are equal, no difference of potential will exist between A and B, and if the galvanometer is connected to them by pressing

the key K_2, no current will flow through it, for the addition of the galvanometer to the circuit will not alter the value of either I_1 or I_2. The condition under which no deflection of the galvanometer will occur is therefore

$$I_1 R_1 = I_2 R_2$$

but

$$I_1 = \frac{E}{R_1 + R_3},\ I_2 = \frac{E}{\mathrm{R}_2 + R_4}$$

the condition may therefore be expressed as

$$\frac{E R_1}{R_1 + R_3} = \frac{E R_2}{R_2 \times R_4}$$

or as

$$\frac{R_1 \times R_3}{R_1} = \frac{R_2 \times R_4}{R_2}$$

$$1 + \frac{R_3}{R_1} = 1 + \frac{R_4}{R_2}$$

or finally as

$$\frac{R_1}{R_3} = \frac{R_2}{R_4}$$

this is known as the condition in which the bridge is balanced. If as above stated R_1 and R_2 are of fixed value and the ratio between them is known, then R_3 and R_4 are in the same ratio because the last equation can be transposed giving

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

Thus if $\frac{R_1}{R_2} = 10$, and balance is obtained when $R_3 = 1$ ohm, then $R_4 = \frac{1}{10}$ ohm, while if $\frac{R_1}{R_2} = \frac{1}{100}$ and balance is obtained when $R_3 = 10{,}000$ ohms, $R_4 = 10{,}000 \times 100 = 1{,}000{,}000$ ohms.

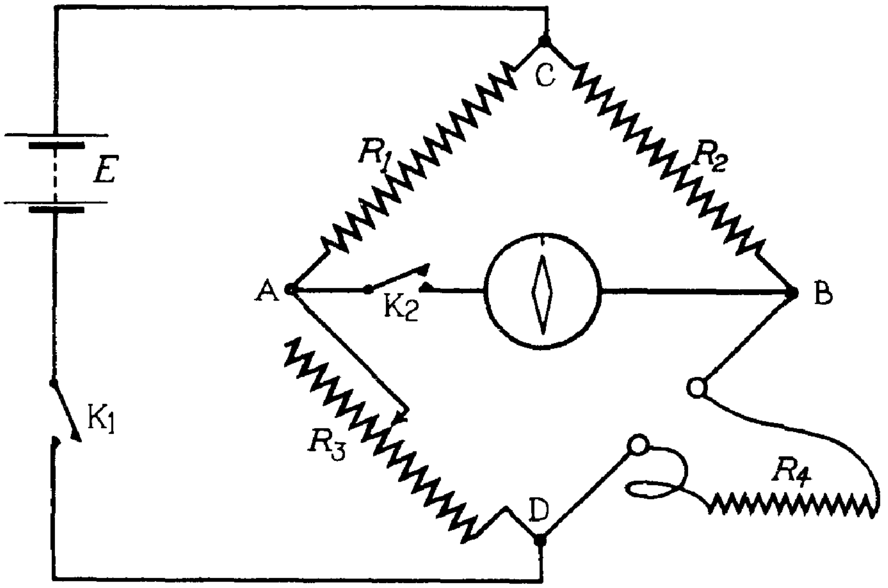


FIG. 16, CHAP. I.—Wheatstone's bridge.

The resistances R_1 and R_2 are each usually adjustable in three steps, e.g., 10, 100, 1,000 ohms, while R_3 consists of a resistance which is adjustable in steps of one ohm from zero to 9,999 ohms. The latter arrangement is called a decade resistance, and consists of four separate resistances, each of which carries 10 tappings. Calling these R_a, R_b, R_c and R_d, we have R_a adjustable in one-ohm steps, from 0 to 9 ohms, R_b in ten-ohm steps from 0 to 90 ohms, R_c in one hundred-ohm steps from 0 to 900 ohms and R_d in one thousand-ohm steps from 0 to 9,000 ohms. Any integral value of resistance from 0 to 9,999 ohms is therefore available. The principle of the Wheatstone bridge can be also applied to the measurement of capacitance and inductance.

Power

39. So far we have dealt with the conversion of energy between different points without reference to the time taken for this conversion to take place. The rate at which energy is being converted is known as power. In other words, power is the rate of doing work. The C.G.S. unit of power is the erg per second, and the practical unit is the joule per second or watt. Since one joule of energy is converted when one coulomb passes between two points whose P.D. is one volt, the power is one watt if this conversion takes place in one second. But a rate of flow of one coulomb per second is one ampere, so that the power developed between two points whose P.D. is one volt, when a current of one ampere flows, is one watt. A larger unit of 1,000 watts is also used and is called the kilowatt. (KW.)

The symbol for power is P

$$P = \frac{W}{t} = \frac{QV}{t}$$

$$\text{Since } \frac{Q}{t} = I$$

$$P = I\,V$$

A power of one watt developed continuously for one hour, will correspond with a transformation of $\frac{1 \text{ joule}}{\text{sec.}} \times 3{,}600$ secs. or 3,600 joules. This unit is called the watt-hour. A still larger unit, the kilo-watt-hour, (Kwh.) or Board of Trade Unit (B.O.T.U.) is also used. It is equal to $3 \cdot 6 \times 10^6$ joules, and constitutes the ordinary commercial unit of electrical energy. Expressions such as " a forty-watt lamp " are occasionally used. This must be interpreted as meaning that when used at the voltage for which it was designed, it will take such a current from the supply source that the power dissipated will be 40 watts. If used on an incorrect voltage, its energy consumption will not be at the rate of 40 watts and it is desirable to state the voltage at which the appliance should be used, e.g., a 200-watt 220-volt soldering iron.

By the application of Ohm's law, expressions for power may be obtained in terms of any two of the quantities voltage, current, and resistance, for since $P = IV$, and $V = IR$.

$$\text{(i) } P = I \times IR = I^2R$$

$$\text{(ii) } P = V \times \frac{V}{R} = \frac{V^2}{R}$$

Examples

1. In the circuit of fig. 11 find the power expended in the $5 \cdot 1$-ohm resistance.

As the current through the resistance is known, use the relation $P = I^2R$ giving $P = (0 \cdot 5)^2 \times 5 \cdot 1 = \frac{5 \cdot 1}{4} = 1 \cdot 275$ watts.

2. At what rate is chemical energy being converted into electrical energy in the battery ?

The energy transformed in T seconds is EIT joules, hence the rate of conversion is EI joules per second or EI watts. This is equal to $10 \times 0 \cdot 5$ or 5 watts.

3. In what time would 1 B.O.T.U. of electrical energy be expended in the whole circuit ?

$$1 \text{ B.O.T.U.} = 1{,}000 \text{ watt-hours}$$

Energy is being expended at a rate of 5 watts, hence the time taken to expend 1,000 watt-hours would be $\frac{1{,}000}{5} = 200$ hours.

4. A certain motor gives an output of 50 horse power. Assuming it has no losses, find the annual cost of running 8 hours a day 300 days per annum, if electrical energy costs 1*d.* per B.O.T.U.

$$50 \text{ H.P.} = 50 \times 746 \text{ watts}$$

$$\begin{aligned}
\text{Total energy required} &= 50 \times 746 \text{ watts} \times 300 \times 8 \text{ hours} \\
&= 50 \times 2{,}400 \times 746 \text{ watt-hours} \\
&= 5 \times 24 \times 746 \text{ Kilowatt-hours or B.O.T.U.} \\
\text{Cost of energy at 1d. per B.O.T.U.} &= 5 \times 24 \times 746 \text{ pence} \\
&= 7{,}460 \text{ shillings} \\
&= \underline{\underline{£373.}}
\end{aligned}$$

40. (i) If no mechanical work is performed the whole of the electrical energy supplied to a circuit is expended in producing heat. The only exception to this rule is when electromagnetic radiation is produced, e.g. light or wireless waves. The relation between the energy expended and the heat produced was discovered by the British scientist Joule, who performed a very large number of experiments in which a quantity of water was stirred continuously by various mechanical methods, and the increase in the temperature of the water was measured. He found that about 780 ft.-lb. of work is required to raise the temperature of 1 lb. of water through 1° Fahrenheit. In the C.G.S. system the unit of heat is the calorie, which is the quantity of heat necessary to raise the temperature of one gram of water by 1° Centigrade. The calorie is equal to 4·2 joules, and as the heat developed by a current of I amperes flowing through a resistance of R ohms for t seconds is I^2Rt joules, it is also equal to $\frac{I^2Rt}{4 \cdot 2}$ calories.

(ii) When the temperature of a body is increased by θ° C., the amount of heat gained (in calories) is equal to product of the mass of the body in grams, the increase of temperature, and to a constant known as the specific heat of the material of which the body is composed. This constant is defined as the ratio

$$\frac{\text{Heat required to raise 1 gram of the substance through } 1^\circ}{\text{Heat required to raise 1 gram of water through } 1^\circ}$$

The specific heat of water is obviously unity, and is much less than unity for all metals. If m is the mass of a body and s its specific heat, an increase in its temperature of θ° C. causes the body to gain a quantity of heat, h, and

$$h = m \, s \, \theta \text{ calories.}$$

This equation, together with the relation 1 calorie = 4·2 joules, enables the electrical engineer to make calculations regarding the cost of heating by electrical means, as in the following example.

If electrical energy is 2d. per B.O.T.U. find the cost of boiling 10 gallons of water, if its initial temperature is 25° C., assuming no heat is wasted.

Temperature rise = 75° C.

The mass of 1 gallon of water is 10 lb., and of 10 gallons, 100 lb. or 100 × 453·6 grams.

$$\begin{aligned} h &= m\,\theta \text{ since for water } s = 1 \\ \therefore\quad h &= 453{\cdot}6 \times 100 \times 75 \text{ calories} \\ &= 4{\cdot}2 \times 453{\cdot}6 \times 100 \times 75 \text{ joules} \\ &= \frac{4{\cdot}2 \times 453{\cdot}6 \times 100 \times 75}{3{,}600 \times 1{,}000} \text{ Kilowatt-hours or B.O.T.U.} \\ &= 4 \text{ B.O.T.U. approx., costing eightpence.} \end{aligned}$$

In many cases the conversion data given in Table VII, Appendix A, will be found of assistance. The above example may be worked as under.

From the Table it is found that one H.P.-hour is the amount of energy required to raise 17·2 lb. of water from 62° F. to 212° F., that is through 150° F.

As 25° C. = 77° F., the water must be raised only 212° − 77° = 135° F. 1 H.P.-hour will raise $\frac{150}{135} \times 17{\cdot}2 = 19{\cdot}1$ lb. of water through this range of temperature.

To raise the temperature of 100 lb. will require $\frac{100}{19{\cdot}1}$ H.P.-hour.

$$\begin{aligned} &= \frac{746 \times 100}{19{\cdot}1} \text{ watt-hour.} \\ &= 3{\cdot}9 \text{ B.O.T.U. at a cost of } 7{\cdot}8 \text{ pence.} \end{aligned}$$

Electric batteries

41. An electric battery consists of any number of primary or secondary cells arranged either in series, in parallel, or in a series parallel combination. Each cell may be considered to have an E.M.F. of E volts and an internal resistance of r ohms. If a number s of similar cells are arranged in series, the total E.M.F. of the combination will be sE volts and the total internal resistance $s\,r$ ohms. If this battery is connected to an external circuit having a resistance of R ohms, the current in the circuit will be

$$I = \frac{s\,E}{R + s\,r} \text{ amperes.}$$

On the other hand if a number p of similar cells are connected in parallel the E.M.F. is not increased but remains equal to that of a single cell, in fact the sum of all the positive elements may be considered to form a single positive element and the negative elements may be treated similarly. The effect of the parallel group is therefore that of a single cell with elements p times as large as those of one cell, and although the E.M.F. is not increased the internal resistance is decreased, being only $\frac{1}{p}$th of the resistance of each cell. The current in the external circuit is

$$I = \frac{E}{R + \frac{r}{p}},$$

a current $\frac{I}{p}$ flowing through each cell.

If p groups, each consisting of s cells in series, are arranged in parallel, each group of cells in series may be considered to form a single cell of E.M.F. $s\,E$ volts, and internal resistance $s\,r$ ohms. A number p of these groups in parallel will then have E.M.F. $s\,E$ volts and internal resistance $\frac{s\,r}{p}$ ohms. If connected to an external resistance of R ohms the current in the external circuit is

$$I = \frac{s\,E}{R + \frac{s\,r}{p}} \text{ amperes.}$$

If only a certain number of cells are available, for a given resistance in the external circuit there is always some method of arranging the cells which will give the greatest value of current, and consequently the maximum expenditure of power in the external circuit. It is found that the best arrangement for the fulfilment of these requirements is such that $\frac{r\,s}{p} = R$, that is, the total effective internal resistance should be equal to the external resistance if maximum current is required. This condition will also make I^2R a maximum, and therefore is the best arrangement when it is desired to dissipate the greatest possible power in the external circuit. If the number of cells available is n, and they are arranged s in series and p in parallel, $n = s\,p$, or $\frac{s}{p} = \frac{n}{p^2}$.

For maximum heating effect

$$R = \frac{s}{p}\,r$$

$$R = \frac{n}{p^2}\,r$$

$$p^2 = \frac{n\,r}{R}$$

$$\therefore\ p = \sqrt{\frac{n\,r}{R}}$$

Example.—20 cells each of internal resistance ·1 ohm are to be arranged to give maximum current through a resistance of ·08 ohms. What is the best arrangement?

The best arrangement is p groups in parallel of s cells in series, where

$$p^2 = \frac{20 \times \cdot 1}{\cdot 08}$$

$$= \frac{2}{\cdot 08}$$

$$= \frac{200}{8} = \frac{100}{4}$$

$$p = \frac{10}{2} = 5$$

Answer.—5 parallel groups of 4 in series.

If the E.M.F. of each cell is 2 volts, the current with this arrangement will be

$$\frac{sE}{2R} = \frac{8}{\cdot 16} \text{ or 50 amperes.}$$

CONDUCTORS AND RESISTANCES

42. Conductors are used for two different purposes, (i) to convey electrical energy to the point at which it is to be utilised, and (ii) to control and regulate electrical currents and voltages. In the former application the resistance of the conductor is a disadvantage as it entails a loss of energy. This loss of energy takes place at a rate of I^2R joules per second, I being the mean value of the current and R the resistance of the conductor. For this reason, only materials of low specific resistance are used for " supply leads ", as such conductors are generally termed, copper being employed for preference, although considerations of tensile strength sometimes necessitate the use of iron wire and considerations of weight sometimes cause aluminium to be employed, e.g. in long spans of overhead power lines. In the second application of conductors, the control is obtained by variation in the amount of resistance included in the circuit, and high specific resistance is then a desirable property of the conductor, as it allows a smaller and cheaper design than would be possible with a good conductor. Resistances used for control purposes

receive many special names, but can generally be classed as rheostats, potentiometers and fixed resistors, while two broad divisions may also be made according to the character of the conductor employed, thus giving rise to "wire wound" and "composition" types of resistances. Wire wound resistances are almost invariably manufactured from one of the high resistance alloys. These are substances of high specific resistance and almost negligible temperature coefficient, the principal being platinum silver, platinoid, German silver, manganin and eureka. The specific resistance of these alloys is from fifteen to thirty times that of copper, while the temperature coefficient is less than one-tenth that of copper. The advantage of the negligible temperature coefficient is that the resistance of the circuit is not appreciably dependent upon the amount of current flowing, as is the case when a substance of high temperature coefficient is used. Particulars of the alloys mentioned above will be found in Table I, Appendix A.

Rheostats and potentiometers

43. (i) A variable resistance arranged in series with other devices in order to effect a control of current flowing through the latter, is called a rheostat. For currents up to about 20 amperes, the resistance unit generally takes the form of a slab or tube of insulating material, upon which is carried a winding of eureka or manganin wire. A sliding contact is arranged to make electrical contact with the wire at any point along the length of the slab or tube, or else a number of tappings is brought from the wire to a row of contacts, connection to the latter being effected by a rotating arm. These are shewn diagrammatically in fig. 17.

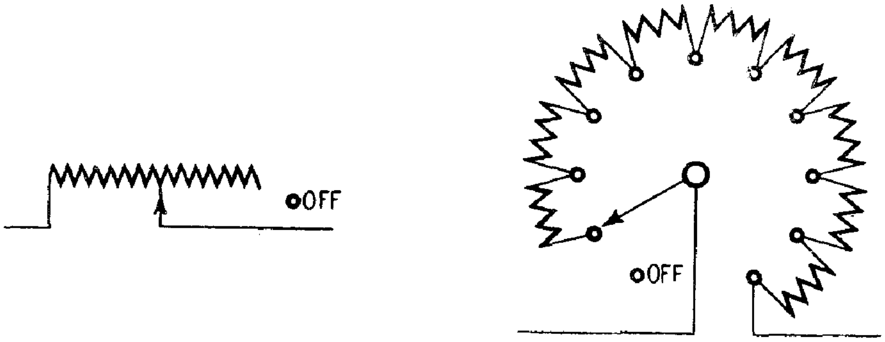


FIG. 17, CHAP. I.—Rheostats.

(ii) A potentiometer is a variable resistance arranged in such a manner that a certain proportion of the available P.D. may be applied to a particular instrument. In fig. 18a is shewn a 2-volt accumulator, and a potentiometer so connected as to allow any fraction of the available E.M.F. to be applied to the instrument X, the nature and purpose of the latter being immaterial

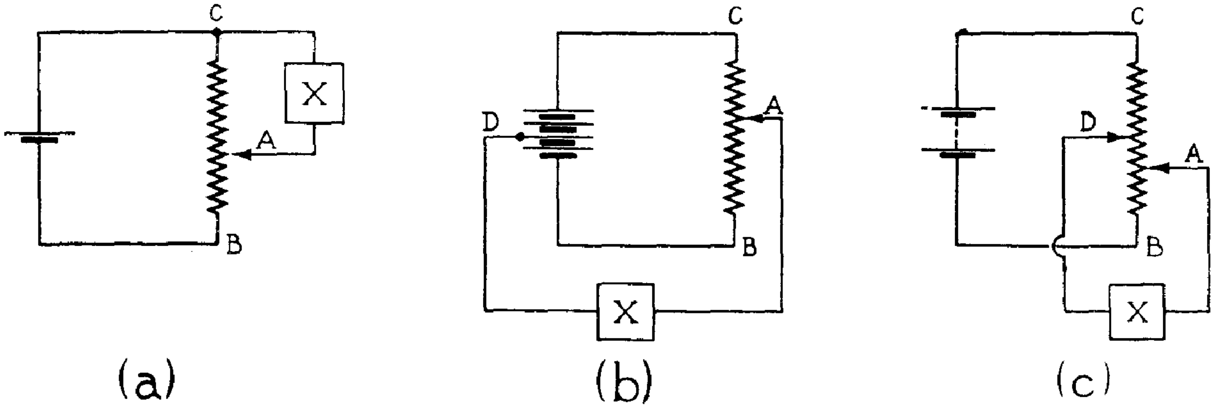
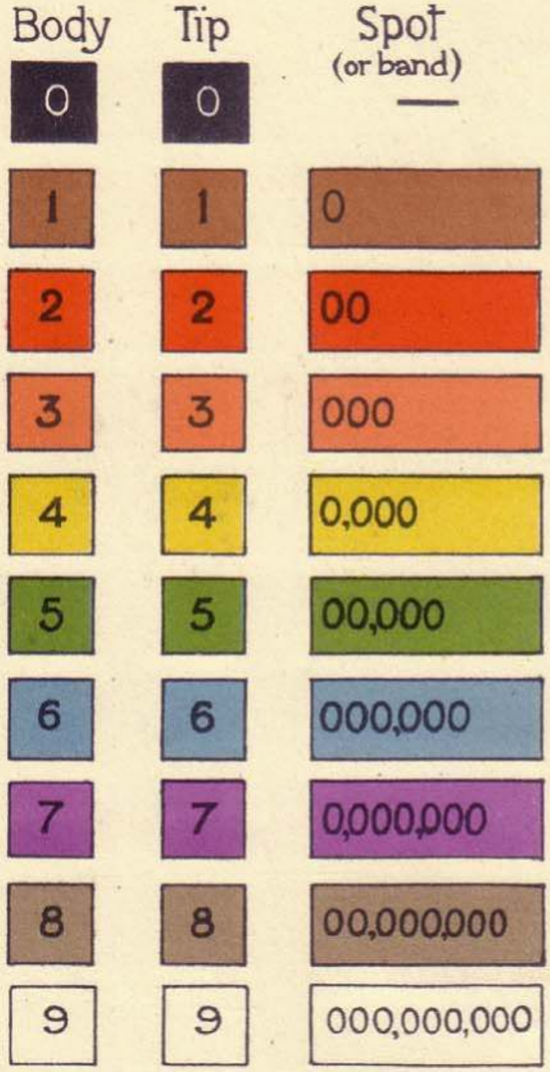


FIG. 18, CHAP. I.—Potentiometers.

COLOUR CODE FOR SMALL RESISTANCES USED IN RADIO APPARATUS



Body	Tip	Spot (or band)
0	0	—
1	1	0
2	2	00
3	3	000
4	4	0,000
5	5	00,000
6	6	000,000
7	7	0,000,000
8	8	00,000,000
9	9	000,000,000

Example

Explanation

The colours used have the numerical values indicated above, the numbers being set down in the order Body, Tip, Spot. In the example, the body, being green, gives the number 5. The tip (red) indicates 2 and the spot (blue) shows that six noughts follow. The value of the resistance in ohms is therefore 52,000,000

Fig. 19.

to the present discussion. When the slider A is carried to the end of the winding B, the whole of the available 2 volts is applied to X, but on carrying the slider to position C, no voltage is applied to X, while at any intermediate point the voltage applied to the instrument will lie between these limiting values. Two methods of connecting a potentiometer by which a reversal of direction of applied voltage can be obtained, are shewn in fig. 18b and c. The first necessitates a battery of twice the maximum voltage which it is desired to apply to the instrument. The second method overcomes this disadvantage.

44. Resistors, or fixed resistances, are often fitted in radio instruments for different purposes. Many of these are of the order of 10^5 or 10^6 ohms, and it is necessary to obtain this value in as small a space as possible. In some instances a large number of turns of very fine wire (having an insulating surface formed by oxidisation) are wound in spiral form upon a cord about $^1/_{12}$ in. in diameter, the ends of the wire being pressed into metal connectors and the cord covered by a tube of insulating material. In another type an extremely fine wire is wound in sections upon a fireclay tube, being afterwards covered with porcelain and " fired " in order to glaze the covering. These are called vitreous resistances, although the term vitreous does not apply to the resistance element but to the glass-like exterior. Such resistances are made in units of from a few ohms to one hundred thousand ohms. For resistances of a higher order but very low current-carrying capacity, a metallic film of minute thickness may be applied to a rod of insulating material, connecting leads being connected to the ends and the whole enclosed in a glass or cardboard tube. Suitable steps are taken to exclude moisture, e.g. by coating with paraffin wax or similar material. When resistances of this design are made, a colour code is adopted to denote the value of the resistance. The resistance carried three colours placed in the positions indicated on the typical resistance illustrated in fig. 19. Ten different colours are used, and are read in the order " body ", " tip " and " spot " or band. The numerical values and method of reading the code are given in the figure. The use of this code is practically confined to high value resistors of small physical dimensions which form component parts of modern radio apparatus.

Fuses

45. Fuses are protective devices, which are generally placed in series with circuits in such a manner as to interrupt the circuit if the current exceeds a certain value. The fuse consists of a short length of wire, generally of tin or an alloy of tin and lead. If the current becomes excessive, the heat generated in the fuse will be sufficient to melt it, and the circuit is broken. In order that the hot metal shall not spray out and ignite any inflammable material in the vicinity, it is usual to enclose the wire in a porcelain holder.

THE CARBON MICROPHONE

46. This instrument is dealt with in this chapter because it is essentially a special form of resistance, the value of which can be controlled by sound waves. In its simplest form it consists of two polished carbon plates which serve as terminal electrodes, and between them is placed a small quantity of granulated carbon. One of the electrodes may be rigidly fixed to some support, and the other electrode is then mounted upon a flexible insulating diaphragm, mica being usually employed. Fig. 20 shews the carbon microphone in section, and also the manner in which it is connected to a battery and telephone receiver in order to form a simple telephone. The action of the instrument is as follows :—When a sound wave impinges upon the flexible diaphragm, the alternate compression and rarefaction of the atmosphere causes corresponding movement of the diaphragm, and the resistance of the microphone varies accordingly. In the absence of a sound wave, the microphone carries a steady current from a suitable battery, which is also caused to flow through the windings of a telephone receiver. Variation of the resistance of the microphone causes corresponding variations of the current flowing through the telephone receiver and the diaphragm of the latter is set into vibration by the variations of current through the winding, setting up in the surrounding air a sound wave having characteristics similar to

the original sound. The action of the telephone receiver is dealt with in Chapter II, and a more complete description of a service type of microphone designed for use in aircraft is given in A.P. 1186 (Signal Manual, Part IV, Section V, Chapter XII).

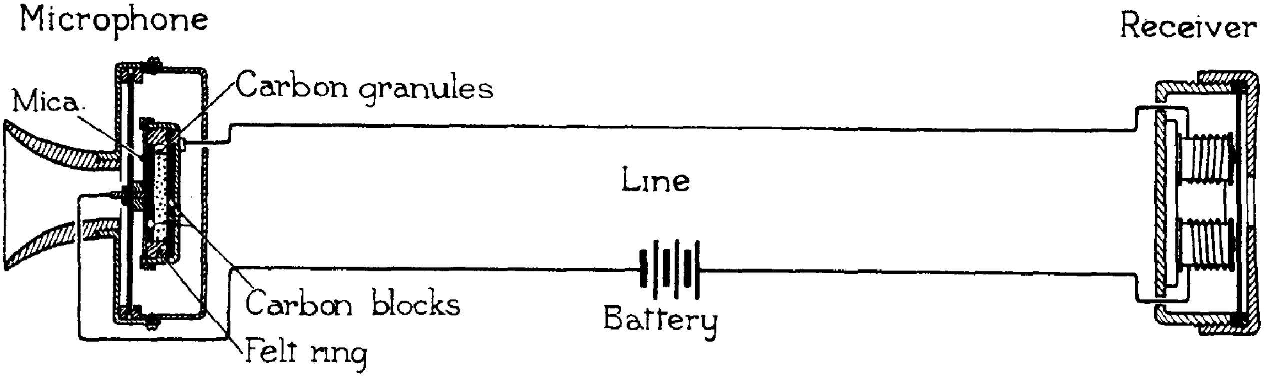


FIG. 20, CHAP. I.—Simple telephone.

ELECTROSTATICS

47. A charged body has already been defined as one which has gained or lost electrons. The forces of attraction and repulsion exhibited by such bodies are exerted in a region surrounding them, which is called a field of electric force or an electric field. It may be imagined to consist of an infinite number of lines of electric force, a line of force being a line which shews the direction in which the force is acting at all points along its length. A field of force is shewn diagrammatically in fig. 21, the particular case chosen being that of a charged sphere remote from all other bodies.

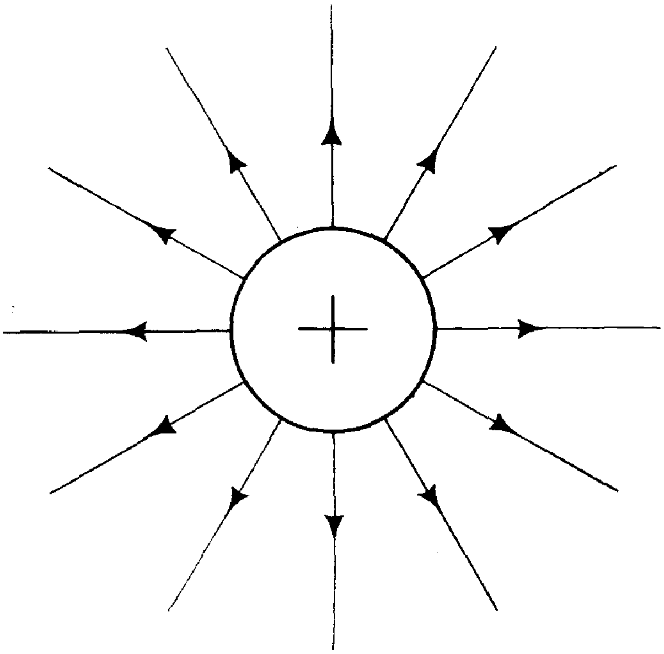


FIG. 21, CHAP. I.—Field of electric force.

The size and nature of the charge are denoted by a number denoting the number of unit charges carried and a + or — sign to denote positive or negative charge respectively. A further convention is the arrow head shewn on a number of the lines, in order to indicate the direction in which a positive charge would be urged if placed in the field.

Electric flux and flux density

48. The electric field may be considered as an electric stress applied to the medium surrounding the charge, which in its turn causes the medium to undergo a strain or displacement. This strain, when speaking of the whole area of the field perpendicular to the direction of the force, is called the electric flux. The word " stress " has a definite technical meaning although it is often misused. In mechanics, stress is any force (per unit area) applied to a body in such a manner as to alter its shape or size, the resulting fractional change in dimensions of the body being called the strain. Under certain conditions, the strain produced (D units) is proportional to the stress applied (F units) and the numerical relation between stress and strain may then be expressed by the equation $F = KD$, where K is a constant for any particular material, and is called the modulus of elasticity. Now the stress F and the strain D are of an entirely different physical nature, and in like manner, it is considered that the electric stress Γ, also called the electric field strength*, causes an electric strain or displacement D, which is also called the electric flux density. If any small area is taken in the electric field, perpendicular to its direction, the lines of force through all adjacent points bounding this area may be considered to enclose a tube of electric flux. These tubes of flux may be thought of as elastic bands, tending to contract in the direction of their length while expanding in their cross-section, this tendency being due to the applied force. If one end of a tube of flux is situated upon a positive charge, the opposite end must be terminated upon an equal and opposite charge. The imaginary elastic property of the tube then tends to draw the two charges together, and accounts for the attraction between like charges. Repulsion may also be explained by the tendency of the tubes to increase in cross-section. Two adjacent tubes of unlike sign tend to unite, contracting in such a way as to form a single tube. This conception is illustrated in fig. 22, which shews various stages in the contraction of the field between two unlike charges, as they approach each other.

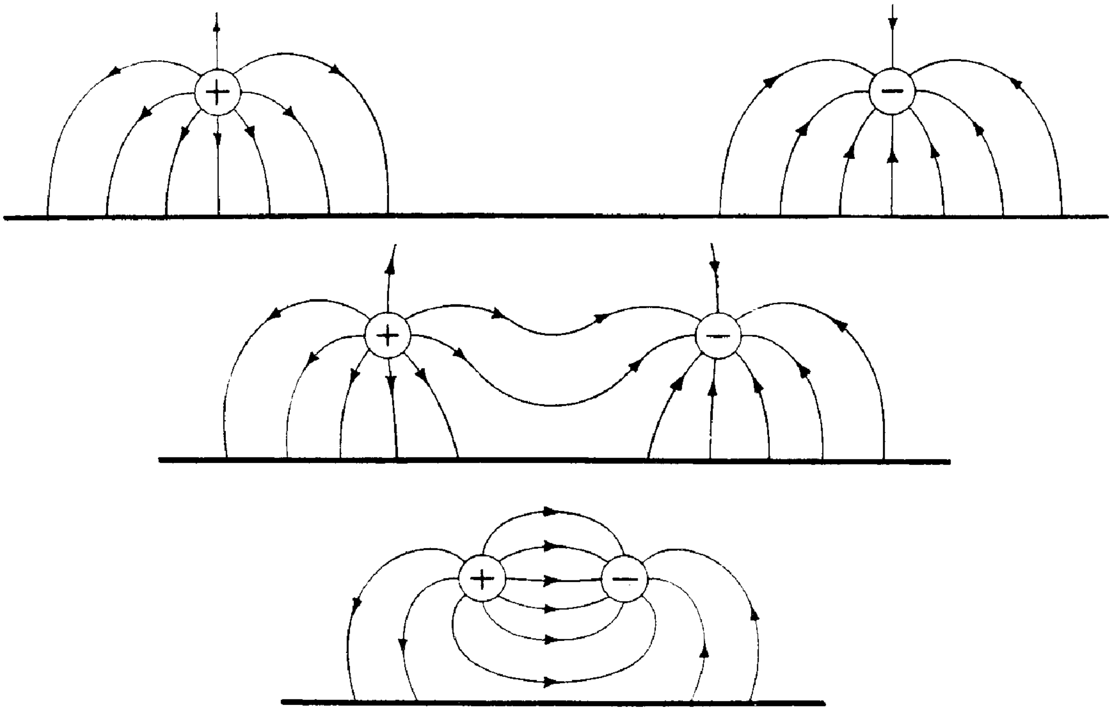


FIG. 22, CHAP. I.—Fields between unlike charges.

Electrostatic system of units

49. It has been found experimentally that the force exerted between two charged bodies varies inversely as the square of the distance between them. The system of units based on these forces is known as the electrostatic system (E.S.U.).

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* The symbol ε (epsilon) is sometimes used to denote electric field strength, but in this publication Γ (gamma) has been adopted in order to avoid confusion with the base of Naperian logarithms.

The basis of this system is the electrostatic unit of quantity, or electrostatic unit charge, which is defined as follows. If two equal charges placed one centimetre apart in vacuo exert upon each other a force of one dyne, then each is a unit charge. The E.S.U. of quantity is a very small unit, being $\frac{1}{3 \times 10^9}$ of the practical unit or coulomb. A single unit charge can be isolated as follows. A pith ball, exactly 2 cm. in diameter, and covered with gold leaf in order to make its surface conductive, is suspended in the middle of a large room by means of a single silk fibre. A battery having an E.M.F. of 300 volts has its positive terminal connected to the wall of the room, and the pith ball is then touched with the end of a fine wire which is connected to the negative terminal of the battery. The pith ball then acquires a charge of one E.S.U. Two such charges placed one cm. apart in vacuo repel each other with a force of one dyne. If larger charges are given, say Q_1 and Q_2 E.S.U. respectively, then under the same conditions the force exerted is $Q_1 \times Q_2$ dynes, and in general, the force exerted between two charges Q_1, Q_2, the distance apart being d cms. (in vacuo) is $\frac{Q_1 \times Q_2}{d^2}$ dynes.

If the charges are situated in some material medium, the force exerted is not the same as if they are situated in vacuo. For instance, if they are placed in pure vaseline—which is almost a perfect insulant and therefore will allow practically none of the charge to leak away—the force would be reduced to about one half that exerted in vacuo. On the other hand, in air the forces are practically the same as in vacuo. The force exerted between charged bodies thus depends upon a property of the medium in which they are situated. This property is called its " dielectric constant " or " permittivity " or formerly its " specific inductive capacity ". The symbol for permittivity is $\varkappa$.

The complete relation between the force and the charges in any medium of permittivity $\varkappa$ is therefore

$$\text{Force} = \frac{Q_1 Q_2}{\varkappa d^2} \text{ dynes.}$$

Electric field strength

50. The strength of an electric field at any point is defined as the force exerted upon a unit charge placed at that point. The electric field strength at a distance d from a point charge of Q units in a medium of permittivity $\varkappa$ is

$$\Gamma = \frac{Q}{\varkappa d^2} \text{ dynes per unit charge.}$$

One unit tube of electric flux is assumed to start from a unit positive charge, or to end on a unit negative charge. The total number of unit tubes of electric flux emanating from a charge is the electrostatic flux or electric flux. (Symbol Ψ).

The electrostatic flux density or electric flux density is the amount of electrostatic flux per unit area normal to the direction of the flux. Its symbol is D.

$$\text{Thus } D = \frac{\Psi}{A}$$

where Ψ is the flux (assumed uniform) through an area A square centimetres.

Since one tube of electric force is associated with each unit charge, the total flux over a surface enclosing a charge of Q units must be Q tubes. If then a sphere of radius r centimetres encloses a point charge of Q units, the surface area of the sphere being $4\pi r^2$ square centimetres, the electrostatic flux density at this surface is

$$D = \frac{Q}{4 \pi r^2} \text{ tubes per square centimetre}$$

but the electric field strength Γ is equal to $\frac{Q}{\varkappa r^2}$;

$$\text{so that } \Gamma = \frac{4 \pi r^2 D}{\varkappa r^2} = \frac{4 \pi D}{\varkappa}$$

$$\text{or } D = \frac{\varkappa \Gamma}{4 \pi} \text{ tubes per square centimetre.}$$

The dielectric constant or permittivity

51. The permittivity of a perfect vacuum is assumed to be unity. For all insulating substances or dielectrics, it is greater than unity, and does not vary appreciably at ordinary temperatures with slight temperature changes. Dry air has a permittivity very slightly greater than unity. Table II, Appendix A gives the value of this constant for several common substances. The reader is warned, however, that the permittivity of a material does depend upon the amount of ionisation or upon the number of free electrons present. Thus certain regions of space between the earth and the sun apear to have dielectric constants less than unity. Again, suppose two bodies carrying unlike charge were placed in a conducting medium, then the surplus electrons composing the one charge would flow to the body having a deficit of electrons, and therefore after a very short—in fact infinitesimal—period there would be no force between them. From this aspect, the permittivity of a perfect conductor is infinitely great. The principal occasion upon which this effect is of importance is in the consideration of the travel of wireless waves in the upper regions of the atmosphere, which is dealt with later.

Energy stored in an electric field

52. If one of the charged bodies hitherto considered were fixed, while the other were free to move it is obvious that under the influence of the electric force, motion would take place, or work would be done. Hence the electric field possesses the capability to do work—which is our conception of energy. Whenever an electric field is established, potential energy is stored. If motion does take place, this potential energy is converted into kinetic energy, and current flows from a point of higher potential to a point of lower potential. This leads to the notion of a difference of potential between the two points, just as in the case of conduction current. The P.D. between two points in an electric field is the work done when a unit charge moves from one point to the other. If the movement of a unit positive charge is due to the electric field, then the first point is at a higher potential than the second. If the unit positive charge is moved against the opposition of the electric field, then the first point is at a lower potential than the second. The earth's surface is assumed to be at zero potential, and the potential of any point in the field can be stated with reference to this surface. The E.S.U. of P.D. is the P.D. between two points if one erg of work is performed in moving a unit charge from one point to the other, thus

$$\text{E.S. Unit P.D.} = \frac{1 \text{ erg}}{\text{E.S. unit charge}}$$

The practical unit of P.D. is the volt, and the practical unit of work the joule ($= 10^7$ ergs).

$$\text{Hence one E.S. unit of P.D.} = \frac{\frac{1}{10^7} \text{ joule}}{\frac{1}{3 \times 10^9} \text{ coulomb}} = 300 \text{ joules per coulomb}$$

$$= \underline{\underline{300 \text{ volts}}}$$

The significance of the 300-volt battery used to obtain an E.S. unit charge will now be appreciated.

Capacitance

53. The potential of a charged body is proportional to its charge. This relation may be written $Q \propto V$ or $Q = CV$, where C is a constant. This constant, the ratio of charge to potential, is called the capacitance of the body. The charge which a given body can hold at a given potential can be increased by concentrating the region in which its field exists. An arrangement by which the capacitance is thus increased is called a condenser. In effect, a condenser may be considered as an arrangement of conductors in which the tubes of flux are packed more closely together, and the extra work required to accomplish this appears as an increase of potential energy. The capacitance of some bodies is easily determined. Thus consider a sphere of radius r, remote from all other bodies in space. If its surface is given a charge of Q units, the work which would have to be done in order to concentrate that charge on its centre is the potential at the centre. That is

$$V = \frac{Q}{r^2} \times r = \frac{Q}{r}$$

because $\frac{Q}{r^2}$ is the force at the centre and r is the distance, while work = force × distance.

Since Capacitance is the ratio $\frac{\text{Charge}}{\text{Potential}}$, or $\frac{Q}{V}$, we have $C = \frac{Q}{V} = Q \div \frac{Q}{r} = r$, hence the capacitance of a sphere is equal to its radius; the E.S. unit of capacitance is also called the centimetre. A body of unit capacitance has a potential of one E.S. unit when it is given unit charge. In isolating our unit charge, a pith ball (assumed spherical and of radius 1 cm.) was given a potential (with respect to earth or zero potential) of 300 volts or 1 E.S.U. Hence it acquired a charge of 1 E.S.U. The E.S. unit of capacitance is inconveniently small for most commercial purposes, and the practical unit of capacitance is the farad; a body has a capacitance of one farad if a charge of one coulomb raises its potential by one volt. However, this unit is too large for actual use and the microfarad or one of its subdivisions is generally employed.

$$1 \text{ coulomb} = 3 \times 10^9 \text{ E.S.U. of quantity}$$

$$1 \text{ volt} = \frac{1}{3 \times 10^2} \text{ E.S.U. of potential}$$

Hence

$$1 \text{ farad} = 9 \times 10^{11} \text{ E.S.U. of capacitance}$$

$$\underset{(\mu F)}{1 \text{ microfarad}} = \frac{1}{10^6} \text{ farad}$$

$$\underset{(\text{m. } \mu F)}{1 \text{ millimicrofarad}} = \frac{1}{10^3} \text{ microfarad}$$

$$\underset{(\mu\mu F)}{1 \text{ micro-microfarad}} = \frac{1}{10^6} \text{ microfarad}$$

$$= \frac{1}{10^{12}} \text{ farad}$$

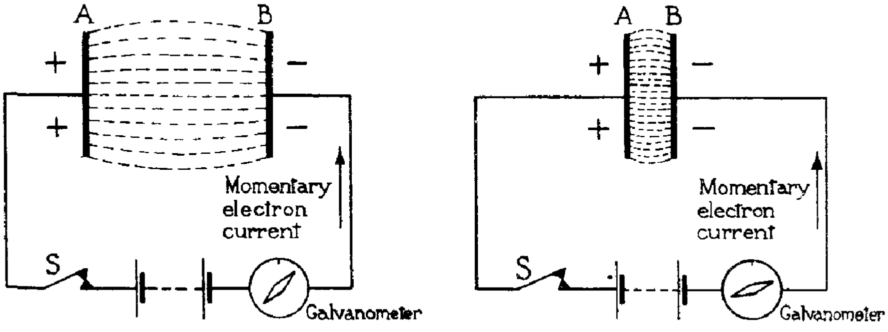
Capacitance of a condenser

54. A common form of condenser consists of two parallel plates separated by, or immersed in, an insulating material. If one of these plates is given a positive charge, and the other a negative charge, the plates themselves being remote from each other, the lines of flux from each plate would terminate on the earth. If the two plates are now brought near to each other, the lines of force can shorten and link from one plate to the other, so that the electric field is considerably concentrated.

55. Consider an uncharged parallel plate condenser connected to a battery, switch and galvanometer, the latter being an instrument which indicates the presence and direction of a current.

First, let the plates be well separated as in fig. 23a. On closing the switch, the electromotive force of the battery will urge electrons along the circuit, so that electrons flow from the plate A through the battery and to plate B. This current of electrons will be shewn by the deflection of the galvanometer. When the P.D. between the plates is equal to the E.M.F. of the battery, there will be no further flow of electrons. This will occur a fraction of a second after closing the switch. The two plates are now oppositely charged, plate A having a deficit of electrons, and plate B a surplus. At the same time an electric field is established between the plates in the medium separating them, and a displacement of electrons will occur in this medium, the electrons trying to move toward the plate A, which has a deficit of electrons. As has already been stated, although the electrons in an insulating material cannot leave their own atoms, they are strained in their orbits, and this slight movement constitutes a displacement current.

If now the two plates are brought more closely together as in fig. 23b, the negative charge on plate B tends to nullify the positive charge on plate A so that the P.D. between the plates is decreased and a momentary electron flow takes place into plate B, restoring the P.D. to equality with the E.M.F. of the battery. On breaking the switch, each plate is left in a charged state, the P.D. between the plates being equal to that of the battery from which the condenser was charged.



(a) (b)

FIG. 23, CHAP. I.—Increase of capacitance of condenser.

If now the plates are connected by a conductor, the surplus of electrons on plate B will surge into the conductor displacing other electrons and causing a conduction current to flow. Electrons from the end of the conductor nearest to plate A will flow into the plate and unite with the atoms which are deficient in electrons, restoring them to their neutral state. At the same time, the strain on the electrons in the material of the dielectric will be released, the electrons will recover their normal orbits, and in so moving constitute a displacement current in the reverse direction to the displacement current set up by the charging process.

Capacitance of a parallel plate condenser

56. The capacitance of a parallel plate condenser may be derived as follows :—

Assuming that the charge on each plate is equally distributed over its surface, the lines of force will be parallel and the flux density uniform.

Let V = the P.D. between the plates (E.S.U.)
Q = the charge on one plate (E.S.U.)
d = the distance between plates in cm.
A = the area of plates in cm.^{2}.

Then the flux density $D = \frac{Q}{A} \frac{\text{tubes}}{\text{cm.}^2}$.

The electric field strength is Γ, and

$$\Gamma = \frac{4 \pi D}{z}$$

The P.D. between the plates = the work done in moving a unit charge against a force Γ through a distance d.

$$\text{i.e. } V = \Gamma d$$

$$\therefore \quad V = \frac{4\pi D}{\varkappa} \times d$$

$$= \frac{4\pi Q}{\varkappa A} \times d$$

There is a further relationship between V and Q, namely

$$V = \frac{Q}{C} \text{ or } C = \frac{Q}{V}$$

Hence $$C = \frac{Q}{\frac{4\pi Q d}{\varkappa A}} = \frac{A\varkappa}{4\pi d} \text{ (E.S.U.)}$$

If C is to be expressed in microfarads,

$$C = \frac{A\varkappa}{4\pi d \times 9 \times 10^5} \text{ microfarads.}$$

Energy stored in a condenser

57 It has already been stated that work must be done in order to establish an electric field and this work is stored in the field as potential energy. The amount of energy stored in a condenser of C farads when charged to a P.D. of V volts will now be calculated. The charge introduced into the condenser is given by the equation $Q = CV$. The average charging current, during the time t taken to charge the condenser will be $\frac{Q}{t}$ or $\frac{CV}{t}$ and since the P.D. at beginning of charge is zero, while at the end it is V, the average voltage during charge is $\frac{V}{2}$. The average rate of doing work is therefore $\frac{CV}{t} \times \frac{V}{2}$ joules per second, and the total work done in t seconds is therefore $\frac{CV^2}{2}$ joules. This work done is stored as energy in the charged condenser.

A useful analogy is the storage of air in a closed metal cylinder by means of an air pump. Let the cylinder have a capacity of C cubic feet at atmospheric pressure, then it will hold $C \times V$ cubic feet at a pressure V. Now, to force the first additional particle of air into the cylinder requires practically no pressure. When the cylinder has been pumped up to a pressure of V lb. per square foot, a pressure of just over V Lb. per square foot will be necessary in order to force in another particle of air. Thus the average pressure during the whole operation will be $\frac{V}{2}$ Lb. per square foot and the total work done will be

$$\frac{V}{2}\frac{\text{Lb.}}{\text{ft.}^2} \times CV \text{ ft.}^3 = \frac{CV^2}{2} \text{ ft. Lb.}$$

and this is the amount of work which could be done by the compressed air.

Energy density

58. It is sometimes convenient to consider the amount of energy stored in a dielectric without reference to the capacitance. This may be illustrated by a consideration of the parallel plate condenser, the field being assumed to be parallel and uniform.

The capacitance of such a condenser in E.S.U. is $\frac{A}{4\pi d}$ units and the energy stored is $\frac{1}{2} CV^2$ ergs, if V is the P.D. between the plates, also in E.S.U.

Hence the energy stored $= \frac{1}{2}V^2 \times \frac{A\varkappa}{4\pi d}$ ergs and since the total volume of the dielectric is Ad, this is equivalent to an energy density of $\left(\frac{V^2}{2} \times \frac{A\varkappa}{4\pi d}\right) \div Ad$ ergs per cubic centimetre.

Now $$\left(\frac{V^2}{2} \times \frac{A\varkappa}{4\pi d}\right) \div Ad = \frac{\varkappa}{8\pi}\left(\frac{V}{d}\right)^2$$

V is the work done on a unit charge in moving it from one plate to the other.

$\frac{V}{d}$ is the work done per centimetre, i.e. is the electric field strength Γ of the field.

Hence the energy density in a uniform field of strength Γ is $\frac{\varkappa \Gamma^2}{8\pi}$ ergs per cubic centimetre.

The conception of electric field strength as the P.D. per centimetre leads to a practical unit of electric field strength—the volt per centimetre.

One E.S.U. of field strength = 300 volts per centimetre. A submultiple of this, the milli volt per metre, is frequently used to measure the strength of an electric field due to a distant radio transmitter, at any point where wireless reception is contemplated.

Charge and discharge of a condenser

59. It is now proposed to consider the phenomena associated with the charging of a condenser through a resistance. The circuit shewn in fig. 24 comprises a source of constant E.M.F. of E volts, a condenser of C farads and a resistance of R ohms. The condenser and resistance (in series) can be connected to the source of supply by means of the switch S_1. Before this switch is closed the condenser possesses no charge and the P.D. between its plates is zero. On closing the switch a current will commence to flow, charging the condenser, the magnitude of this current at the instant of completing the circuit being $\frac{E}{R}$ amperes: note particularly that as the condenser offers no "back pressure" or counter-E.M.F., the initial charging current is the same as if the condenser were short circuited. In a very short interval of time, however, the condenser will receive a charge, e.g. in t seconds a charge q, equal to $I \times t$ or $\frac{E}{R}t$ coulombs, and will therefore exert a counter-E.M.F., e, equal to $\frac{E}{CR}t$ volts, because $e = \frac{q}{C}$ and $q = \frac{E}{R}t$. In order to shew the effect, let us assume that $E = 200$ volts, $C = 10\ \mu F$, $R = 1{,}000$ ohms. Then when $\cdot 0025$ second has elapsed from the time of closing the switch the counter-E.M.F. will be $\frac{200}{1{,}000} \times \frac{10^6}{10} \times \cdot 0025$ which is 50 volts. Now the final charge of the condenser will be CE or $\frac{1}{10^5} \times 200 = \cdot 002$ coulombs, and if the initial rate of charge were maintained the voltage of the condenser would reach its final value E in a time T, where $\frac{E}{CR}\ T = E$ or $T = CR$ seconds.

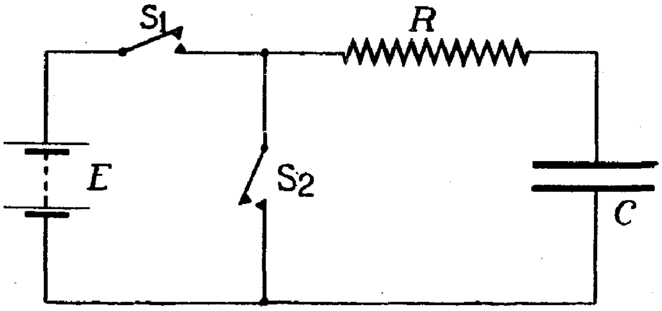
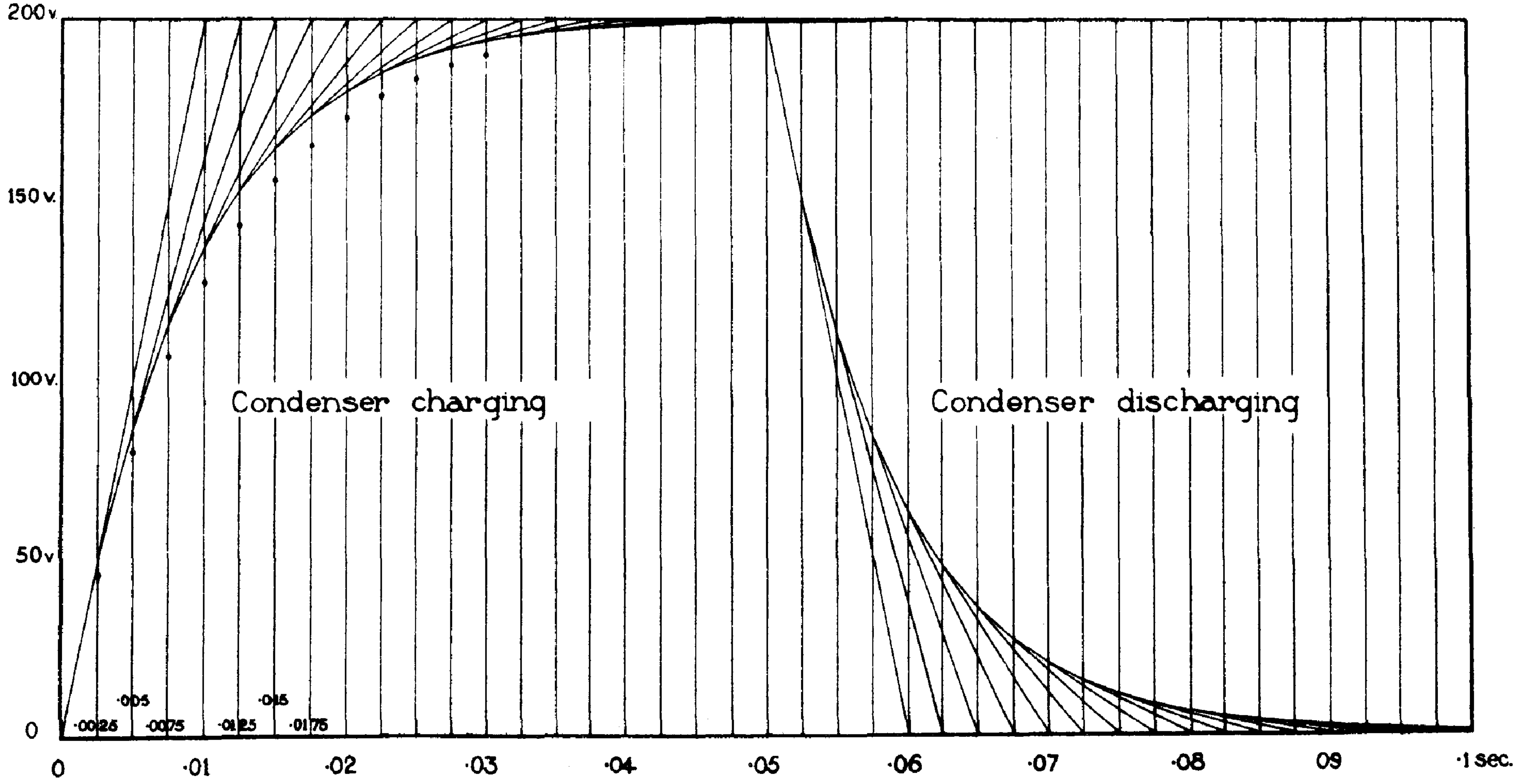


FIG. 24, CHAP. I.—Condenser and resistance in series.

The time which would be taken to charge the condenser to a voltage equal to that applied, if the initial rate of charging could be maintained, is called the time constant of the circuit. In practice the condenser does not charge at the initial rate, because the counter-E.M.F. opposes the applied voltage, and therefore the charging current falls as the counter-E.M.F. increases. Thus after an interval ·0025 second, the counter-E.M.F. is 50 volts, and only 150 volts are available to cause a further charge. During a second interval of time of the same duration, the current which will flow will be $\frac{150}{1{,}000}$ amperes, the charge ·15 × ·0025 coulombs, and the increase of voltage $\frac{Q}{C}$ or ·15 × ·0025 × 10^5 which is 37·5 volts. At the end of the second interval the counter-E.M.F. will therefore be 50 + 37·5 or 87·5 volts. The voltage available to cause a further charge is now reduced to 112·5 volts, and at the end of yet another interval of ·0025 second the current will be ·1125 ampere, the additional charge ·1125 × ·0025 coulomb, and the increase of counter-E.M.F. ·1125 × ·0025 × 10^5 or 28·125 volts. The total counter-E.M.F. at the end of the third interval is therefore 87·5 + 28·125 = 115·625 volts. Proceeding in this manner we may complete a table as follows, and plot the results on squared paper. The resulting curve will then shew the rate at which the condenser P.D. rises.

Interval	Average Current, $i = \frac{E - e}{R}$	Charge in coulombs during interval $q = i\,t$	Counter-E.M.F. produced during interval $\frac{q}{C}$	Total counter-E.M.F.	Voltage available for further charge
1	·2	·0005	50	50	150
2	·15	·000375	37·5	87·5	112·5
3	·1125	·00028125	28·125	115·625	84·375
4	·084375	·000212	21·2	136·825	63·175
etc.	etc.	etc.	etc.	etc.	etc.

The results can be obtained graphically as follows. Prepare the axes of the graph, as in fig. 25, shewing voltage up to 200 volts and time up to, say ·1 second. From the origin of the graph draw a straight line to the point $E = 200$, $t = CR =$ ·01 second. This shews the rate at which the counter-E.M.F. of the condenser would increase if the initial charging current were maintained. It is seen that the P.D. of the condenser plates after ·0025 second would be 50 volts, as calculated above. The difference between the applied and counter-E.M.F. (150 volts) will now tend to cause the condenser P.D. to rise from 50 to 200 volts in ·01 second, and therefore a line is drawn from the point 50 volts, ·0025 second, to the point 200 volts, ·0125 second, i.e. ·01 second further along the time axis, but on the 200 volt line. At ·005 second, this line gives the condenser P.D. as 87·5 volts, as in the table. The complete curve shewing the increase of condenser P.D. can be constructed in this manner, drawing in each successive " voltage increase " line to a point on the 200 volts ordinate, a time interval of ·01 second ahead of the previous line. The graphical process should be performed by the reader for other values of the circuit constants, as the construction has many other applications, for instance in Chapter II we find the growth of current through an inductive circuit in the same way. It must however be pointed out that the curve obtained in the figure is not quite accurate, because the time interval, ·0025 second, during which the charging current is assumed to remain constant at each successive value, is much too long. The shorter this interval is assumed to be, the greater will be the accuracy of the graphical construction. It can be proved that the current will reach ·632 of its maximum value in a time equal to the time constant of the circuit. By the graphical construction given above, the voltage rises to 136·8, which is ·685 of the maximum value, in a time equal to the time constant. If the intervals are halved, the graphical construction gives a curve which rises to ·64 of the maximum value in the time $T = CR$, i.e. ·01 second, and is then a good approximation to the true curve; in fig. 25 several points on the latter are indicated by small circles. The reason for taking the longer time interval in the above example is simply to avoid crowding the lines on the graph.



METHOD OF PLOTTING CONDENSER VOLTAGE WHEN CHARGED AND DISCHARGED

FIG. 25
CHAP. 1.

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Discharge of condenser through resistance

60. In fig. 25 the condenser P.D. is practically equal to the applied voltage after an interval of ·05 second from the instant of closing the switch. If the switch S_1 is opened, the condenser would remain charged to this voltage if its insulation were perfect. As there is no such thing as a perfect insulant, the charge will gradually leak away, and the lower the insulation resistance between the plates, the more rapid will be the discharge. Let us suppose that we expedite the discharge by connecting the 1,000 ohm resistance across the terminals of the condenser by closing the switch S_2. A current commences to flow as soon as the circuit is completed, its value, momentarily, being $\frac{V}{R}$, V being the P.D. between the plates and equal to E, the voltage of the charging battery. The quantity of electricity which will pass in the short interval t seconds will be $\frac{V}{R}t$, and the fall in P.D. will be the quantity divided by the capacitance, or $\frac{V}{CR}t$. If this rate of discharge could be maintained, the condenser voltage would fall to zero in a time T, where $\frac{V}{CR}T$ is the total fall of P.D., i.e. V volts. The time T is therefore CR seconds, which it will be remembered is the time which would be taken to charge the condenser to the voltage of the supply if the initial rate of charge could be maintained. We now see that the initial rate of discharge is equal to the initial rate of charge provided the resistance of the circuit is the same in both charging and discharging. The initial rate of discharge can be shewn on the graph by a straight line drawn from the point $t = \cdot 05$, $E = 200$ volts to the point $t = \cdot 06$ second, $E = 0$. The discharging process is very similar to the process of charge, in that after a short interval of time t, the voltage available to cause current to flow is not V, but $V - \frac{V}{CR}t$. When $t = \cdot 0525$ second, the voltage available to cause further current to flow is only 150 volts, which should be compared with the voltage available for charging in the previous example. This 150 volts will now tend to discharge completely the condenser in a further ·01 second, and so a new " voltage fall " line may be drawn from the point $E = 150$ volts, $t = \cdot 0525$, to the point $E = 0$, $t = \cdot 0625$. Continued repetition of this process gives the discharge curve of the condenser. Instead of falling to zero in a time CR or ·01 second, the P.D. falls to 36·8 per cent. of its original value. The rate of charge and discharge of a condenser when associated with a resistance becomes of practical importance in certain radio instruments, for example, the " grid condenser and leak " commonly found in valve transmitting apparatus.

Dielectric strength

61. (i) If the P.D. applied to a condenser exceeds a certain limit the strain in the dielectric becomes so great that the atoms composing it are forced to allow a conduction current to flow, and the dielectric is then said to be punctured. In a solid dielectric the puncture actually takes the form of a hole which is burnt through the dielectric, and a plate of insulating material which has suffered in this way is of no further service. If the construction of the condenser is such that the defective plate cannot be removed, the whole condenser is rendered unserviceable by the failure of the one plate of dielectric, hence it is important that the rated safe voltage of any condenser shall not be exceeded. In liquid and gaseous dielectrics, the insulating substance closes round the puncture, and such substances are said to be self-sealing, but it must be appreciated that in a liquid dielectric such as oil the phenomenon of puncture will be accompanied by carbonisation of the oil and its insulating properties will be impaired. Puncture of liquid or gaseous dielectrics is facilitated by the presence of foreign bodies of poor insulating qualities, e.g. dust, metallic particles or fluff, and great care should be exercised in the exclusion of such substances when assembling or reassembling any condenser.

(ii) The dielectric strength of any material is defined as the voltage required to puncture a plate of the material one mil. (·001 in.) in thickness, the types of electrode used to apply the voltage to the dielectric itself being specified. For reasons into which it is unnecessary to enter, the dielectric strength between sharp points is less than between flat plates, or than between spherical balls, and condenser dielectrics are usually tested under the conditions in which they will be used, i.e. with flat metallic electrodes between which the dielectric is clamped. A thin sheet of dielectric is found experimentally to be proportionately stronger than a thicker one of the same material. The reason for this is obscure but appears to be associated with the fact that as the thickness of the material increases, the electric field strength in the dielectric departs to a greater degree from uniformity, and in certain places may reach a higher value than is calculated on the assumption of uniform field strength. The dielectric strength of some common insulating materials is given in Table II, Appendix A. It must be borne in mind that dielectrics puncture at lower voltages if subjected to alternating E.M.F. than if subjected to steady E.M.F. and the higher the frequency of the applied voltage the lower is the voltage at which a given dielectric will puncture. Hence condensers are generally marked with their test voltage, its nature whether alternating or steady being also stated. Thus a condenser marked " 4,000 volts, D.C. test ", means that it has passed a test in which a steady voltage of 4,000 volts was applied for a considerable period. The latter stipulation is important, for if the dielectric allows a small conductive current to flow its temperature will increase and the dielectric may be weaker at the higher temperature than at the lower. This point must also receive due attention in applying a condenser to any particular purpose. If the charging and discharging currents are very high, the metal plates forming the condenser may become heated, and the consequent heating of the dielectric may cause it to fail at voltages below the test voltage.

INSULATING MATERIALS

62. The insulating materials used in general electrical work may be either solid or liquid, the former comprising hygroscopic materials such as fibre, paper, asbestos, etc., and non-hygroscopic materials such as rubber, mica, glass, etc. The liquid insulators are practically confined to oils which are hygroscopic, and varnishes which are non-hygroscopic after baking at a high temperature. The following brief notes deal with some of the principal characteristics of various insulants.

Non-hygroscopic substances

63. *Rubber.*—This substance is a complex vegetable hydrocarbon occurring in the natural form as a sticky mass called latex, which is obtained from certain trees in the equatorial zone. The natural product is converted into rubber by first evaporating the moisture from the latex in a wood fire while stirring with a wooden paddle. The latex is then dried and hardened, and subjected to a purifying process, which consists of soaking in hot water for a long period, slicing the softened rubber, and then washing and drying, the resulting product emerging as sheets of crepe rubber, which is dried in a dark room at a temperature of about 130° F. The density of rubber is from 0·92 to 0·96, and its specific resistance at 24° C. is 11×10^{15} ohms per cm. cube. By mixing with from 2 to 3 per cent. of sulphur under the application of heat, a process which is termed vulcanisation, a material called vulcanised rubber is produced, and this material is not affected by temperature changes to the same extent as pure rubber. A slight increase in sulphur content results in the production of hard rubber or ebonite.

64. *Gutta percha.*—This material is also the coagulated sap of certain trees, and resembles rubber in some respects. It differs however in the following characteristics :—

(i) It softens at a low temperature of about 65° C.
(ii) It is unaffected by immersion in water provided it is screened from light.

The latter property suggests its principal use, which is the insulation of submarine cables. The density of gutta percha is about 0·98 and its specific resistance 2×10^9 ohm per cm. cube.

Chatterton's compound, which is used extensively in cable repair work, is made from the following materials. Gutta percha 60 per cent., Stockholm tar 20 per cent, resin 20 per cent.

65. *Mica.*—Mica is one of the most important electrical insulators, having a high dielectric strength and being capable of withstanding extremely high temperatures. It has certain disadvantages, however, being mechanically weak and only obtainable in thin sheets. It is a

mineral and is mined in India, Canada and U.S.A., being found in the crevices of certain igneous rocks, and its high price is in part owing to this, for often one ton of rock must be removed in order to obtain one pound of mica. The varieties of mica known as amber, green and ruby are slightly different in composition and the ruby is most used for high class work. Mica is not easily corroded and it withstands most acids and alkalies, but oil penetrates between its laminae in course of time and causes disintegration. The laminated structure is the outstanding feature of this substance, no other mineral possessing it.

The principal uses of mica for electrical purposes are :—

(i) Insulation of commutator segments (*see* Chapter IV). Canadian amber mica is used for this purpose, because under friction against a carbon brush it wears at the same rate as copper.

(ii) Insulation of heating units in apparatus such as electric soldering irons.

(iii) Manufacture of condensers for radio purposes, and also for magnetos. Ruby mica is invariably used for these, only the highest quality being accepted for transmitting condensers or magneto condensers.

(iv) Insulation of central electrode of sparking plugs for petrol engines. (*See* A.P. 1464, Engineering Manual.)

Micanite is extensively used in tubular form, e.g. in the slots of the armatures of dynamo electric machinery. (Chapter IV.) It is made by pasting together with shellac-varnish layers of mica flakes, sometimes with the addition of thin paper or cloth.

66. *Porcelain* is an artificial product, composed of china clay, flint and other ingredients which are ground to a fine powder with water, forming a plastic substance which is moulded to shape and afterwards baked. There is considerable shrinkage during the latter process, and it is not adapted for work which requires fine limits. It has no superior for such purposes as transformer terminal insulators, and for the insulation of overhead wires.

Marble and *slate* are good insulators possessing considerable mechanical strength, and like porcelain they are incombustible. Their chief use is in large switch-board panels.

Shellac is a natural product, the deposit of a certain kind of insect. It is a reddish brown substance which is sold in flakes, but is invariably used as a varnish which consists of flake shellac dissolved in alcohol.

Hygroscopic substances

67. *Paper* is extensively employed for insulating cables, being wound round the conductor in spiral form, and afterwards varnished and lead sheathed, the latter being almost compulsory owing to the hygroscopic nature of paper. In the manufacture of small parts such as magneto armatures and meter coils, a manilla paper coated with shellac is often used.

68. *Press-pahn* and *vulcanised fibre* are fibrous materials built up from laminae which are pressed together. Press-pahn is usually used in sheet form, while vulcanised fibre can be obtained in the form of sheet, rod or tube. Small bushes are often made of fibre in preference to ebonite on account of its greater mechanical strength, the bushes being frequently soaked in molten paraffin wax, which is an extremely good insulant, but is too weak mechanically for use except as a filling for such purposes, and for the construction of waxed-paper condensers.

69. *Asbestos.* This is a mineral which is found principally in Canada, South Africa and Italy. It is very hygroscopic, but can withstand extremely high temperatures. It is not used alone, except for the insulation of resistance elements, but forms an ingredient of several moulded compositions such as ebonestos and isolite.

Moulded compositions

70. The use of moulded parts has greatly increased of late years, owing to the reduction of cost compared with machined parts. The materials used generally consist of two principal ingredients, called the binder and the filler respectively. Moulding materials are classified according to the nature of the binder, the principal being rubber, natural resins and synthetic resins.

71. *Ebonite.*—This is the best known rubber composition. It consists of crepe rubber with the addition of about 40 per cent. by weight of sulphur, the mixture being amalgamated under hot rollers. This product, which is called " dough ", is pressed to the required shape in a steam-heated hydraulic press during which process partial vulcanisation occurs, the process being completed by " cureing " the moulding in a chamber filled with steam. Ebonite cannot be moulded within fine tolerances, some machining being invariably necessary. Ebonite has the following disadvantages, viz. extreme brittleness and poor mechanical strength, it undergoes chemical decomposition under the influence of sunlight, and it softens at about 60° C. On the other hand, its dielectric strength is very high.

72. *Stabalite.*—This material contains rubber and sulphur with the addition of certain mineral ingredients, and is chiefly used in the manufacture of certain radio parts, and in magnetos, particularly the distributor of the latter. It has all the advantages of ebonite, but none of its drawbacks. It will safely stand temperatures up to 100° C.

The materials using natural resin, such as shellac, resin, asphalt or bitumen, as the binder, are known by many proprietary names ; the fillers used are often wood pulp, magnesia, lime, sand and asbestos. None of these can be compared with ebonite or stabalite for dielectric strength and few will withstand greater temperatures than ebonite.

The synthetic resinous compounds consist of a binder which is formed by the action of phenol and formaldehyde, the fillers being wood pulp and asbestos. The best known of these products is bakelite which has good mechanical strength, high dielectric strength, and heat resisting properties, being efficient at temperatures up to 200° C. A further advantage is its excellent moulding properties, which have made it possible to mould items within a tolerance of a few thousandths of an inch. Other phenolic compounds are used for the panels of aircraft radio equipment.

Types of condensers

73. It was formerly usual to distinguish between " transmitting " and " receiving " condensers, but the necessity for this demarcation has disappeared to a large extent, because the peak voltages used in modern transmitters (other than those of very high power) are much lower than in the early days of radio communication, while on the other hand the efficiency of receiving condensers which formerly was not regarded as of very great importance, now receives a considerable amount of attention. A more useful classification is (i) low voltage, large capacitance, fixed value condensers, (ii) low voltage, small capacitance, fixed value condensers, (iii) high voltage, small capacitance, variable condensers. The main features and application of these classes will now be given.

74. Condensers of class (i) are commonly further subdivided into (*a*) non-inductive and (*b*) inductive types. The inductive type offers no electrical advantages and in some circumstances has positive drawbacks, but it is inexpensive and can be produced by automatic machinery. The dielectric is invariably of waxed paper, and carries a metallic coating which may be tin, lead or aluminium foil, but latterly is often applied to the dielectric by spraying, an alloy of low melting point being used. Two paper strips with their metal electrodes together with unmetallised paper strips for separating purposes are rolled upon a mandril, values of capacitance up to 10 μ F being obtained. This method of construction gives long thin electrodes, and the current density in the dielectric near the points to which terminal connection is made is greater than at points remote from the terminal connections. A condenser having this " rolled-up " form possesses an inherent inductance which is of the order of a few microhenries and in certain circuits this causes serious complications. The non-inductive type is preferable in all respects, but is more expensive to make, as it is built up of flat plates, interleaved with a suitable dielectric, which may be waxed paper but is more often thin mica. Even so, there must be some slight residual inductance, but this is much less than the inductance of a condenser of rolled up construction. Non-inductive condensers are made in all values of capacitance up to about ·1 μ F, larger values than this being seldom required. It is important to observe that even a few inches of connecting wire may seriously prejudice the behaviour of such a condenser, but further consideration of this point must be deferred until later.

75. Condensers of class (ii) are of similar construction to the non-inductive type just discussed, but either mica or air is invariably used as the dielectric. When mica is adopted the condenser is often assembled in two, three or four sections which are connected in series, in order that the condenser will withstand the desired voltage. Copper foil electrodes are usually employed, and a range of capacitance between ·00005 and ·005 μ F can be obtained, the overall dimensions being quite small, e.g. a ·005 μ F condenser for 500 volts D.C. test may occupy about 0·5 cubic inch. When extremely low dielectric losses are essential, and the desired capacitance does not exceed about ·0001 μ F, air dielectric may be employed; the construction then resembles an air dielectric variable condenser, except that no provision is made for alteration of capacitance. Condensers of class (iii) are commonly employed in the radio frequency circuits of both transmitters and receivers. The condenser consists of a number of fixed plates of brass or aluminium, which are in electrical connection and form one electrode of the condenser. A second set of plates, generally called the moving vanes, are capable of rotation about a central axis. These vanes are often of semi-circular shape, and rotation of the spindle upon which they are mounted causes them to mesh into the spaces between the fixed plates so forming a condenser, the capacitance of which can be altered by variation of the amount of overlap between the fixed plates and the moving vanes. Air dielectric is almost universal for these condensers although occasionally thin ebonite, synthetic resin or mica plates are inserted between fixed and moving vanes, and are generally free to rotate with the latter. The dielectric then consists partly of air and partly of solid material and the capacitance is somewhat increased. In the service Type 7 condenser, which is a variable condenser of ·0009 μ F maximum capacitance normally, and is of very robust construction, the plates are enclosed in a glass vessel which can be filled with oil, if necessary. By this means the maximum capacitance can be increased to a value about three times its normal.

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