

Electrical and Radio Fundamentals

2-1 Fundamentals of a Radio System

THE BASIS of radio communication is the transmission of electromagnetic waves through space. The production of suitable waves constitutes radio transmission, and their detection, or conversion at a distant point into the intelligence put into them at the originating point, is radio reception. There are several distinct processes involved in the complete chain. At the transmitting point it is necessary first to generate power in such form that when it is applied to an appropriate radiator, called the antenna, it will be sent off into space in electromagnetic waves. The message to be conveyed must be superimposed on that power by suitable means, a process called modulation.

As the waves spread outward from the transmitter they rapidly become weaker, so at the receiving point an antenna again is used to abstract as much energy as possible from them as they pass. The wave energy is transformed into an electric current which is then amplified, or increased in amplitude, to a suitable value. Then the modulation is changed back into the form it originally had at the transmitter. Thus the message becomes intelligible.

Since these processes are performed by electrical means, a knowledge of the principles of electricity is necessary to understand them.

2-2 The Nature of Electricity

Electrons — All matter — solids, liquids and gases — is made up of fundamental units, called *molecules*. The molecule, the smallest subdivision of a substance retaining all its characteristic properties, is constructed of *atoms* of the elements comprising the substance.

The atom is made up of a central part, called the *nucleus*, around which minute particles or charges of electricity, called *electrons*, circulate. The atom can be compared roughly to the solar system, with the sun representing the nucleus and the planets the electrons. By far the greater part of the mass or weight of an atom is in the nucleus, but because of its extreme compactness the nucleus occupies only a small part of the space taken up by the atom. In the normal or *neutral* atom the electrical "charge" on each electron is balanced by an equal charge of opposite kind associated with the nucleus. The kind of electricity represented by the electron is called *negative*, while that associated with the nucleus is called *positive*.

The greater mass of the nucleus (the nucleus is more than 1800 times as heavy as the electrons associated with it) is considered to be principally in neutral particles — that is, particles which exhibit no electrical effects — bound together by some means. These neutral particles each may actually be the result of the combination of a positive and a negative particle, so that the charge on each is neutralized. The net positive charge associated with the nucleus can be looked upon as an excess of positive particles, or as an absence of enough negative charges to neutralize completely the positive charges present. Ordinary electrical activity is the result of movements of the electrons, or negative charges, so it is customary to consider electrical phenomena as caused by the presence or absence of these negative particles.

In the atoms of many substances, one or two of the outer electrons associated with the nucleus can be detached from the atom by suitable means, thus leaving the atom as a whole with a net positive charge. When this occurs, electrical activity becomes evident.

The unit of quantity — The amount of electricity represented by a single electron is extremely small — far too small to be used as a unit of quantity in practical electrical work. The practical unit of electrical quantity is the *coulomb*. One coulomb is equal to about 6.2×10^{18} electrons. Because the electron is so minute, the "granular" nature of electricity is not apparent in practical work.

Static and current electricity — An electrical charge may be either at rest (*static*) or moving. *Electrostatics* is that branch of electrical theory which deals with the behavior of electricity at rest. If an electrical charge is moving, its movement constitutes a *current* of electricity. The movement may take place through a vacuum, through a gas or liquid, or through solid materials (usually metals) called *conductors*. When the movement is through a solid, the collection of electrons constituting the original charge does not move as a unit through the entire path; instead, individual electrons all along the path are urged to leave the atoms to which they are attached. Each electron travels only a relatively short distance before finding another atom which is electron-deficient, and to which it tends to attach itself. The motion is, therefore, transmitted along the path from electron to electron, much in the same way that motion in a chain is transmitted from link

to link. Naturally, the ease with which the electron motion is transmitted depends upon the ease with which an electron can be detached from an atom of the substance through which the current is moving.

The flow of current through a conductor is accompanied by heating of the conductor, which may be explained as resulting from collisions between moving electrons and atoms, setting the latter into vibration. Thus there is a loss of energy, in the form of heat, accompanying the flow of current.

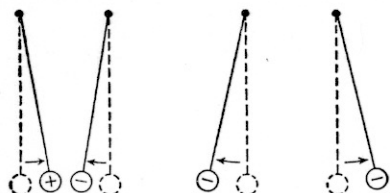


Fig. 201 — Attraction and repulsion of charged objects, as demonstrated by the pith-ball experiment described.

Insulators and conductors — Materials whose atoms will readily give up an electron are called *conductors*, while those in which all the electrons are firmly bound in the atom are called *insulators* or *dielectrics*. Most metals are good conductors, as also are acid or salt solutions. Among the insulators are wood, hard rubber, bakelite, quartz, glass, porcelain, textiles and many other nonmetallic materials.

Resistance — No substance is a perfect conductor, and there is also no such thing as a perfect insulator. The measure of the difficulty in moving an electron by electrical means is called *resistance*. Good conductors have low resistance (high *conductivity*), good insulators very high resistance. Between the two are materials which are neither good conductors nor good insulators, but nonetheless are useful since there often is need for intermediate values of resistance in electrical circuits.

Circuits — A circuit is simply a complete path along which electrons can move. There will normally be a source of energy (a battery, for instance), and a *load*, or portion of the circuit where the current is made to do useful work. There must be an unbroken path through which the electrons can move, with the source of energy acting as an electron pump and sending them around the circuit. The circuit is said to be *open* when no charges can move, because of a break in the path. It is *closed* when no break exists — when switches are closed and all connections are made.

2-3 Static Electricity

The electric charge — Many materials that have a high resistance can be made to acquire a charge (surplus or deficiency of electrons) by mechanical means, such as friction. The familiar crackling when a hard-rubber comb is run through hair on a dry winter day is an example of an electric charge generated by friction. Objects can have either a surplus or a

deficiency of electrons — a surplus of electrons is called a *negative* charge; a lack of them is called a *positive* charge. The kind of charge is called its *polarity*. A negatively charged object is frequently called a *negative pole*, and a positively charged object a *positive pole*.

Attraction and repulsion — Unlike charges (one positive, one negative) exert an attraction on each other. This can be demonstrated by giving charges of opposite polarity to two very light, well-insulated conductors, such as bits of metal foil suspended from dry thread (Fig. 201). (Pith balls covered with foil frequently are used in this experiment.) When the two charged objects are brought close together, they will be attracted to each other. If the charges are equal and the charged bodies are permitted to touch, the surplus electrons on the negatively charged object will transfer to the positively charged object (i.e., the one deficient in electrons) and the two charges will neutralize, leaving both bodies uncharged. If the charges are not equal, the weaker charge neutralizes an equal amount of the stronger when the two bodies touch, upon which the excess of the stronger charge distributes itself over both. Both bodies then have charges of the same polarity, and a force of repulsion is exercised between them. Consequently, the bits of foil tend to spring away from each other. *Unlike charges attract, like charges repel.*

Electrostatic field — From the foregoing it is evident that an electric charge can exert a force through the space surrounding the charged object. The region in which this force is exerted is considered to be pervaded by an *electrostatic field*, this concept of a field being adopted to explain the "action at a distance" of the charge. The field is pictured as consisting of *lines of force* originating on the charge and spreading in all directions, finally terminating on other charges of opposite polarity. These other charges may be a very large distance away. The number of lines of force per unit area is a measure of the intensity of the field.

The general picture of a charged object in isolated space is shown in Fig. 202. This is an idealized situation, since in practice the charged object could not be completely isolated. The presence of other charges, or simply of insulators or conductors, in the vicinity will greatly change the configuration of the field. The direction of the field, as indicated by the

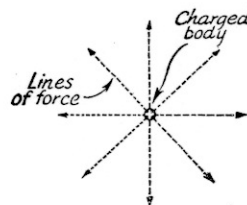


Fig. 202 — Lines of force from a charged object extend outward radially. Although only two dimensions are shown, the field extends in all directions from the charge, and should be visualized in three dimensions.

arrowheads, is away from a positively charged object; if the charge were negative, the direction would be toward the charge.

It should be understood that the field picture as represented above is a convenient method of explaining observed effects, and is not to be taken too literally. The electric force does not consist of separate lines like strings or rods, but completely pervades the medium through which the force is exerted. With this understanding, it is *convenient* to talk of lines of force and to measure the field intensity in terms of number of lines per unit area.

The intensity of the field dies away with distance from the charged object in a manner determined by its shape and the circumstances of its surroundings. In the case of an isolated charge at a point (an infinitesimally small object), the field strength is inversely proportional to the square of the distance. However, this relationship is not true in many other cases; in some important practical applications the field intensity is inversely proportional to the distance, not to its square.

Electrostatic induction — If a piece of conducting material is brought near a charged object, the field will exert a force on the electrons of the metal so that those free to move will do so. If the object is positively charged, as indicated in Fig. 203, the free electrons will move toward the end of the conductor nearest the charged body, leaving a deficiency of electrons at the other end. Hence, one end of the conductor becomes negatively charged while the other end has an equal positive charge. The lines of force from the charged body terminate on the conductor, where sufficient electrons accumulate to provide an electric intensity equal and opposite to that of the field at that point. Because of this effect, the electrostatic field inside the conductor is completely neutralized by the induced charge; in other words, the field does not penetrate the conductor. In radio work this provides the means by which electrostatic fields may be excluded from regions where they are not wanted.

Charges induced in a conductor as shown in Fig. 203-A are held in existence by the field from the charged object. On taking the conductor out of the field the electrons will redistribute themselves so that the charges disappear. However, if the conductor is connected to the earth through a wire while under the influence of the field, as shown in Fig. 203-B, the induced positive charge will tend to move as far as possible from the source of the field (that is, electrons will flow from the earth to the conductor). If the grounding wire is then removed, the conductor will be left with an excess of electrons and will have acquired a "permanent" charge — permanent, that is, so long as the conductor is well enough insulated to prevent the charge from escaping to earth or to other objects. The polarity of the induced charge always is opposite to the polarity of the charge which set up the original field.

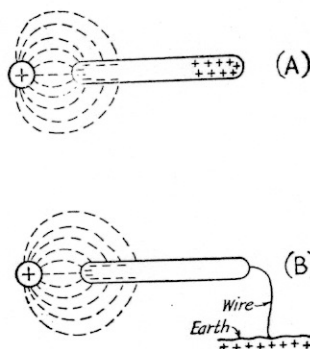


Fig. 203 — Electrostatic induction. The field from the positively charged body attracts electrons, which accumulate to form a negative charge. The opposite end of the conductor consequently acquires a positive charge. This may be "drained off" to earth, as shown at (B).

Energy in the electrostatic field — The expenditure of energy is necessary to place an electrical charge upon an object and thus establish an electrostatic field. Once the field is established and is constant, no further expenditure of energy is required. The energy supplied to establish the field is stored in the field; thus the field represents *potential energy* (that is, energy available for use). The potential energy is acquired in the same way that potential energy is given any object (a 10-pound weight, for instance) lifted against the gravitational pull of the earth. If the weight is allowed to drop, its potential energy is changed into the energy of motion. Similarly, if the electrostatic field is made to disappear, its potential energy is transformed into a movement of electrons, or into an electric current.

The potential energy of the lifted weight is measured by its weight and the distance it is lifted; that is, by the work done in lifting it. Similarly, the potential energy (called simply *potential*) of the electrostatic field at any point is measured by the work done in moving a charge of specified value to that point, against the repulsion of the field. In practice, absolute potential is of less interest than the *difference of potential* between two points in the field.

Potential difference — If two objects are charged differently, a potential difference exists between them. Potential difference is measured by an electrical unit called the *volt*. The greater the potential difference, the higher (numerically) the voltage. This voltage exerts an electrical pressure or *force* as explained above, and is often called *electromotive force* or, simply, *e.m.f.* It is not necessary to have unlike charges in order to have a difference of potential; both, for instance, may be negative, so long as one charge is more intense than the other. From the viewpoint of the stronger charge, the weaker one appears to be positive in such a case, since it has a smaller number of excess electrons; in other words, its *relative polarity* is positive. The greater the potential difference, the more intense is the electrostatic field between the two charged objects.

Capacity—More work must be done in moving a given charge against the repulsion of a strong field than against a weak one; hence, potential is proportional to the strength of the field. In turn, field strength is proportional to the charge or quantity of electricity on the charged object, so that potential also is proportional to charge. By inserting a suitable constant, the proportionality can be changed to an equality:

$$Q = CE$$

where Q is the quantity of charge, E is the potential, and C is a constant depending upon the charged object (usually a conductor) and its surroundings and is called the *capacity* of the object. Capacity is the ratio of quantity of charge to the potential resulting from it, or

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

When Q is in coulombs and E in volts, C is measured in *farads*. A conductor has a capacity of one farad when the addition of one coulomb to its charge raises its potential by one volt.

The farad is much too large a unit for practical purposes. In radio work, the *microfarad* (one millionth of a farad) and the *micro-microfarad* (one millionth of a microfarad) are the units most frequently used. They are abbreviated $\mu fd.$ and $\mu\mu fd.$, respectively.

The capacity of a conductor in air depends upon its size and shape. A given charge on a small conductor results in a more intense electrostatic field in its vicinity than the same charge on a larger conductor. This is because the charge distributes itself over the surface, hence its density (the quantity of electricity per unit area) is smaller on the larger conductor. Consequently, the potential of the larger conductor is smaller, for the same amount of charge. In other words, its capacity is greater because a greater charge is required to raise its potential by the same amount.

Condensers—If a grounded conductor, A (Fig. 204), is brought near a second conductor, B , which is charged, the former will acquire a charge by electrostatic induction. Since the

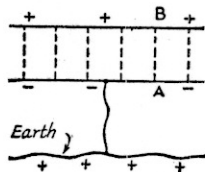


Fig. 204—The principle of the condenser.

charge on A is opposite in polarity to that on B , the field set up by the induced charge on A will oppose the original field set up by the charge on B , hence the potential of B will be lowered. Because of this, more charge must be placed on B to raise its potential to its original value; in other words, its *capacity has been increased* by the presence of the second conductor. The combination is called a *condenser*.

The capacity of a condenser depends upon the areas of the conductors, as before, and also becomes greater as the distance between the conductors is decreased, since, with a fixed amount of charge, the potential difference between them decreases as they are moved closer together.

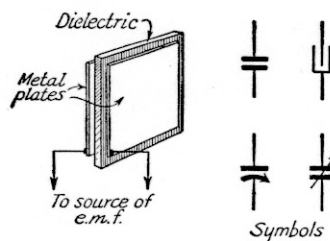


Fig. 205—A simple type of condenser, consisting of two metal plates separated by dielectric material. Diagrammatic symbols for condensers are shown at the right. The two at the top indicate condensers of fixed capacity; the two below, condensers whose capacity is variable. The symbols on the left are commonly used.

If insulating or dielectric material other than air is inserted between the conductors, it is found that the potential difference is lowered still more—that is, there is a further increase in capacity. This lowering of the potential difference is considered to be the result of *polarization* of the dielectric. By this it is meant that the molecules of the substance tend to be distorted under the influence of the electrostatic field in such a way that the negative charges within the molecule are drawn toward the positively charged conductor, leaving the other end of the molecule with a positive charge facing the negatively charged conductor. Since the electrons are firmly bound in the atoms of the dielectric, there is no flow of current and the total charge on each atom is still zero, but there is a *tendency* toward separation which causes a reaction on the electrostatic field. The dielectric of a charged condenser thus is under mechanical stress, and if the potential difference between the plates of the condenser is great enough the dielectric may break down mechanically and electrically.

The ratio of the capacity of a condenser with a given dielectric material between its plates to the capacity of the same condenser with air as a dielectric is called the *specific inductive capacity* of the dielectric, or, probably more commonly, the *dielectric constant*. Strictly speaking, the comparison should be made to empty space (i.e., a vacuum) rather than to air, but the dielectric constant of air is so nearly that of a vacuum that the practical difference is negligible. A table of dielectric constants is given in Chapter Twenty-One.

Condensers have many uses in electrical and radio circuits, all based on their ability to store energy in the electric field when a potential difference or voltage is caused to exist between the plates—energy which later can be released to perform useful functions.

2-4 The Electric Current

Conduction in metals — When a difference of potential is maintained between the ends of a metallic conductor, there is a continuous drift of electrons through the conductor toward the end having a positive potential (relative polarity positive). This electron drift constitutes an electric current through the metal (§ 2-2). The speed with which the electron movement is established is very nearly the speed of light (300,000,000 meters, or approximately 186,000 miles, per second), so that the current is said to travel at nearly the speed of light. By this it is meant that the time interval between the application of the electromotive force and the flow of current in all parts of a circuit, even one extending over hundreds of miles, is negligible. However, the individual electrons do not move at anything approaching such a speed. The situation is similar to that existing when a mechanical force is transmitted by means of a rigid rod. A force applied to one end of the rod is transmitted practically instantaneously to the other end, even though the rod itself moves relatively slowly or not at all.

The magnitude of the electric current is the rate at which electricity is moved past a point in the circuit. If the rate is constant, then the current is equal to the quantity of electricity moved past a given point in some selected time interval. That is,

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

where I is the intensity or magnitude of the current, Q is the quantity of electricity, and t is the time. If Q is in coulombs and t in seconds, the unit for I is called the *ampere*. One ampere of current is equal to one coulomb of electricity moving or "flowing" past a given point in a circuit in one second.

The currents used by different electrical devices vary greatly in magnitude. The current which flows in an ordinary 60-watt lamp, for instance, is about one-half ampere, the current in an electric iron is about 5 amperes, and that in a radio tube may be as low as 0.001 ampere.

When a current flows through a metallic conductor there is no visible or chemical effect on the conductor. The only physical effect is the heat developed (§ 2-2) as the result of energy loss in the conductor. Under normal conditions the rate at which heat is generated and that at which it is radiated by the conductor will quickly reach equilibrium. However, if the heat is developed at a more rapid rate than it can be radiated, the temperature will continue to rise until the conductor burns or melts.

Experimental measurements have shown that the current which flows in a given metallic conductor is directly proportional to the applied e.m.f., so long as the temperature of the conductor is held constant. There is no e.m.f. so small but that some current will flow as a result of its application to a metallic conductor.

Gaseous conduction — In any gas or mixture of gases (such as air, for example) there are always some free electrons — that is, electrons not attached to an atom — and also some atoms lacking an electron. Thus there are both positively and negatively charged particles in the gas, as well as many neutral atoms. An atom lacking an electron is called a *positive ion*, while the free electron is called a *negative ion*. The term *ion* is, in fact, applied to any elemental particle which has an electric charge.

If the gas is in an electric field, the free electrons will be attracted toward the source of positive potential and the positive ions will be attracted toward the source of negative potential. If the gas is at atmospheric pressure neither particle can travel very far before meeting an ion of the opposite kind, when the two combine to form a neutral atom. Since a neutral atom is not affected by the electric field, there is no flow of current through the gas.

However, if the gas is enclosed in a glass container in which two separate metal pieces called *electrodes* are sealed, and the gas pressure is then reduced by pumping out most of the gas, a different set of conditions results. At low pressure there is a comparatively large distance between each atom, and when an electric field is established by applying a difference of potential to the electrodes the ions can travel a considerable distance before meeting another ion or atom. The farther the ion travels the greater the velocity it acquires, since the effect of the field is to accelerate its motion. If the field is strong enough the ions will acquire such velocity that when one happens to collide with a neutral atom the force of the collision will knock an electron out of the atom, so that this atom also becomes *ionized*. The process is cumulative, and the freed electrons are attracted to the positive electrode while the positive ions are attracted to the negative electrode. This movement of charged particles constitutes an electric current through the gas.

Since an ion must acquire a certain velocity before it can knock an electron out of a neutral atom, a definite field strength is required before conduction can take place in a gas. That is, a certain value of potential difference, called the *ionizing potential*, must be applied to the electrodes. If less voltage is applied, the

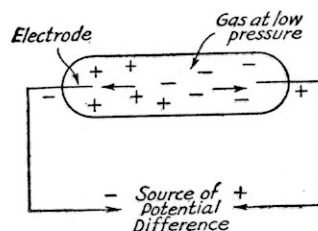


Fig. 206 — Illustrating conduction through a gas at low pressure. Positive ions are attracted to the negative electrode, while electrons are attracted to the positive electrode. This takes place only after the gas is ionized.

gas does not ionize and the current is negligible. On the other hand, once the gas is ionized an increase in potential does not have much effect on the current, since the ions already have sufficient velocity to maintain the ionization. The ionizing potential required depends upon the kind of gas and the pressure. Ionization is usually accompanied by a colored glow in the gas, different kinds of gases having different characteristic colors.

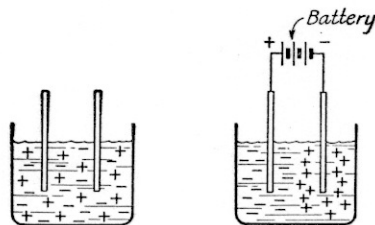


Fig. 207 — Electrolytic conduction. When an e.m.f. is applied to the electrodes, negative ions are attracted to the positively charged plate and positive ions to the negatively charged plate. The battery, which is the source of the e.m.f., is indicated by its customary symbol.

Current flow in liquids — A very large number of chemical compounds have the peculiar characteristic that, when they are put into solution, the component parts become ionized. For example, common table salt (sodium chloride), each molecule of which is made up of one atom of sodium and one of chlorine, will, when put into water, break down into a sodium ion (positive, with one electron deficient) and a chlorine ion (negative, with one excess electron). This can only occur so long as the salt is in solution — take away the water and the ions are recombined into the neutral sodium chloride. This spontaneous *dissociation* in solution is another form of ionization, and if two wires with a difference of potential across them are placed in the solution, the negative wire will attract the positive sodium ions and the positive wire will attract the negative chlorine ions. Thus an electric current will flow through the solution. When the ions reach the wires the electron surplus or deficiency will be remedied, and a neutral atom will be formed.

In this process, the water is decomposed into its gaseous constituents, hydrogen and oxygen. The energy used up in decomposing the water and in moving the ions is supplied by the source of potential difference. The energy used in decomposing the water is equivalent to an opposing e.m.f., of the order of a volt or two. If this constant "back voltage" is subtracted from the applied voltage, it is found that the current flowing through a given solution, or *electrolyte*, is proportional to the difference between the two voltages.

Current flow in vacuum — If a suitable metallic conductor is heated to a high temperature in a vacuum, electrons will be emitted from the surface. The electrons are freed from this *filament* or *cathode* because it has been

heated to a temperature that gives them sufficient energy of motion to allow them to break away from the surface. The process is called *thermionic electron emission*. Now, if a metal plate is placed in the vacuum and given a positive charge with respect to the cathode, this plate or *anode* will attract a number of the electrons that surround the cathode. The passage of the electrons from cathode to anode constitutes an electric current. All thermionic vacuum tubes depend for their operation on the emission of electrons from a hot cathode.

Since the electrons emitted from the hot cathode are negatively charged, it is evident that they will be attracted to the plate only when the latter is at a positive potential with respect to the cathode. If the plate is negatively charged with respect to the cathode the electrons will be repelled back to the cathode, hence no current will flow through the vacuum. Consequently, a thermionic vacuum tube conducts current in *one direction only*. When the plate is positive, it is found that (if the potential is not too large) the current increases with an increase in potential difference between the plate and cathode. However, the relationship between current and applied voltage is not a simple one. If the voltage is made large enough all the electrons emitted by the cathode will be drawn to the plate, and a further increase in voltage therefore cannot cause a further increase in current. The number of electrons emitted by the cathode depends upon the temperature of the cathode and the material of which it is constructed.

Direction of current flow — Use was being made of electricity for a long time before its electronic nature was understood. While it is now clear that current flow is a drift of negative electrical charges or electrons toward a source of positive potential, in the era preceding the electron theory it was *assumed* that the current flowed from the point of higher positive potential to a point of lower (i.e., less positive or more negative) potential. While this assump-

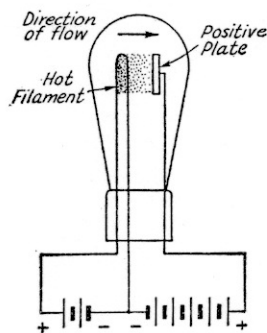


Fig. 208 — Illustrating conduction by thermionic emission of electrons in a vacuum tube. One battery is used only to heat the filament to a temperature where it will emit electrons. The other battery places a potential on the plate which is positive with respect to the filament, and as a result the electrons are attracted to the plate. The flow of electrons from filament to plate completes the electrical path, and current flows in the plate circuit.

tion turned out to be wholly wrong, it is still customary to speak of current as flowing "from positive to negative" in many applications. The practice often causes confusion, but this distinction between "current" flow and "electron" flow often must be taken into account. If electron flow is specifically mentioned there is of course no doubt as to the meaning, but when the direction of *current* flow is specified it may be taken, by convention, as being opposite to the direction of electron movement.

Primary cells—If two electrodes of dissimilar metals are immersed in an electrolyte, it is found that a small difference of potential exists between the electrodes. Such a combination is called a *cell*. If the two electrodes are connected together by a conductor external to the cell, an electric current will flow between them. In such a cell, chemical energy is converted into electrical energy. The difference of potential arises as a result of the fact that material from one or both of the electrodes goes into solution in the electrolyte, and in the process ions are formed in the vicinity of the electrodes. The electrodes acquire charges because of the electric field associated with the charged ions. The difference of potential between the electrodes is principally a function of the metals used, and is more or less independent of the kind of electrolyte or the size of the cell.

When current is supplied to an external circuit, two principal effects occur within the cell. The negative electrode (negative as viewed from outside the cell) loses weight as its material is used up in furnishing energy, and hydrogen bubbles form on the positive electrode. Since the gas bubbles are non-conducting, their accumulation tends to reduce the effective area of the positive electrode, and consequently reduces the current. The effect is cumulative, and eventually the electrode will be completely covered and no further current can flow. This effect is called *polarization*. If the bubbles are removed, or prevented from forming by chemical means, polarization is reduced and current can flow as long as there is material in the negative electrode to furnish the energy. A chemical which prevents the formation of hydrogen bubbles in a cell is called a *depolarizer*.

In addition to polarization effects, a cell has a certain amount of *internal resistance* because of the resistance of the electrodes and the electrolyte and the contact resistance between the electrodes and electrolyte. The *internal resistance* depends upon the materials used and the size and electrode spacing of the cell. Large cells with the electrodes close together will have smaller internal resistance than small cells made of the same materials.

A collection of cells connected together is called a *battery*. The term battery also is applied frequently (although incorrectly) to a single cell.

Dry cells—The most familiar form of primary cell is the *dry cell*. Like the elementary type of cell just described, it has a liquid elec-

trolyte, but the liquid is mixed with other materials to form a paste. The cell therefore can be used in any position and handled as though it actually were dry.

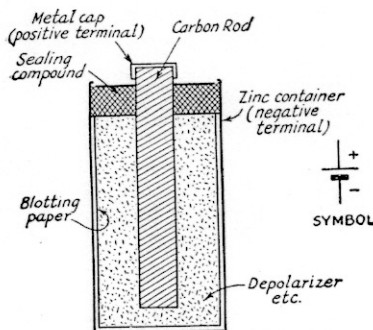


Fig. 209 — Construction of a dry cell.

The construction of an ordinary dry cell is shown in Fig. 209. The container is the negative electrode and is made of zinc. Next to it is a section of blotting material saturated with the electrolyte, a solution of sal ammoniac. The positive electrode is a carbon rod, and the space between it and the blotting paper is filled with a mixture of carbon, manganese dioxide (the depolarizer) and the electrolyte. The top is filled with sealing compound to prevent evaporation, since the cell will not work when the electrolyte dries out. The e.m.f. of a dry cell is about 1.5 volts.

Dry cells are made in various sizes, depending upon the current which they will be called upon to furnish. The construction frequently varies from that shown in Fig. 209, although in general the basic materials are the same in all dry cells. Batteries of small cells are assembled together as a unit for furnishing plate current for the vacuum tubes used in portable receiving sets; such "B" batteries, as they are called, can supply a current of a few hundredths of an ampere continuously. Larger cells, such as the common "No. 6" cell, can deliver currents of a fraction of an ampere continuously, or currents of several amperes for very short periods of time. The total amount of energy delivered by a dry cell is larger when the cell is used only intermittently, as compared with continuous use. The cell will deteriorate even without use, and should be put into service within a year or so from the time it is manufactured. The period during which it is usable (without having been put in service) is known as the "shelf life" of the cell or battery.

Secondary cells—The types of cells just described are known as *primary cells*, because the electrical energy is obtained directly from chemical energy. In some types of cells the chemical actions are reversible; that is, forcing a current through the cell, in the opposite direction to the current flow when the cell is delivering electrical energy, causes just the reverse chemical action. This tends to restore the cell to its original condition, and electrical

energy is transformed into chemical energy. The process is called *charging* the cell. A cell which must first be charged before it can deliver electrical energy is called a *secondary cell*.

A simple form of secondary cell can be made by immersing two lead electrodes in a dilute solution of sulphuric acid. If a current is forced through the cell, the surface of the electrode which is connected to the positive terminal of the charging e.m.f. will be changed to lead peroxide and the surface of the electrode connected to the negative terminal will be changed to spongy lead. After a period of charging the charging source can be disconnected, and the cell will be found to have an e.m.f. of about 2.1 volts. It will furnish a small current to an external circuit for a period of time. This *discharge* of electrical energy is accompanied by chemical action which forms lead sulphate on both electrodes. When the lead peroxide and spongy lead are converted to lead sulphate there is no longer a difference of potential, since both electrodes are now the same material, and the cell is completely discharged.

The lead storage battery — The most common form of secondary cell is the lead storage cell. The common storage battery for automobile starting consists of three such cells connected together electrically and assembled in a single container. The principle of operation is similar to that just described, but the construction of the cell is considerably more complicated. To obtain large currents it is necessary to use electrodes having a great deal of surface area and to put them as close together as possible. The electrodes are made in the form of rectangular flat plates, consisting of a latticework or grid of lead or an alloy of lead. The interstices of the latticework are filled with a paste of lead oxide. The electrolyte is a solution of sulphuric acid in water. When the cell is charged, the lead oxide in the positive plate is converted to lead peroxide and that in the negative plate to spongy lead. To obtain high current capacity, a cell consists of a number of positive plates, all connected together, and a number of negative plates likewise connected together. They are arranged as shown in Fig. 210, with alternate negative and positive plates kept from touching by means of thin separators of insulating material, generally

treated wood or perforated hard rubber. The separators preferably should be porous, so that the electrolyte can pass through them freely; thus they do not impede the passage of current from one plate to the next. There is always one extra negative plate in such an assembly, because the active material in the positive plate expands when the cell is being charged and if all the expansion took place on one side the plate would be distorted out of shape.

The e.m.f. of a fully charged storage cell is about 2.1 volts. When the e.m.f. drops to about 1.75 volts on discharge, the cell is considered to be completely discharged. Discharge beyond this limit may result in the formation of so much lead sulphate on the plates that the cell cannot be recharged, since lead sulphate is an insulator. During the charging process water in the electrolyte is used up, with the result that the sulphuric acid solution becomes more concentrated. The higher concentration increases the specific gravity of the solution, so that the specific gravity may be used to indicate the state of the battery with respect to charge. In the ordinary lead storage cell the solution is such that a specific gravity of 1.285 to 1.300 indicates a fully charged cell, while a discharged cell is indicated by a specific gravity of 1.150 to 1.175. The specific gravity can be measured by means of a *hydrometer*, shown in Fig. 211. For use with portable batteries, the hydrometer usually consists of a glass tube fitted with a syringe so that some of the electrolyte can be drawn from the cell into the tube. The hydrometer float is a smaller glass tube, air-tight and partly filled with shot to make it sink into the solution. The lower the specific gravity of the solution, the farther the float sinks into it. A graduated scale on the float shows the specific gravity directly, being read at the level of the solution.

Storage cells are rated in *ampere-hour capacity*, based on the number of amperes which can be furnished continuously for a stated period of time. For example, the cell may have a rating of 100 ampere-hours at an 8-hour discharge rate. This means that the cell will deliver 100/8 or 12.5 amperes continuously for 8 hours after having been fully charged. The ampere-hour capacity of a cell will vary with the discharge rate, becoming smaller as the rated time of discharge is made shorter. It also depends upon the size of the plates and their number. In automobile-type batteries the dimensions of the plates are fairly well standardized, so that the ampere-hour capacity is chiefly determined by the number of plates in a cell. It is, therefore, common practice to speak of "11-plate," "15-plate," etc., batteries as an indication of the battery capacity.

Lead storage batteries must be kept fully charged if they are to stay in good condition. If a discharged battery is left standing idle, lead sulphate will

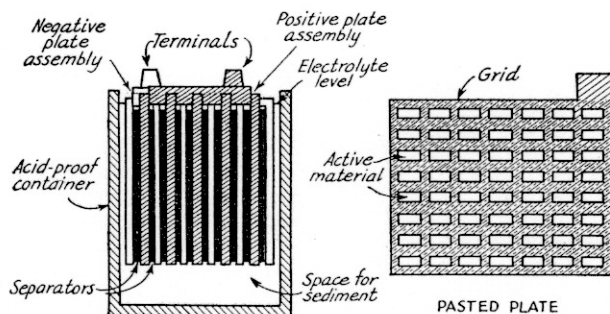


Fig. 210 — Details of typical lead storage-battery construction.

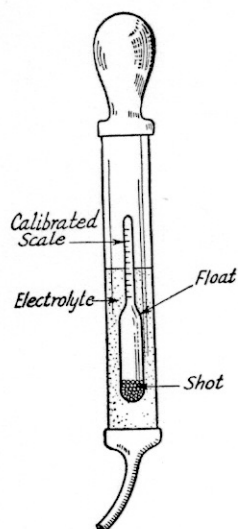


Fig. 211 — The hydrometer, a device with a calibrated scale for measuring the specific gravity of the electrolyte, used to determine the state of charge of a lead storage battery.

form on the plates and eventually the battery will be useless. When the battery is being charged, hydrogen bubbles are given off by the electrolyte which, in bursting at the surface, throw out fine drops of the electrolyte. This is called "gassing." The sulphuric-acid solution spray from gassing will attack many materials, and consequently care must be used to see that it is not permitted to fall on near-by objects. It should also be wiped off the battery itself.

A lead battery may be charged at its nominal discharge rate; i.e., a 100-ampere-hour battery, 8-hour rating, can be charged at 100/8, or 12.5 amperes. The charging voltage required is slightly more than the output voltage of the cell. The preferred method is to charge at the full rate until the cells start to "gas" freely, after which the charging rate should be dropped to about half its initial value until the battery is fully charged, as indicated by the hydrometer reading. Alternatively, the battery may be charged from a constant-potential source (about 2.3 volts per cell), when the rise of terminal voltage of the battery as it accumulates a charge will automatically "taper" the charging rate.

The solution in a lead storage battery will freeze at a temperature of about zero degrees Fahrenheit when the battery is discharged, but a fully charged battery will not freeze until the temperature reaches about 90 degrees below zero. Keeping the battery charged therefore will prevent damage by freezing.

Cells in series and parallel — For proper operation, many electrical devices require higher voltage or current than can be obtained from a single cell. If greater voltage is needed, cells may be connected in *series*, as shown in Fig. 212-A. The negative terminal of one cell is connected to the positive terminal of the next, so that the total e.m.f. of the battery is equal to the sum of the e.m.f.s of the individual cells. For radio purposes, batteries of 45 and 90 volts or more are built up in this way from 1.5-volt dry cells. An automobile storage battery consists of three lead storage cells in series, totaling 6.3 volts — or, in round figures, 6 volts. The current which may be taken safely from a battery composed of cells in series is the same as that which may be taken safely from one cell alone; since the same current flows through all cells, the current capacity is unchanged.

When the device or load to which the battery is to be connected requires more current than can be taken safely from a single cell, the cells may be connected in parallel, as shown in Fig. 212-B. In this case the total current is the sum of the currents contributed by the individual cells, each contributing the same amount if the cells are all alike. When cells are connected in parallel it is essential that the e.m.f.s all be the same, since if one cell generated a larger voltage than the others it would force current through the other cells in the reverse direction and thus would take most, if not all, of the load. Also, if one cell has a lower terminal voltage than the others it will take current from the others rather than carrying its fair share.

Cells may be connected in series-parallel, as in Fig. 212-C, to increase both the voltage and the current-carrying capacity of the battery.

2-5 Electromagnetism

The magnetic field — Everyone is familiar with the fact that a bar or horseshoe magnet will attract small pieces of iron. Just as in the case of electrostatic attraction (§ 2-3) the concept of a *field*, in this case a field of *magnetic force*, is adopted to explain the magnetic action. The field is visualized as being made up of *lines of magnetic force*, the number of which per unit area determines the field strength. As in the case of the electrostatic field, the lines of force do not have physical existence but simply represent a convenient way of describing the properties of the force.

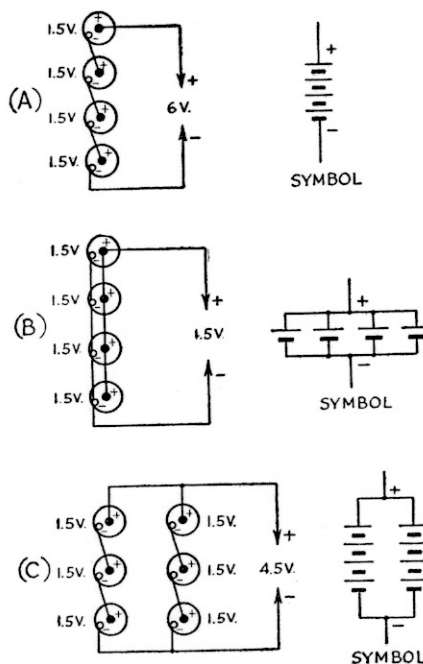


Fig. 212 — Series, parallel, and series-parallel connection of cells. Series connection increases the total voltage without changing current capacity; parallel connection increases current capacity without increasing voltage.

Magnetic attraction and repulsion — The forces exerted by the magnetic field are analogous to electrostatic forces. Corresponding to positive and negative electric charges, it is found that there are two kinds of magnetic poles. Instead of being called "positive" and "negative," however, the magnetic poles are called "north" (N) and "south" (S) poles. These names arise from the fact that, when a magnetized steel rod is freely suspended, it will turn into such a position that one end points toward the north. The end which points north is called the "north-seeking," or simply the "north," pole.

Unlike electric lines of force, which terminate on charges of opposite polarity (§ 2-3), magnetic lines of force are *closed upon themselves*. This is illustrated by the field about a bar magnet, as shown in Fig. 213-A. The lines extend through the magnet, the direction being taken from S to N inside the magnet and from N to S outside the magnet. If similar poles of two magnets are brought near each other, there is a force of repulsion between them, while dissimilar poles are attracted when brought close together. As in the case of electric charges, like poles repel, unlike poles attract.

If a bar magnet is cut in half, as in Fig. 213-B, it is found that the cut ends also are poles, of opposite kind to the original poles on the same piece. Such cutting can be continued indefinitely, and, no matter how small the pieces are made, there are always two opposite poles associated with each piece. In other words, a single magnetic pole cannot exist alone; it must always be associated with a pole of the opposite kind.

To explain this property of a magnet, it is considered that each molecule of a magnetic substance is itself a miniature magnet. If the material is not magnetized, the molecules are

in random positions and the total magnetic effect is zero since there are just as many molecules tending to set up a magnetic field in one direction as there are others tending to set up a field in the opposite direction. When the substance becomes magnetized, however, the molecules are aligned so that most or all of the N poles of the molecular magnets are turned toward one end of the material while the S poles point toward the other end.

Magnetic induction — When an unmagnetized piece of iron is brought into the field of a magnet, its molecules tend to align themselves as described in the preceding paragraph. If one end of the iron is near the N pole of the magnet, the S poles of the molecules will turn toward that end and an S pole is said to be *induced* in the iron. An N pole will appear at the opposite end. Because of the attraction between opposite poles, the iron will be drawn toward the magnet. Since the iron has become a magnet under the influence of the field, it also possesses the property of attracting other pieces of iron.

When the magnetic field is removed, the molecules may or may not resume their random positions. If the material is soft iron the magnetism disappears quite rapidly when the field is removed, but in some types of steel the molecules are slow to resume their random positions and such materials will retain magnetism for a long time. A magnet which loses its magnetism quickly when there is no external magnetizing force is called a *temporary magnet*, while one which retains its magnetism for a long time is called a *permanent magnet*. The tendency to retain magnetism is called *retentivity*. The process of destroying magnetism can be hastened by heating, which increases the motion of the molecules within the substance, as well as by mechanical shock, which also tends to disturb the molecular alignment.

Electric current and the magnetic field — Experiment shows that a moving electron generates a magnetic field of exactly the same nature as that existing about a permanent magnet. Since a moving electron, or group of electrons moving together, constitutes an electric current, it follows that the flow of current is accompanied by the creation of a magnetic field. When the conductor is a wire the magnetic lines of force are in the form of concentric circles around it and lie in planes at right angles to it, as shown in Fig. 214. The direction of this field is controlled by the direction of current flow.

There is an easily remembered method for finding the relative directions of the current and of the magnetic field it sets up. Imagine the fingers of the right hand curled about the wire, with the thumb extended along the wire in the direction of current flow (the conventional direction, from positive to negative, not the direction of electron movement). Then the fingers will be found to point in the direction of the magnetic field; that is, from N to S.

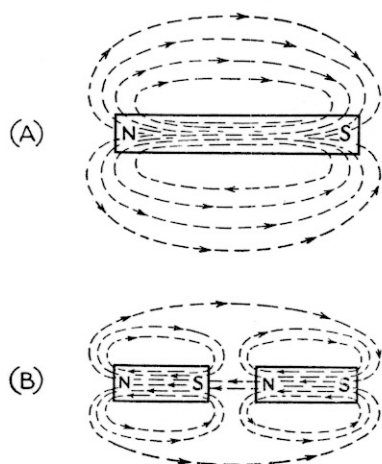


Fig. 213 — (A) The field about a bar magnet. The magnetic lines of force are continuous, part of the path being inside the magnet and part outside. (B) Cutting a magnet produces two magnets, each complete with N and S poles. With the magnets in the positions shown, some of the lines of force are common to both magnets.

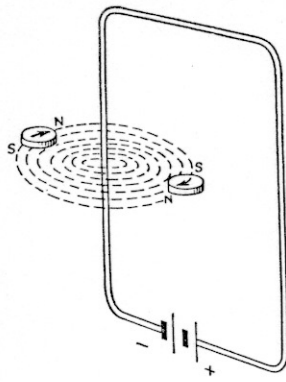


Fig. 214—Whenever electric current passes through a wire, magnetic lines of force are set up in the form of concentric circles at right angles to the wire, and a magnetic field exists around the wire. The direction of this field is controlled by the direction of current flow, and can be traced by means of a small compass.

Magnetomotive force—The force which causes the magnetic field is called *magnetomotive force*, abbreviated *m.m.f.* It corresponds to electromotive force or *e.m.f.* in the electric circuit. The greater the magnetomotive force, the stronger the magnetic field; that is, the larger the number of magnetic lines per unit area. Magnetomotive force is proportional to the current flowing. When the wire carrying the current is formed into a coil so that the magnetic flux will be concentrated instead of being spread over a large area, the *m.m.f.* also is proportional to the number of turns in the coil. Consequently magnetomotive force can be expressed in terms of the product of current and turns, and the *ampere-turn*, as this product is called, is in fact the common unit of magnetomotive force. The same magnetizing effect can be secured with a great many turns and a weak current or with a few turns and a strong current. For example, if 10 amperes flow in one turn of wire, the magnetizing effect is 10 ampere-turns. If one ampere flows in 10 turns of wire, the *m.m.f.* also is 10 ampere-turns.

The magnetic circuit—Since magnetic lines of force are always closed upon themselves, it is possible to draw an analogy between the magnetic circuit and the ordinary electrical circuit. The electrical circuit also must be closed so that a complete path is provided around which the electrons or current can flow. However, there is no insulator for the magnetic field, so that the magnetic circuit is always complete even though no magnetic material (such as iron) may be present.

The number of lines of magnetic force, or *flux*, is equivalent in the magnetic circuit to current in the electric circuit. However, it is usual practice to express the strength of the field in terms of the number of lines per unit area, or *flux density*. The unit of flux density is the *gauss*, which is equal to one line per square centimeter, but the terms "lines per square centimeter" or "lines per square inch" are commonly used instead.

Corresponding to resistance in the electric circuit is the tendency to obstruct the passage of magnetic flux, which is called *reluctance*. The reluctance of good magnetic materials, such as iron and steel, is quite low.

The *permeability* of a material is the ratio of the flux which would be set up in a closed magnetic path or circuit of the material to the flux that would exist in a path of the same dimensions in air, the same *m.m.f.* being used in both cases. The permeability of air is assigned the value 1. The permeability of steels of various types varies from about 50 to several thousand, depending upon the materials alloyed with the steel. Very high permeabilities are attained in special materials such as "perm-alloy," which is an alloy of iron and nickel.

The permeability of magnetic materials depends upon the density of magnetic flux in the material. At very high flux densities the permeability is less than its value at low or moderate flux densities. This is because the flux in magnetic materials is proportional to the applied *m.m.f.* only over a limited range. As the *m.m.f.* increases more and more of the molecular magnets within the material become aligned, until eventually a point is reached where a very great increase in *m.m.f.* is required to cause a relatively small increase in flux. This is called *magnetic saturation*. In this region of saturation the permeability decreases, since the *ratio* between the number of lines in the material and the number in air, for the same *m.m.f.*, is smaller than when the flux density is below the saturation point.

Energy in the magnetic field—Like the electrostatic field (§ 2-3), the magnetic field represents potential energy. Consequently the expenditure of energy is necessary to set up a magnetic field, but once the field has been established and remains constant no further energy is consumed in maintaining it. If by some means the field is caused to disappear, the stored-up magnetic energy is converted to energy in some other form. In other words the energy undergoes a transformation when the magnetic field is *changing*, being stored in the field when the field strength is increasing and being released from the field when the field strength is decreasing.

When a magnetic field is set up by a current flowing in a wire or coil, a certain amount of energy is used initially in bringing the field into existence. Thereafter the current must continue to flow, if the field is to be maintained at steady strength, but no expenditure of energy is required for this purpose. (There will be a steady energy loss in the circuit, but only because of the resistance of the wire.) If the current stops the energy of the field is transformed back into electrical energy, tending to keep the current flowing. The amount of energy stored and subsequently released depends upon the strength of the field, which in turn depends upon the intensity of the current and the circuit conditions, i.e., the relationship between field strength and current in the circuit.

Induced voltage—Since a magnetic field is set up by an electric current, it is not surprising to find that, in turn, a magnetic field can cause a current to flow in a closed electrical circuit.

That is, an e.m.f. can be *induced* in a wire in a magnetic field. However, since a *change* in the field is required for energy transformation, an e.m.f. will be induced only when there is a change in the field with respect to the wire.

This change may be an actual change in the field strength or may be caused by relative motion of the field and wire; e.g., a moving field and a stationary wire, or a moving wire and a stationary field. It is convenient to consider this induced e.m.f. as resulting from the wire's "cutting through" the lines of force of the field. The strength of the e.m.f. so induced is proportional to the *rate* of cutting of the lines of force.

If the conductor is moving parallel with the lines of force in a field, no voltage is induced since no lines are cut. Maximum cutting results when the conductor moves through the field in such a way that both its longer dimension and direction of motion are perpendicular to the lines of force, as shown in Fig. 215. When the conductor is stationary and the field strength varies, the induced voltage results from the alternate increase and decrease in the number of lines of force cutting the wire as the m.m.f. varies in intensity.

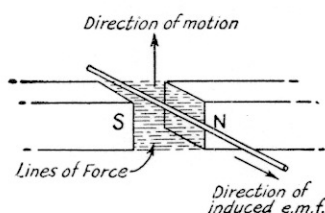


Fig. 215 — Showing how e.m.f. is induced in a conductor moving through a stationary magnetic field, cutting the lines of force. Conversely, a current sent through the conductor in the same direction by means of an external e.m.f. will cause the conductor to move downward.

Lenz's Law — When a voltage is induced and current flows in a conductor moving in a magnetic field, energy of motion is transformed into electrical energy. That is, mechanical *work* is done in moving the conductor when an induced current flows in it. If this were not so the induced voltage would be creating electrical energy, in violation of the fundamental principle of physics that energy can neither be created nor destroyed but only transformed. It is found, therefore, that the flow of current creates an opposing magnetic force tending to stop the movement of the wire. The statement of this principle is known as Lenz's Law: "In all cases of electromagnetic induction, the induced currents have such a direction that their reaction tends to stop the motion which produces them."

Motor principle — The fact that current flowing in a conductor moving through a magnetic field tends to oppose the motion indicates that current sent through a *stationary* conductor in a magnetic field would tend to *set the conductor in motion*. Such is the case. If moving

the conductor through the field in the direction indicated in Fig. 215 causes a current to flow as shown, then, if the conductor is stationary and an e.m.f. is applied to send a current through the conductor in the same direction, the conductor will tend to move across the field in the *opposite* direction.

This principle is used in the electric motor. The same rotating machine frequently may be used either as a generator or motor; as a generator it is turned mechanically to cause an induced e.m.f., and as a motor electric current through it causes mechanical motion.

Self-induction — When an e.m.f. is applied to a wire or coil, current begins to flow and a magnetic field is created. Just before closing the circuit there was no field; just after closing it the field exists. Consequently, at the instant of closing the circuit the *rate of change* of the field is very rapid. Since the wire or coil carrying the current is a conductor in a changing field, an e.m.f. will be induced in the wire. This induced voltage is the *e.m.f. of self-induction*, so called because it results from the current flowing in the wire itself.

By the principle of conservation of energy (and Lenz's Law), the polarity of the induced voltage must be such as to oppose the applied voltage; that is, the induced voltage must tend to send current through the circuit in the direction opposite to that of the current caused by the applied voltage. At the instant of closing the circuit the field changes at such a rate that the induced voltage equals the applied voltage (it cannot exceed the applied voltage, because then it would be supplying energy to the source of applied e.m.f.), but after a short interval the rate of change of the field no longer is so rapid and the induced voltage decreases. Thus the current flowing is very small at first when the applied and induced e.m.f.s are about equal, but rises as the induced voltage becomes smaller. The process is cumulative, the current eventually reaching a final value determined only by the resistance in the circuit.

In forcing current through the circuit against the pressure of the induced or "back" voltage, work is done. The total amount of work done during the time that the current is rising to its final value is equal to the amount of energy stored in the magnetic field, neglecting heat losses in the wire itself. As explained before, no further energy is put into the field once the current becomes steady. However, if the circuit is opened and current flow caused by the applied e.m.f. ceases, the field collapses. The rate of change of field strength is very great in this case, and a voltage is again induced in the coil or wire. This voltage causes a current flow in the *same* direction as that of the applied e.m.f., since energy is now being restored to the circuit. The energy usually is dissipated in the spark which occurs when such a circuit is opened. Since the field collapses very rapidly when the switch is opened, the induced e.m.f. at such a time can be extremely high.

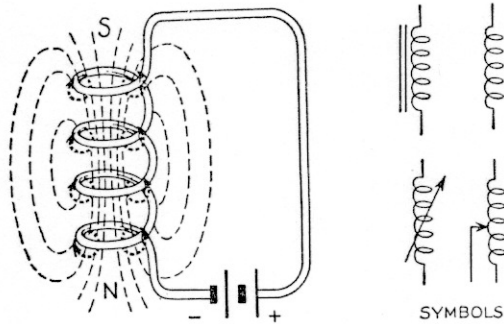


Fig. 216 — When the conducting wire is coiled, the individual magnetic fields of each turn are in such a direction as to produce a field similar to that of a bar magnet. The schematic symbols for inductance are shown at the right. The symbol at the left in the top row indicates an iron-core inductance; at the right, air core. Variable inductances are shown in the bottom row.

Inductance — As explained above, the strength of the self-induced voltage is proportional to the rate of change of the field. However, it is also apparent from the foregoing that it depends as well upon the properties of the circuit, since, if a number of similar conductors are in the same varying field, the same voltage will be induced in each. By combining the conductors properly, the total induced voltage in such a case will be the sum of the voltages induced in each wire. Also, the rate of change of field strength depends upon the strength of the field set up by a given amount of current flowing in the wire or coil, and this in turn depends upon the ampere-turns, permeability, length and cross-section of the magnetic path, etc. For a given circuit, however, the field strength will be determined by the current, and the rate of change of the field consequently will be determined by the rate of change of current. Hence, it is possible to group all the other factors into one quantity, a property of the circuit. This property is called *inductance*. When this is done, the equation giving the value of the induced voltage becomes:

$$\text{Induced voltage} = L \times \text{rate of change of current}$$

where L is the inductance.

Inductance is a property associated with all circuits, although in many cases it may be so small in comparison to other circuit properties (such as resistance) that no error results from neglecting it. The inductance of a straight wire increases with the length of the wire and decreases with increasing wire diameter. The inductance of such a wire is small, however. For a given length of wire, much greater inductance can be secured by winding the wire into a coil so that the total flux from the wire is concentrated into a small space and the flux density correspondingly increased. The unit of inductance is the *henry*. A circuit or coil has an inductance of one henry if an e.m.f. of one volt is induced when the current changes at the rate of one ampere per second. In radio work

it is frequently convenient to use smaller units; those commonly used are the *millihenry* (one thousandth of a henry) and the *microhenry* (one millionth of a henry).

It will be recognized that the relationship between inductance and the magnetic field is similar to that between capacity and the electrostatic field. The greater the inductance, the greater the amount of energy stored in the magnetic field for a given amount of current; the greater the capacity, the greater the amount of energy stored in the electrostatic field for a given voltage.

The inductance of a coil of wire depends upon the number of turns, the cross-sectional dimensions of the coil, and the length of the winding. It also depends upon the permeability of the material on which the coil is wound, or *core*. Formulas for computing the inductance of air-core coils of the type commonly used in radio work, are given in Chapter Twenty-One.

Mutual inductance — If two coils are arranged with their axes coinciding, as shown in Fig. 217, a current sent through Coil 1 will cause a magnetic field which cuts Coil 2. Consequently, an e.m.f. will be induced in Coil 2 whenever the field strength is changing. This induced e.m.f. is similar to the e.m.f. of self-induction; that is,

$$\begin{aligned} \text{Induced e.m.f.} \\ = M \times \text{rate of change of current} \end{aligned}$$

where M is a quantity called the *mutual inductance* of the two coils. The mutual inductance may be large or small, depending upon the self-inductances of the coils and the proportions of the total flux set up by one coil which cuts the turns of the other coil. If all the flux set up by one coil cuts all the turns of the other coil the mutual inductance has its maximum possible value, while if only a small part of the flux set up by one coil cuts the turns of the other the mutual inductance may be relatively small. Two coils having mutual inductance are said to be *coupled*.

The *degree of coupling* expresses the ratio of actual mutual inductance to the maximum possible value. Coils which have nearly the maximum possible mutual inductance are said to be *closely*, or *tightly*, coupled, while if the

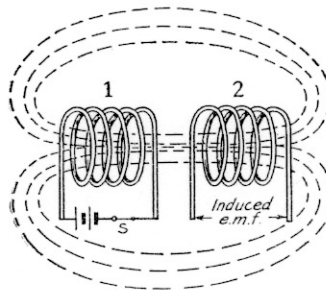


Fig. 217 — Mutual inductance. When the switch, S , is closed current flows through Coil 1, setting up a magnetic field which induces an e.m.f. in the turns of Coil 2.

mutual inductance is relatively small the coils are said to be *loosely* coupled. The degree of coupling depends upon the physical spacing between the coils and how they are placed with respect to each other. Maximum coupling exists when they have a common axis, as shown in Fig. 217, and are as close together as possible.

If two coils having mutual inductance are connected in the same circuit, the directions of the respective magnetic fields may be such as to add or oppose. In the former case the mutual inductance is said to be "positive"; in the latter case, "negative." Positive mutual inductance in such a circuit means that the total inductance is greater than the sum of the two individual inductances, while negative inductance means that the total inductance is less than the sum of the two individual inductances. The mutual inductance may be made either positive or negative simply by reversing the connections to one of the coils.

2-6 Fundamental Relations

Direct current — A current which always flows in the same direction through a circuit is called a *direct current*, frequently abbreviated *d.c.* Current flow caused by batteries, for example, is direct current. One terminal of each cell is always positive and the other always negative, hence electrons are attracted only in the one direction around the circuit. To make the current change direction, the connections to the battery terminals must be reversed.

Work, energy and power — When a quantity of electricity is moved from a point of one potential to a point at a second potential, work is done. The work done is measured by the product of the quantity of electricity and the difference of potential through which it is moved; that is,

$$W = QE$$

In the practical system of units, with Q in coulombs and E in volts, the unit of work is called the *joule*. Energy, which is the capacity for doing work, is measured in the same units.

Since $I = Q/t$ when the current is constant (§ 2-1), $Q = It$. Substituting for Q in the equation above gives

$$W = EIt$$

where E is in volts, I in amperes, and t in seconds. One ampere flowing through a difference of potential of one volt for one second does one joule of work. *Power* is the time rate at which work is done, so that, if the work is done at a uniform rate, dividing the equation by t will give the electrical power:

$$P = EI$$

The unit of power is called the *watt*.

In practical work, the term "joule" is seldom used for the unit of work or energy. The more common name is *watt-second* (one joule is equal to one watt applied for one second). The watt-second is a relatively small unit; a larger

one, the *watt-hour* (one watt of power applied for one hour) is more frequently used. Again, for some purposes the watt is too small a unit, and the *kilowatt* (1000 watts) is used instead. A still larger energy unit is the *kilowatt-hour*, the meaning of which is easily interpreted.

Fractional and multiple units — As illustrated by the examples in the preceding paragraph, it is frequently convenient to change the value of a unit so that it will not be necessary to use very large or very small numbers. As applied to electrical units, the practice is to add a prefix to the name of the fundamental unit to indicate whether the modified unit is larger or smaller. The common prefixes are *micro* (one millionth), *milli* (one thousandth), *kilo* (one thousand) and *mega* (one million). Thus, a microvolt is one millionth of a volt, a milliamperere is one thousandth of an ampere, a kilovolt is one thousand volts, and so on.

Unless there is some indication to the contrary, it should be assumed that, whenever a formula is given in terms of unprefix letters (E , I , P , R , etc.), the fundamental units are meant. If the quantities to be substituted in the equation are given in fractional or multiple units, conversion to the fundamental units is necessary before the equation can be used.

Ohm's Law — In any metallic conductor, the current which flows is directly proportional to the applied electromotive force. This relationship, which is known as *Ohm's Law*, can be written

$$E = RI$$

where E is the e.m.f., I is the current, and R is a constant, depending on the conductor, called the *resistance* of the conductor. By definition, a conductor has one unit of resistance when an applied e.m.f. of one volt causes a current of one ampere to flow. The unit of resistance is called the *ohm*.

Ohm's Law does not apply to all types of conduction, particularly to conduction through gases and in a vacuum. The law is of very great importance, however, because practically all electrical circuits use metallic conduction in whole or in part.

By transposing the equation, the following equally useful forms are obtained:

$$R = \frac{E}{I} \qquad I = \frac{E}{R}$$

The three equations state that, in a circuit to which Ohm's Law applies, the voltage across the circuit is equal to the current multiplied by the resistance; the resistance of the circuit is equal to the voltage divided by the current; and the current in the circuit is equal to the voltage divided by the resistance.

Resistance and resistivity — The resistance of a conductor is determined by the material of which it is made and its temperature, and is directly proportional to the length of the conductor (that is, the length of the path of the current through the conductor) and inversely

proportional to the area through which the current flows. If the temperature is constant,

$$R = k \frac{L}{A}$$

where R is the resistance, k is a constant depending upon the material of which the conductor is made, L is the length and A the area. For the purpose of giving a specific value to k , L is taken as one centimeter and A as one square centimeter (a cube of the material measuring one centimeter on a side); k is then the resistance in ohms of such a cube at a specified temperature. It is called the *specific resistance* or *resistivity* of the material. If the resistivity is known, the resistance of any conductor of known length and uniform cross-section readily can be determined by the formula above. The length must be in centimeters and the area in square centimeters.

The relationships given above are true only for unidirectional (direct) currents and low-frequency alternating currents. Modifications must be made when the current reverses its direction many times each second (§ 2-8).

Conductance and conductivity—The reciprocal of resistance is called *conductance*, and has the opposite properties to resistance. The lower the resistance of a circuit, the higher is the conductance, and vice versa. The symbol of conductance is G , and the relationship to resistance is

$$G = \frac{1}{R} \quad R = \frac{1}{G}$$

The unit of conductance is called the *mho*. A circuit or conductor which has a resistance of one ohm has a conductance of one mho. By substituting $1/G$ for R in Ohm's Law,

$$G = \frac{I}{E} \quad I = EG \quad E = \frac{I}{G}$$

The reciprocal of resistivity is called the *specific conductance* or *conductivity* of a material, and is measured in mhos per centimeter cube. It is frequently useful to know the *relative* conductivity of different materials. This is usually expressed in *per cent conductivity*, the conductivity of annealed copper being taken as 100 per cent. A table of per cent conductivities is given in Chapter Twenty-One.

Power used in resistance—If two conductors of different resistances have the same current flowing through them, then by Ohm's Law the conductor with the larger resistance will have a greater difference of potential across its terminals. Consequently, more energy is supplied to the larger resistance, since in a given period of time the same amount of electricity is moved through a greater potential difference. The energy appears in the form of heat in the conductor. With a steady current, the heat will raise the temperature of the conductor until a balance is reached between the heat generated and that radiated to the surrounding air or otherwise carried away.

Since $P = EI$, substituting for E the appropriate form of Ohm's Law ($E = IR$) gives

$$P = I^2 R$$

and making a similar substitution for I gives

$$P = \frac{E^2}{R}$$

That is, the power used in heating a resistance (or *dissipated* in the resistance) is proportional to the square of the voltage applied or to the square of the current flowing. In these formulas P is in watts, E in volts and I in amperes.

Further transposition of the equations gives the following forms, useful when the resistance and power are known:

$$E = \sqrt{PR} \quad I = \sqrt{\frac{P}{R}}$$

Unless the circuit containing the resistance is being used for the specific purpose of generating heat, the power used in heating a resistance is generally considered as a loss. However, there are very many applications in radio circuits where, despite the loss of power, a useful purpose is served by introducing resistance deliberately. Resistances made to specified values and provided with connecting terminals are called *resistors*. They are frequently wound on ceramic or other heat-resisting tubing with wire having high resistivity.

Temperature coefficient of resistance—The resistance of most pure metals increases with an increase in temperature. The resistance of a wire at any temperature is given by the formula

$$R = R_0 (1 + at)$$

where R is the required resistance, R_0 is the resistance at 0 degrees C. (temperature of melting ice), t is the temperature (Centigrade), and a is the *temperature coefficient of resistance*. For copper, a is about 0.004; that is, starting from a temperature of 0° C., the resistance increases 0.4 per cent per degree above zero.

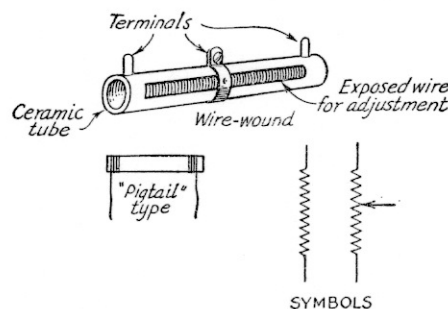


Fig. 218 — Two common types of fixed resistors. The wire-wound type is used for dissipating power of the order of 5 watts or more. "Pigtail" resistors, usually made of carbon or other resistance material in the form of a molded rod or as a thin coating on an insulating tube, rather than being wound with wire, are small in size but do not safely dissipate much power. Schematic symbols for fixed and variable resistors are shown at lower right.

Temperature coefficient of resistance becomes of importance when conductors operate at high temperatures. In the case of resistors used in electrical and radio circuits, the heat developed by current flow may raise the temperature of the resistance wire to several hundred degrees F.

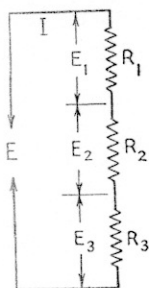


Fig. 219 — Resistances in series.

In such a case the resistance at operating temperature can be very considerably higher than the resistance at room temperature. Consequently such resistors are wound with wire which has a low temperature coefficient of resistance, so that the resistance will be as nearly constant as possible under all working conditions.

Resistances in series —

When two or more resistances are connected so that the same current flows through each in turn, as shown in Fig. 219, they are said to be connected *in series*. Then, by Ohm's Law,

$$E_1 = IR_1$$

$$E_2 = IR_2$$

$$E_3 = IR_3$$

etc., where the subscripts 1, 2, 3 indicate the first, second and third resistor, and the voltages E_1 , E_2 and E_3 are the voltages appearing across the terminals of the respective resistors. Adding the three voltages gives the total voltage across the three resistors:

$$E = E_1 + E_2 + E_3 = IR_1 + IR_2 + IR_3 = I(R_1 + R_2 + R_3) = IR$$

That is, the voltage across the resistors in series is equal to the current multiplied by the sum of the individual resistances. In the above equation, R , which denotes this sum, may be called the *equivalent* resistance or *total* resistance. The equivalent resistance of a number of resistors connected in series is, therefore, equal to the sum of the individual resistances.

Resistances in parallel — When a number of resistances are connected so that the same voltage is applied to all, as shown in Fig. 220, they are said to be connected *in parallel*. By Ohm's Law,

$$I_1 = \frac{E}{R_1} \quad I_2 = \frac{E}{R_2} \quad I_3 = \frac{E}{R_3}$$

so that the total current, I , which is the sum of the currents in the individual resistors, is

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

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

where R is the equivalent resistance — i.e., the resistance through which the same total current would flow if such a resistance were substituted for the three shown. Therefore,

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

That is, the reciprocal of the equivalent resistance of a number of resistances in parallel is equal to the sum of the reciprocals of the individual resistances. Since the reciprocal of resistance is conductance,

$$G = G_1 + G_2 + G_3$$

where G is the total conductance and G_1 , G_2 , G_3 , etc., are the individual conductances in parallel.

To obtain R instead of its reciprocal the equation above may be inverted, so that

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

The number of terms in the denominator of this equation will, of course, be equal to the actual number of resistors in parallel.

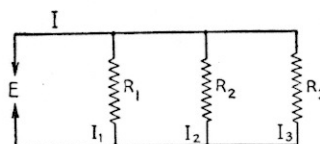


Fig. 220 — Resistances in parallel.

For the special case of only two resistances in parallel, the equation reduces to

$$R = \frac{R_1 R_2}{R_1 + R_2}$$

Series-parallel connection of resistors is shown in Fig. 221. When circuits of this type are encountered the equivalent or total resistance can be found by first adding the series resistances in each group, then treating each group as a single resistor so that the formula for resistors in parallel can be used.

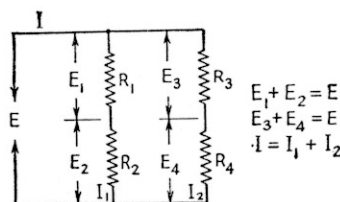


Fig. 221 — Series-parallel connection of resistances. Voltage and current relationships are given at the right.

Voltage dividers and potentiometers —

Since the same current flows through resistors connected in series, it follows from Ohm's Law that the voltage (termed *voltage drop*) across each resistor of a series-connected group is proportional to its resistance. Thus, in Fig. 222-A, the voltage E_1 across R_1 is equal to the applied voltage, E , multiplied by the ratio of R_1 to the total resistance, or

$$E_1 = \frac{R_1}{R_1 + R_2 + R_3} \cdot E$$

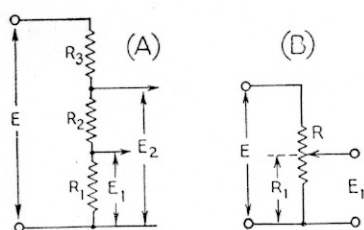


Fig. 222 — Voltage divider (A) and potentiometer (B).

Similarly, the voltage, E_2 , is equal to

$$\frac{R_2}{R_1 + R_2 + R_3} \cdot E$$

Such an arrangement is called a *voltage divider*, since it provides a means for obtaining smaller voltages from a source of fixed voltage. When current is drawn from the divider at the various tap points the above relations are no longer strictly true, since under such conditions the same current does not flow in all parts of the divider. Design data for such cases are given in § 8-10.

A similar arrangement is shown in Fig. 222-B, where the total resistance, R , is equipped with a sliding tap for fine adjustment. Such a resistor is frequently called a *potentiometer*.

Inductances in series and parallel — As explained in § 2-5, inductance determines the voltage induced when the current changes at a given rate. That is, $E = L \times \text{rate of change of current}$. This resembles Ohm's Law, if L corresponds to R and the rate of change of current to I . Thus, by reasoning similar to that used in the case of resistors, it can be shown that, for inductances in series,

$$L = L_1 + L_2 + L_3$$

and for inductances in parallel,

$$L = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3}}$$

where the number of terms in either equation is determined by the actual number of inductances connected in series or parallel.

These equations do not hold if there is mutual inductance (§ 2-5) between the coils.

Condensers in series and parallel — When a number of condensers are in parallel, as in Fig. 223-A, the same e.m.f. is applied to all. Consequently, the quantity of electricity stored in each is in proportion to its capacity. The total quantity stored is the sum of the quantities in the individual condensers:

$$Q = Q_1 + Q_2 + Q_3 = C_1 E + C_2 E + C_3 E = (C_1 + C_2 + C_3) E = CE$$

where C is the equivalent capacity. The equivalent capacity of condensers in parallel is equal to the sum of the individual capacities.

When condensers are connected in series, as in Fig. 223-B, the application of an e.m.f. to the circuit causes a certain quantity of elec-

tricity to accumulate on the top plate of C_1 . By electrostatic induction, an equal charge of opposite polarity (negative in the illustration) appears on the bottom plate of C_1 , and, since the lower plate of C_1 and the upper plate of C_2 are connected together, this must leave an equal positive charge on the upper plate of C_2 . This, in turn, causes the lower plate of C_2 to assume an equal negative charge, and so on down to the plate connected to the negative terminal of the source of e.m.f. In other words the same quantity of electricity is placed on each condenser, and this is equal to the total quantity stored. The voltage across each condenser will depend upon its capacity, and the sum of these voltages must equal the applied voltage. Thus,

$$E = E_1 + E_2 + E_3 = \frac{Q}{C_1} + \frac{Q}{C_2} + \frac{Q}{C_3} =$$

$$Q \left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \right) = \frac{Q}{C}$$

where C is the equivalent capacity. This leads to an expression similar to that for resistances in parallel:

$$C = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}}$$

where the number of terms in the denominator should be the same as the actual number of condensers in series.

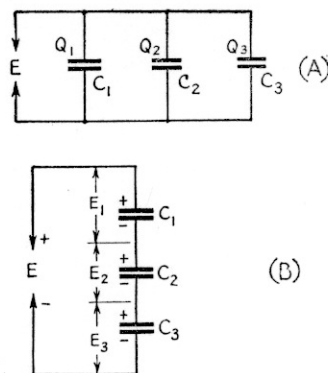


Fig. 223 — Condensers in parallel (A) and in series (B).

Time constant — When a condenser and resistor are connected in series with a source of e.m.f., such as a battery, the initial flow of current into the condenser is limited by the resistance, so that a longer period of time is required to complete the charging of the condenser than would be the case without the resistor. Likewise, when the condenser is discharged through a resistance, a measurable period of time is taken for the current flow to reach a negligible value. In the case of either charge or discharge the time required is proportional to the capacity and resistance, the product of which is called the *time constant* of the circuit. If C is in farads and R in ohms, or C in microfarads and R in megohms, this prod-

uct gives the time in seconds required for the voltage across a discharging condenser to drop to $1/e$, or approximately 37 per cent of its original value. (The constant e is the base of the natural series of logarithms.)

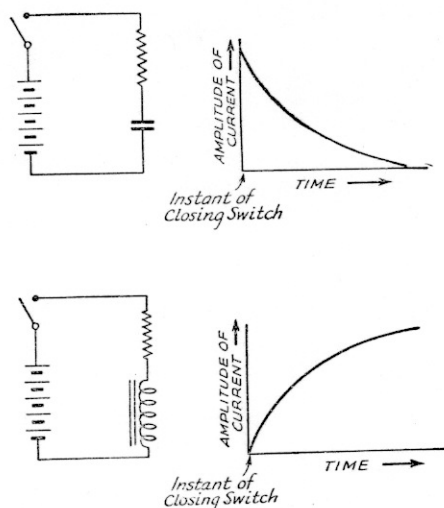


Fig. 224 — Showing how the current in a circuit combining resistance with inductance or capacity takes a finite period of time to reach its steady-state value.

A circuit containing inductance and resistance also has a time constant, for similar reasons. The time constant of an inductive circuit is equal to L/R , where L is in henrys and R in ohms. It gives the time in seconds required for the current to reach $1-1/e$, or approximately 63 per cent of its final steady value when a constant voltage is applied.

Measuring instruments — Instruments for measuring d.c. current and voltage make use of the force acting on a coil carrying current in a magnetic field (§ 2-5), produced by a permanent magnet, to move a pointer along a calibrated scale. All such instruments therefore are current operated, the current required for full-scale deflection of the pointer varying from several milliamperes to a few microamperes according to the sensitivity required. If the instrument is to read high currents, it is *shunted* (paralleled) by a low resistance through which most of the current flows, leaving only enough flowing through the instrument to give a full-scale deflection corresponding to the total current flowing through both meter and shunt. An instrument which reads microamperes is called a *microammeter* or *galvanometer*; one calibrated in milliamperes is called a *milliammeter*; one calibrated in amperes is an *ammeter*. A *voltmeter* is simply a milliammeter with a high resistance in series so that the current will be limited to a suitable value when the instrument is connected across a voltage source; it is calibrated in terms of the voltage which must appear across the terminals to cause a given value of current to flow. The series resistance is called a *multiplier*.

plier. A *wattmeter* is a combination voltmeter and ammeter in which the pointer deflection is proportional to the power in the circuit.

An ammeter or milliammeter is connected in series with the circuit in which current is being measured, so that the current flows through the instrument. A voltmeter is connected in parallel with the circuit.

2-7 Alternating Current

Description — An alternating current is one which periodically reverses its direction of flow. In addition to this alternate change in direction, usually the amount or *amplitude* of the current also varies continually during the period when the current is flowing in one direction. These variations are accompanied by corresponding variations in the magnetic field set up by the current, and it is this feature which makes the alternating current so useful. By means of the varying field, energy may be continually transferred (by induction) from one circuit to another without direct connection, and the voltage may be changed in the process. Neither of these is possible with direct current because, except for brief periods when the circuit is closed or opened, the field accompanying a steady direct current is unchanging, and hence there is no way of inducing an e.m.f. except by moving a conductor through the field (§ 2-5).

Alternating currents may be generated in several ways. Rotating electrical machines (*a.c. generators* or *alternators*) are used for developing large amounts of power when the rate of reversal is relatively slow. However, such machines are not suitable for producing currents which reverse direction thousands or millions of times each second. The thermionic vacuum tube is used for this purpose, as described in Chapter Three.

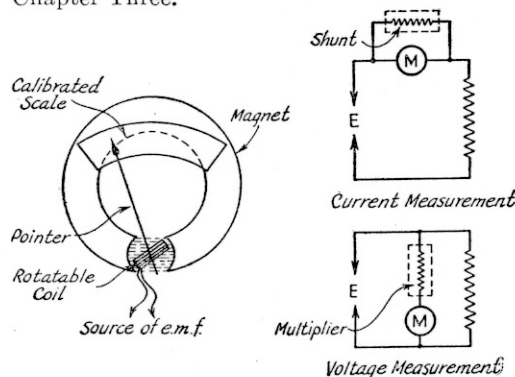


Fig. 225 — Principle of the d.c. measuring instrument. Current flowing through the rotatable coil in the field of the permanent magnet causes a force to act on the coil, tending to turn it. The turning tendency is counteracted by springs (not shown) so that the amount of movement is proportional to the value of the current in the coil. Connections for measuring current and voltage are indicated at the right. The shunt resistor is used for increasing the value of the current which the instrument can measure, by providing an alternate path through which some of the current can flow. The series multiplier limits the current when the instrument is used to measure voltage.

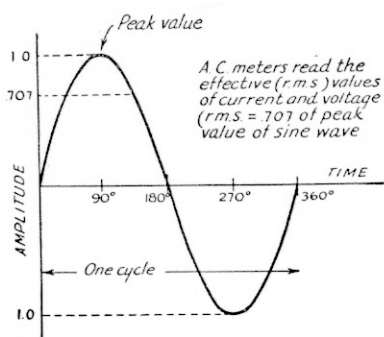


Fig. 226 — Sine-wave alternating current or voltage.

The simplest form of alternating current (or voltage) is shown graphically in Fig. 226. This chart shows that the current starts at zero value, builds up to a maximum in one direction, comes back down to zero, builds up to a maximum in the opposite direction and comes back to zero. The curve follows the sine law and is known as a *sine wave*, because of the wavelike nature of the curve which results when sine values are plotted on rectangular coordinates as a function of angle or time.

An alternating current or voltage of sine-wave form has angular velocity, period, frequency and phase.

Units of frequency — Alternating currents are identified by their frequency, the basic unit for which is the number of cycles per second. In radio work, where frequencies are extremely large, it is convenient to use two other units, *kilocycles per second* (cycles per second $\div$ 1000) and *megacycles per second* (cycles per second $\div$ 1,000,000). These are usually abbreviated kc. and Mc., respectively. Occasionally these abbreviations are written kcs. and Mcs. to indicate “kilocycles per second” and “megacycles per second” rather than simply “kilocycles” and “megacycles,” but in both written and spoken usage it is understood that “per second” is an integral part of the term when the shorter forms are used.

Peak, instantaneous effective and average values — The highest value of current or voltage during the time when the current is flowing in one direction is called the *maximum* or *peak* value. For the sine wave, the peak has the same absolute value on both the positive and negative halves of the cycle. This is not necessarily true of waves having other than the sine form.

The value of current or voltage at any particular point of time in the cycle is called the *instantaneous* value. The instant for which the value is to be found can be specified in terms of time (fraction of the period) or of angle.

Since both the voltage and current are swinging continuously between their positive maximum and negative maximum values, it might be wondered how one can speak of so many amperes of alternating current when the value is changing continuously. The problem is simplified in practical work by considering that an alternating current has an effective value

of one ampere when it produces heat, in flowing through a given resistance, at the same average rate as one ampere of continuous direct current flowing through the same resistance. This effective value is the square root of the mean of all the instantaneous current values squared. For the sine-wave form,

$$E_{\text{eff}} = \sqrt{\frac{1}{2}E_{\text{max}}^2}$$

For this reason, the effective value of an alternating current or voltage is also known as the *root-mean-square*, or *r.m.s.*, value. Hence, the effective value is the square root of $\frac{1}{2}$, or 0.707, times the maximum value.

In a purely a.c. circuit the average current over a whole cycle must be zero, because if the average current on, say, the positive half of the cycle were greater than the average on the negative half, there would be a net current flow in the positive direction. This would correspond to a direct (although intermittent) current, and hence must be excluded because a purely alternating current was assumed. The “average” value of an alternating current is defined as the average current during the part of the cycle when the current is flowing in one direction only. It is of particular importance when alternating current is changed to direct current by the methods considered in later chapters. For a sine wave, the average value is equal to 0.636 of the peak value.

In the sine wave the three voltage values, peak, effective and average, are related to each other as follows:

$$\begin{aligned} E_{\text{max}} &= E_{\text{eff}} \times 1.414 = E_{\text{ave}} \times 1.57 \\ E_{\text{eff}} &= E_{\text{max}} \times 0.707 = E_{\text{ave}} \times 1.11 \\ E_{\text{ave}} &= E_{\text{max}} \times 0.636 = E_{\text{eff}} \times 0.9 \end{aligned}$$

The relationships for current are equivalent to those given above for voltage.

Current, voltage and power in an inductance — When alternating current flows through an inductance, the continually varying magnetic field causes the continuous generation of an e.m.f. of self-induction (§ 2-5). The induced voltage at any instant is proportional to the rate at which the current is changing at that instant. If the current is a sine wave, it can be shown that the rate of change is greatest when the current is passing through zero and is least when the current is maximum. For this reason, the induced voltage is maximum when the current is zero and is zero when the current is maximum. The direction or polarity of the induced voltage is such as to tend to keep the current flowing when the current is decreasing and to prevent it from flowing when the current is increasing (§ 2-5). As a result, the induced voltage in an inductance lags 90 degrees behind the current.

By Lenz's Law, the induced voltage must always oppose the applied voltage; that is, the induced and applied voltages must be in phase opposition, or 180 degrees out of phase. Consequently, the *applied* voltage leads the current

by 90 degrees. These relationships are shown in Fig. 227. Using the voltage as a reference, the current in an inductance lags 90 degrees, or one-quarter cycle, behind the voltage. (In a

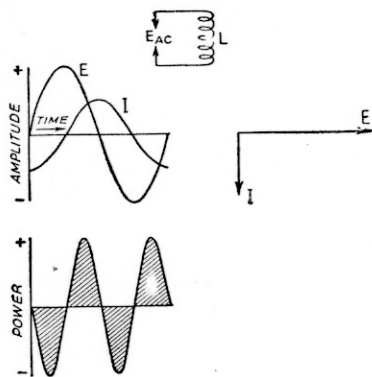


Fig. 227 — Voltage, current and power relations in an alternating-current circuit consisting of inductance only.

vector diagram, the current and voltage cannot be added vectorially because they are different kinds of quantities. In diagrams showing both current and voltage, one is generally used simply as a reference, to establish phase relationships. If several currents are shown on one diagram, they can of course be added together if they are in the same circuit; similarly, several voltages in the same circuit can be added. However, frequent use is made of vector diagrams to show phase relationships in different circuits, in which case the vectors representing current and/or voltage in different circuits cannot be added.)

When the current is increasing in either direction, energy is being stored in the magnetic field. At such times the voltage has the same polarity as the current, so that the product of the two, which gives the instantaneous power fed to the inductance, is positive. When the current is decreasing energy is being restored to the circuit and the applied voltage has the opposite polarity, so that the product of current and voltage is negative. This is also shown in Fig. 227. Positive power means power taken from the source (i.e., the source of the applied e.m.f.), while negative power means power returned to the source. Power is alternately taken and given back in each quarter cycle, and, since the amount given back is the same as that taken, the *average* power in an inductance is zero when considering a whole cycle. In a practical inductance the wire will have some resistance, so that some of the power supplied will be consumed in heating the wire, but if the resistance of the circuit is small compared to the inductance the power consumption is very small compared to the power which is alternately stored and returned.

Current, voltage and power in a condenser — When an alternating voltage is applied to a condenser, the condenser acquires a charge while the voltage is rising and loses its

charge while the voltage is decreasing. The quantity of electricity stored in the condenser at any instant is proportional to the voltage across its terminals at that instant ($Q = CE$). Since current is the *rate* of transfer of quantity of electricity, the current flowing into the condenser (when it is being charged) or out of it (when it is discharging) consequently will be proportional to the rate of change of the applied voltage. If the voltage is a sine wave, its rate of change will be greatest when passing through zero and least when the voltage is maximum. As a result, the current flowing into or out of the condenser is greatest when the voltage is passing through zero and least when the voltage reaches its peak value.

This relationship is shown in Fig. 228. Whenever the voltage is rising (in either direction) the current flow is in the same direction as the applied voltage. When the voltage is decreasing and the condenser is discharging, the current flows in the opposite direction. This is of course the normal condition for charge and discharge of a condenser. The energy stored in the condenser on the charging part of the cycle is restored to the circuit on the discharge part, and the total energy consumed in a whole cycle therefore is zero. A condenser operating on a.c. takes no average power from the source, except for such actual energy losses as may occur as the result of heating of the dielectric (§ 2-3). The energy loss in air condensers used in radio circuits is negligibly small except at extremely high frequencies.

As shown by Fig. 228, the phase relationship between current flow and applied voltage is such that the current leads the voltage by 90 degrees. This is just the opposite to the inductance case.

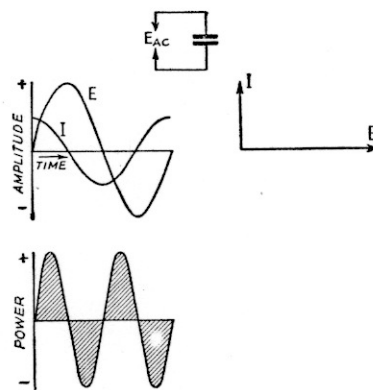


Fig. 228 — Voltage, current and power relations in an alternating-current circuit consisting of capacity only.

Current, voltage and power in resistance

— In a circuit containing resistance only there are no energy storage effects, and consequently the current and voltage are in phase. The current therefore always flows in the same direction as the applied voltage, and, since the power is always positive, there is continual power

dissipation in the resistance. The relationships are shown in Fig. 229.

Strictly speaking, no circuit can have resistance only, because the flow of current always

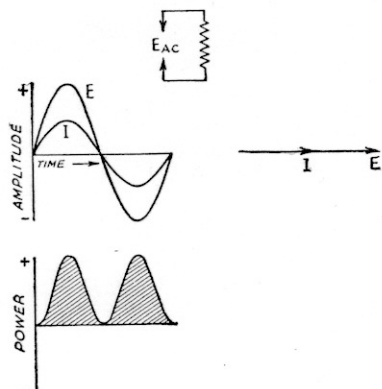


Fig. 229 — Voltage, current and power relations in an alternating-current circuit consisting of resistance only.

is accompanied by the creation of a magnetic field and every conductor also has a certain amount of capacity. Whether or not such residual inductance and capacity are large enough to require consideration is determined by the frequency at which the circuit is to operate.

The a.c. spectrum — Alternating currents of different frequencies have different properties and are useful in many varieties of ways. For the transmission of power to light homes, run motors and perform familiar everyday tasks by electrical means, low frequencies are most suitable. Frequencies of 25, 50 and 60 cycles are in common use, the latter being most widely used in this country. The range of frequencies between about 15 and 15,000 cycles is known as the *audio-frequency* range, because when frequencies of this order are converted from a.c. into air vibrations, as by a loudspeaker or telephone receiver, they are distinguishable as sounds having a tone pitch proportional to the frequency. Frequencies above 15,000 cycles (15 kilocycles) are used for radio communication, because with frequencies of this order it is possible to convert electrical energy into radio waves which can be radiated over long distances.

For convenience in reference, the following classifications for radio frequencies have been recommended by an international technical conference and are now increasingly in use:

10 to 30 kilocycles	Very-low frequencies
30 to 300 kilocycles	Low frequencies
300 to 3000 kilocycles	Medium frequencies
3 to 30 megacycles	High frequencies
30 to 300 megacycles	Very-high frequencies
300 to 3000 megacycles	Ultrahigh frequencies
3000 to 30,000 megacycles	Superhigh frequencies

Until recently, older terminology was in common use; for example, all frequencies above 30 megacycles formerly were considered to be in the "ultrahigh-frequency" region.

2-8 Ohm's Law for Alternating Currents

Resistance — Since current and voltage are always in phase through a resistance, the instantaneous relations for a.c. are equivalent to those in d.c. circuits. By definition, the effective units of current and voltage for a.c. are made equal to those for d.c. in resistive circuits (§ 2-7). Therefore the various formulas expressing Ohm's Law for d.c. circuits apply without any change to a.c. circuits containing resistance only, or for purely resistive parts of complex a.c. circuits. See § 2-6.

In applying the formulas, it must be remembered that consistent units must be used. For example, if the instantaneous value of current is used in finding voltage or power, the voltage found will be the instantaneous voltage and the power will be the instantaneous power. Likewise, if the effective value is used for one quantity in the formula, the unknown will be expressed in effective value. Unless otherwise indicated, the effective value of current or voltage is always understood to be meant when reference is made to "current" or "voltage."

Reactance — In an a.c. circuit containing inductance or capacity, but no resistance, there is no consumption of power — simply a continuous back-and-forth transfer of energy between the magnetic or electric field and the circuit (§ 2-7). Since the average power is zero, the Ohm's Law formulas cannot be applied in terms of peak or effective voltages and currents. Nevertheless, if the frequency is constant the current which flows in an inductive or capacitive circuit is directly proportional to the voltage applied; that is,

$$E = XI$$

where X is a constant depending upon the circuit, and is called the *reactance* of the circuit. By transposition, the formula can be written

$$X = \frac{E}{I} \quad I = \frac{E}{X}$$

These expressions are quite similar to those for the resistive circuit, and the quantity X has the same effect upon current flow as does resistance in a resistive circuit. Consequently, the ohm is used as the unit of reactance, just as it is for resistance. Unlike resistance, however, reactance does not use up or dissipate power.

Inductive reactance — When alternating current flows through an inductance, the induced voltage and applied voltage are equal (§ 2-7). Since the induced voltage is equal to the inductance of the coil multiplied by the rate of change of current, it is evident that a given value of voltage (to oppose a fixed applied voltage) can be induced either by using a large inductance and a small rate of change of current or by using a large rate of current change and a small inductance, so long as the product of the two is constant. The rate of change of current is determined by the amplitude of the current and the angular velocity.

Therefore, for sine-wave current,

$$E = 2\pi fLI, \text{ or } \frac{E}{I} = 2\pi fL$$

Since $X = E/I$, then

$$X_L = 2\pi fL$$

where the subscript L indicates that the reactance is inductive. That is, inductive reactance is proportional to inductance and to the applied frequency. At low frequencies a large inductance must be used to obtain high reactance, but at very high frequencies the same value of reactance can be obtained readily with quite a small inductance.

The fundamental units (ohms, cycles, henrys) must be used in the above equation, or appropriate factors inserted if other units are employed. If inductance is in millihenrys, frequency should be in kilocycles; if inductance is in microhenrys, frequency should be in megacycles, to bring the answer in ohms.

Capacitive reactance — With a fixed value of applied voltage, the quantity of electricity stored in a condenser of given capacity is always the same ($Q = CE$), and, if losses are negligible, the same quantity of electricity is taken out of the condenser on discharge. When an a.c. voltage is applied to a condenser the alternate charge and discharge, as the applied voltage rises and falls and reverses polarity, constitutes current flow "through" the condenser. The amplitude of the current is proportional to the rate of change of the voltage (§ 2-7) and also to the capacity of the condenser, since both these quantities increase the amount of electricity transferred in the circuit in a given period of time. Since rate of change of voltage is proportional to the amplitude of the voltage and the angular velocity, then, for sine-wave voltage,

$$I = 2\pi fCE, \text{ or } \frac{E}{I} = \frac{1}{2\pi fC}$$

Since $X = E/I$, then

$$X_C = \frac{1}{2\pi fC}$$

where the subscript C indicates that the reactance is capacitive. Capacitive reactance is *inversely* proportional to capacity and to the applied frequency. For a given value of capacity, the reactance decreases as the frequency increases.

Fundamental units (farads, cycles per second) must be used in the right-hand side of the equation to obtain the reactance in ohms. Conversion factors must be used if the frequency and capacity are in units other than cycles and farads. If C is in microfarads and f in megacycles, the conversion factors cancel and the reactance will be given in ohms.

Impedance — In any series circuit the same current flows through all parts of the circuit. If a resistance and inductance are connected in series to form an a.c. circuit they both carry the same current, but the voltage across the

resistance is in phase with the current while the voltage across the inductance leads the current by 90 degrees. In a d.c. circuit with resistances in series, the applied voltage is equal to the sum of the voltages across the individual resistances (§ 2-6). This is also true of the a.c. circuit with resistance and inductance in series if the *instantaneous* voltages are added algebraically to find the instantaneous value of applied voltage. But, because of the phase difference between the two voltages, the maximum value of the applied voltage will not be the sum of the maximum values of the two voltages (§ 1-9), so that the effective values cannot be added directly.

The relationships are shown by means of vectors in Fig. 230. If the current vector is used as a reference, the voltage across the resistance is in phase with the current and hence lies on the same line. The voltage across the inductance is 90 degrees ahead of the current, and therefore is drawn at right angles upward. The resultant voltage is, consequently, the hypotenuse of a right triangle, and, by geometry,

$$E^2 = E_L^2 + E_R^2, \text{ or } E = \sqrt{E_R^2 + E_L^2}$$

Since $E_R = IR$ and $E_L = IX_L$, substitution gives

$$E = I \sqrt{R^2 + X_L^2}, \text{ or } \frac{E}{I} = \sqrt{R^2 + X_L^2}$$

E/I is called the *impedance* of the circuit and is designated by the letter Z . The impedance determines the voltage which must be applied to the circuit to cause a given current to flow. The unit of impedance is, therefore, the ohm, just as in the case of resistance and reactance, which also determine the ratio of voltage to current. However, the phase angle between voltage and current must be specified, along with the impedance, for the true nature of the impedance to be known.

Similar consideration of resistance and capacity in series leads to the same expression for the impedance of such a circuit. However, in this case the voltage across the condenser lags the current, so that the "impedance tri-

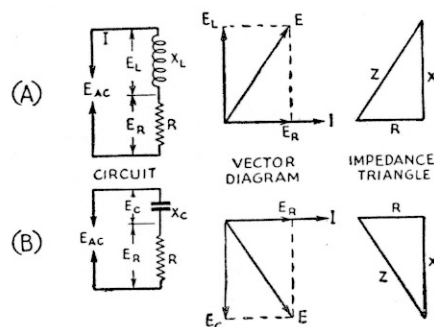


Fig. 230 — Voltage and current relationships in a.c. circuits having resistance and inductance or resistance and capacity. Vector diagrams should be drawn to scale for particular values of voltage or reactance and resistance.

angle" is drawn with the condenser voltage or reactance extending downward. The general formula is

$$Z = \sqrt{R^2 + X^2}$$

Ohm's Law for alternating current circuits then becomes

$$I = \frac{E}{Z}; Z = \frac{E}{I}; E = IZ$$

In summary, impedance is a generalized quantity applying to a.c. or d.c. circuits, simple or complex. In a d.c. circuit or in an a.c. circuit containing resistance only, the phase angle is zero (current and voltage are in phase) and the impedance is equal to the resistance.

In an a.c. circuit containing reactance only the phase angle is 90 degrees, with current lagging the voltage if the reactance is inductive and current leading the voltage if the reactance is capacitive. In either case, the impedance is equal to the reactance.

In an a.c. circuit containing both resistance and reactance the phase angle may have any value between zero and 90 degrees, with the current lagging the voltage if the reactance is inductive and leading the voltage if the reactance is capacitive. The impedance, in ohms, may be found from the equation above.

Series circuits with L, C and R—When inductance, capacity and resistance all are in series in an a.c. circuit, the voltage relations are a combination of the separate cases just considered. The voltage across each element will be proportional to the resistance or reactance of that element, since the current is the same through all. The voltages across the inductance and capacity are 180 degrees out of phase, since one leads the current by 90 degrees and the other lags the current by 90 degrees. This means that the two voltages tend to cancel; in fact, if the voltage across only the inductance and capacity in series is considered (leaving out the resistance), the total voltage is the difference between the two voltages.

This is shown by the vector diagram of Fig. 231. Since the angles of lead and lag are both 90 degrees, the reactance voltage lines are oppositely directed. The effect is exactly the same as though the difference between the two voltages (or reactances, in the impedance diagram) had been found first, and this difference then used as though it were a single voltage (or reactance). The net reactance in a series circuit is, hence, the difference between the inductive and capacitive reactances; or

$$X = X_L - X_C$$

If more than one inductance is present, the total inductive reactance is the sum of the individual reactances; similarly for capacitive reactances. Inductive reactance is conventionally taken as "positive" and capacitive reactance as "negative." With this convention, algebraic addition of all the reactances in a series circuit gives the total or net reactance of the circuit.

Parallel circuits with L, C and R—The equivalent resistance of a number of resistances in parallel in an a.c. circuit is found by the same rules as in the case of d.c. circuits (§ 2-6).

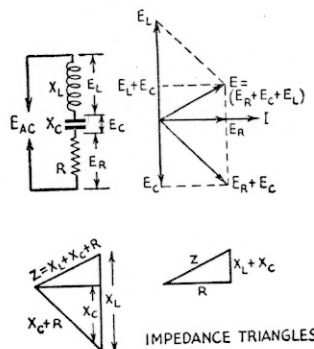


Fig. 231 — Current and voltage relationships in an a.c. circuit containing resistance, inductance and capacity in series. Step-by-step addition of voltage vectors is shown. The + signs are used in the algebraic sense, capacitive voltage or reactance being considered negative.

Parallel reactances of the same kind have an equivalent reactance given by a similar rule:

$$X = \frac{1}{\frac{1}{X_1} + \frac{1}{X_2} + \frac{1}{X_3} + \dots}$$

This formula cannot be used, however, if both inductive and capacitive reactance are in parallel.

When reactances and resistances are in parallel, the same voltage is applied to the various circuit elements. The current which flows is the vector sum of the currents in the various branches; that is, the phase of the currents with respect to the applied voltage must be taken into account in finding the total current. Fig. 232-A shows a resistance and inductance in parallel, with the corresponding vector diagram. The voltage is taken as the reference, since it is common to both branches. The current through the resistance is in phase with the voltage and coincides in direction with the voltage line. The current through the inductance lags the applied voltage by 90 degrees, hence is drawn at right angles downwards. The amplitudes of both currents are found by dividing the voltage by the resistance and reactance, respectively. The total current combines by the right-triangle rule; that is,

$$I = \sqrt{I_R^2 + I_X^2}$$

The impedance of the circuit is equal to E/I , so

$$Z = \frac{E}{\sqrt{I_R^2 + I_X^2}}$$

By assuming some convenient value for the applied voltage and then solving for the currents in the resistance and reactance, the values so found may be substituted in this equation to find the impedance of the circuit.

Resistance and capacity in parallel are shown in Fig. 232-B, with the corresponding vector diagram. Except for the fact that the current now leads the voltage, the relationships are the same as before and the total current and impedance can be found by using the same formulas.

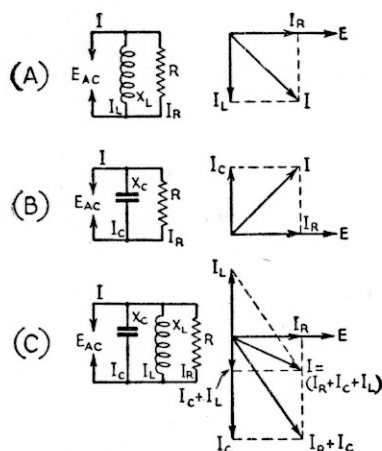


Fig. 232 — Parallel reactance and resistance in a.c. circuits. The various currents add vectorially as indicated.

When resistance, inductance and capacity are combined in parallel, as in Fig. 232-C, the vector diagram has the typical form shown. The currents in the inductance and capacity are 180 degrees out of phase, so that the total current through these elements (neglecting the resistance) is the *difference* between the two currents. Because of this, the current flowing in the line is always smaller than the largest reactive current, indicating that when inductance and capacity are connected in parallel the resultant impedance is larger than either of the individual reactances. The net reactive current may either lead or lag the applied voltage, depending upon whether the inductive or capacitive reactance is larger. The current taken by the parallel resistance is determined solely by the applied voltage. The total current and impedance of such a circuit can be found by the formulas used above, if for I_X the *difference* between the currents in the inductance and capacity is used.

With series-parallel circuits the solution becomes considerably more complicated, since the phase relationships in any parallel branch may not be either 90 degrees or zero. However, the majority of parallel circuits used in radio work can be solved by the rather simple approximate methods described in § 2-10.

Power factor—The power dissipated in an a.c. circuit containing both resistance and reactance is consumed entirely in the resistance, hence is equal to I^2R . However, the reactance is also effective in determining the current or voltage in the circuit, even though it consumes no energy. Hence the product of volts times amperes (which gives the power

consumed in d.c. circuits) for the whole circuit may be several times the actual power used up. The ratio of power dissipated (watts) to the *volt-ampere* product is called the power factor of the circuit, or

$$\text{Power factor} = \frac{\text{Watts}}{\text{Volt-amperes}}$$

Distributed capacity and inductance—It should not be thought that the reactance of coils becomes infinitely high as the frequency is increased to a high value and, likewise, that the reactance of condensers becomes infinitely low at high frequencies. All coils have some capacity between turns, and the reactance of this capacity can become low enough at some high frequencies to tend to cancel the high reactance of the coil. Likewise, the leads and plates of condensers will have considerable inductance at very high frequencies, which will tend to offset the capacitive reactance of the condenser itself. For these reasons, coils for high-frequency work must be designed to have low "distributed" capacity and condensers must be made with short, heavy leads to have low inductance.

Units and instruments—The units used in a.c. circuits may be divided or multiplied to give convenient numerical values to different orders of magnitude, just as in d.c. circuits (§ 2-6). Because the rapidly reversing current is accompanied by similar reversals in the magnetic field, instruments used for measurement of d.c. (§ 2-6) will not operate on a.c. At low frequencies suitable instruments can be constructed by making the current produce both magnetic fields, one by means of a fixed coil and the other by the moving coil. Such instruments are used for measurement of either current or voltage. At radio frequencies this type of instrument is inaccurate because of distributed capacity and other effects, and the only reliable type of direct-reading instrument is the *thermocouple* ammeter or milliammeter. This is a power-operated device consisting of a resistance wire heated by the flow of r.f. current through it, to which is attached a thermocouple or pair of wires of dissimilar metals joined together and possessing the property of developing a small d.c. voltage between the terminals when heated. This voltage, which is proportional to the heat applied to the couple, is used to operate a d.c. instrument of ordinary design.

2-9 The Transformer

Principles—It has been shown in the preceding sections that, when an alternating voltage is applied to an inductance, the flow of alternating current through the coil causes an induced e.m.f. which is opposed to the applied e.m.f. The induced e.m.f. results from the varying magnetic field accompanying the flow of alternating current. If a second coil is brought into the same field, a similar e.m.f. likewise

will be induced in this coil. This induced e.m.f. may be used to force a current through a wire, resistance or other electrical device connected to the terminals of the second coil.

Two coils operating in this way are said to be *coupled*, and the pair of coils constitutes a *transformer*. The coil connected to the source of energy is called the *primary* coil, and the other is called the *secondary* coil. Energy may be taken from the secondary, being transferred from the primary through the medium of the varying magnetic field.

Voltage and turns ratio—For a given varying magnetic field, the voltage induced in a coil in the field will be proportional to the number of turns on the coil. If the two coils of a transformer are in the same field, it follows that the induced voltages will be proportional to the number of turns on each coil. In the case of the primary, or coil connected to the source of power, the induced voltage is practically equal to, and opposes, the applied voltage. Hence, for all practical purposes,

$$E_s = \frac{n_s}{n_p} E_p$$

where E_s is the secondary voltage, E_p is the primary voltage, and n_s and n_p are the number of turns on the secondary and primary, respectively. The ratio n_s/n_p is called the *turns ratio* of the transformer.

This relationship is true *only* when all the flux set up by the primary current cuts all the turns of the secondary. If some of the magnetic flux follows a path which does not make it cut the secondary turns then the secondary voltage is less than given by this formula, since this causes the rate of change of flux to be less in the secondary than in the primary. In general, the equation can be used only when both coils are wound on a closed core of high permeability, so that practically all of the flux can be confined to definite paths.

Types of transformers—The usefulness of the transformer lies in the fact that energy can be transferred from one circuit to another without direct connection, and in the process can be readily changed from one voltage level to another. Thus, if a device to be operated requires, for example, 120 volts and only a 440-volt source is available, a transformer can be used to change the source voltage to that required. The transformer, of course, can be used only on a.c., since no voltage will be induced in the secondary if the magnetic field is not changing. If d.c. is applied to the primary of a transformer, a voltage will be induced in the secondary only at the instant of closing or opening the primary circuit, since it is only at these times that the field is changing.

Transformers for use at radio frequencies are usually wound on nonmagnetic material ("air core") because the losses in ordinary iron cores are excessive at these frequencies. As a general rule, the equation given in the preceding paragraph does not apply to such trans-

formers, because only a small part of the flux set up by the primary cuts the secondary turns. Even when special iron cores are used this statement is usually true of r.f. transformers, for reasons considered in § 2-11.

Transformers for use at power frequencies and audio frequencies are wound on iron cores, hence nearly all of the primary flux cuts the secondary turns. The turns-ratio equation can be used at these frequencies. The following discussion will be confined to such transformers.

Effect of secondary current—The primary current which has been discussed above is usually called the *magnetizing current* of the transformer. Like the current in any inductance, it lags the applied voltage by 90 degrees, neglecting the small energy losses in the resistance of the primary coil and in the iron core.

When current is drawn from the secondary winding, the secondary current sets up a magnetic field of its own in the core. The phase relationship between this field and that caused by the magnetizing current will depend upon the phase relationship between current and voltage in the secondary circuit. In every case there will be an effect upon the original field. To maintain the induced primary voltage equal to the applied voltage, however, the original field *must* be maintained. Consequently, the primary current must change in such a way that the effect of the field set up by the secondary current is completely canceled. This is accomplished when the primary draws an additional current that sets up a field exactly equal to the field set up by the secondary current, but which always opposes the secondary field. The additional primary current is thus 180 degrees out of phase with the secondary current. (This assumes that all the flux cuts both coils.) The total primary current is then the vector sum of the magnetizing current and this additional *load current*.

In rough calculations on transformers it is convenient to neglect the magnetizing current and to assume that the primary current is caused entirely by the secondary load. This is justifiable, because in any well-designed transformer the magnetizing current is quite small in comparison to the load current when the latter is near the rated value.

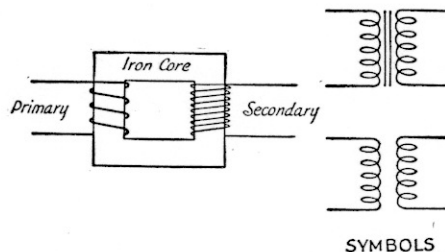


Fig. 233 — The transformer. Power is transferred from the primary coil to the secondary by means of the magnetic field. The upper symbol at right indicates an iron-core transformer, the lower one an air-core transformer.

For the fields set up by the primary and secondary load currents to be equal, the number of ampere turns in the primary must equal the number of ampere turns in the secondary. That is,

$$n_s I_s = n_p I_p$$

Hence,

$$I_p = \frac{n_s}{n_p} I_s$$

The load current in the primary for a given load current in the secondary is proportional to the turns ratio, secondary to primary. This is the opposite of the voltage relationships.

If the magnetizing current is neglected, the phase relationship between current and voltage in the primary circuit will be identical with that existing between the secondary current and voltage. This is because the applied voltage and induced voltage are 180 degrees out of phase, and the primary current and secondary current likewise are 180 degrees out of phase.

Energy relationships; efficiency — A transformer cannot create energy; it can only transfer and transform it. Hence, the power taken from the secondary cannot exceed that taken by the primary from the source of applied e.m.f. Since there is always some power loss in the resistance of the coils and in the iron core, the power taken from the source always will exceed that taken from the secondary. Thus,

$$P_o = n P_i$$

where P_o is the power taken from the secondary, P_i is the power input to the primary, and n is a factor which always is less than 1. It is called the *efficiency* of the transformer and is usually expressed as a percentage. The efficiency of small power transformers such as are used in radio receivers and transmitters may vary between about 60 per cent and 90 per cent, depending upon the size and design.

Leakage reactance — In a practical transformer not all of the magnetic flux is common to both windings, although in well-designed transformers the amount of flux which cuts one coil and not the other is only a small percentage of the total flux. This *leakage flux* acts in the same way as flux about any coil which is not coupled to another coil; that is, it gives rise to self-induction. Consequently, there is a small amount of *leakage inductance* associated with both windings of the transformer, but not

common to them. Leakage inductance acts in exactly the same way as an equivalent amount of ordinary inductance inserted in series with the circuit. It has, therefore, a certain reactance, depending upon the amount of inductance and the frequency. This reactance is called *leakage reactance*.

In the primary the practical effect of leakage reactance is equivalent to a reduction in applied voltage, since the primary current flowing through the leakage reactance causes a voltage drop. This voltage drop increases with increasing primary current, hence it increases as more current is drawn from the secondary. The induced voltage consequently decreases, since the applied voltage (which the induced voltage must equal in the primary) has been effectively reduced. The secondary induced voltage also decreases proportionately. When current flows in the secondary circuit the secondary leakage reactance causes an additional voltage drop, which results in a further reduction in the voltage available from the secondary terminals. Thus, the greater the secondary current, the smaller the secondary terminal voltage becomes. The resistance of the primary and secondary windings of the transformer also causes voltage drops when current is flowing, and, although these voltage drops are not in phase with those caused by leakage reactance, together they result in a lower secondary voltage under load than is indicated by the turns ratio of the transformer. At power frequencies (60 cycles) the voltage at the secondary, with a reasonably well-designed transformer, should not drop more than about 10 per cent under load. The drop in voltage may be considerably more than this in a transformer operating at audio frequencies, however, since the leakage reactance in a transformer increases directly with the frequency.

Impedance ratio — In an ideal transformer having no losses or leakage reactance, the primary and secondary volt-amperes are equal; that is,

$$E_p I_p = E_s I_s$$

On this assumption, and by making use of the relationships between voltage, current and turns ratio previously given, it can be shown that

$$\frac{E_p}{I_p} = \frac{E_s}{I_s} \left(\frac{n_p}{n_s} \right)^2$$

Since $Z = E/I$, E_s/I_s is the impedance of the load on the secondary circuit, and E_p/I_p is the impedance of the loaded transformer as viewed from the line. The equation states that the impedance presented by the primary of the transformer to the line, or source of power, is equal to the secondary load impedance multiplied by the square of the primary-to-secondary turns ratio. This primary impedance is called the *reflected impedance* or *reflected load*. The reflected impedance will have the same phase angle as the secondary load impedance,

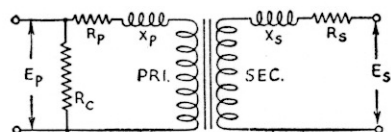


Fig. 234 — The equivalent circuit of a transformer includes the effects of leakage inductance and resistance of both primary and secondary windings. The resistance R_c is an equivalent resistance representing the constant core losses. Since these are comparatively small, their effect may be neglected in many approximate calculations.

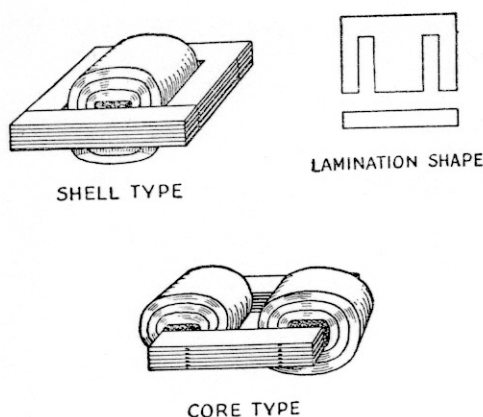


Fig. 235 — Two common types of transformer construction. Core pieces are interleaved to provide a continuous magnetic path with as low reluctance as possible.

as previously explained. If the secondary load is resistive only, then the input terminals of the transformer primary will appear to the source of e.m.f. as a pure resistance.

In practice there is always some leakage reactance and power loss in the transformer, so that the relationship above does not hold exactly. However, it gives results which are adequate for many practical cases. The *impedance ratio* of the transformer consequently is considered to be equal to the square of the turns ratio, both ratios being taken from the same winding to the other.

Impedance matching — Many devices require a specific value of load resistance (or impedance) for optimum operation. The resistance of the actual load which is to dissipate the power may differ widely from this value, hence the transformer, with its impedance-transforming properties, is frequently called upon to change the actual load to the desired value. This is called *impedance matching*. From the preceding paragraph,

$$\frac{n_s}{n_p} = \sqrt{\frac{Z_s}{Z_p}}$$

where n_s/n_p is the required secondary-to-primary turns ratio, Z_s is the impedance of the actual load, and Z_p is the impedance required for optimum operation of the device delivering the power.

Transformer construction — Transformers are generally built so that flux leakage is minimized insofar as possible. The magnetic path is laid out so that it is as short as possible, since this reduces its reluctance and hence the number of ampere-turns required for a given flux density, and also tends to minimize flux leakage. Two core shapes are in common use, as shown in Fig. 235. In the shell type both windings are placed on the inner leg, while in the core type the primary and secondary windings may be placed on separate legs, if desired. This is sometimes done when it is necessary to minimize capacity effects between the primary and

secondary, or when there is a large difference of potential between primary and secondary.

Core material for small transformers is usually silicon steel, called "transformer iron." The core is built up of thin sheets, called *laminations*, insulated from each other (by a thin coating of shellac, for example) to prevent the flow of *eddy currents* which are induced in the iron at right angles to the direction of the field. If allowed to flow, these eddy currents would cause considerable loss of energy in overcoming the resistance of the core material. The separate laminations are overlapped, to make the magnetic path as continuous as possible and thus reduce leakage.

The number of turns required on the primary for a given applied e.m.f. is determined by the maximum permissible flux density in the type of core material used, the frequency, and the magnetomotive force required to force the flux through the iron. As a rough indication, windings of small power transformers frequently have about two turns per volt for a core of 1 square inch cross-section and a magnetic path 10 or 12 inches in length. A longer path or smaller cross section would require more turns per volt, and vice versa.

In most transformers the coils are wound in layers, with a thin sheet of paper insulation between each layer. Thicker insulation is used between separate coils and between the coils and the core.

In power transformers distributed capacity in the windings is of little consequence, but in audio-frequency transformers it may cause undesired resonance effects (see § 2-10 for a discussion of resonance). High-grade audio transformers often have special types of windings designed to minimize distributed capacity.

The autotransformer — The transformer principle can be utilized with only one winding instead of two, as shown in Fig. 236; the principles just discussed apply equally well. The *autotransformer* has the advantage that, since the line and load currents are out of phase, the section of the winding common to both circuits carries less current than the remainder of the coil. This advantage is not very marked unless the primary and secondary voltages do not differ very greatly, while it is frequently disadvantageous to have a direct connection between primary and secondary circuits. For these reasons, application of the autotransformer is usually limited to boosting or reducing the line voltage by a relatively small amount for purposes of voltage correction.

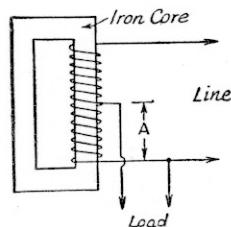


Fig. 236 — The auto-transformer is based on the transformer principle, but uses only one winding. The line and load currents in the common winding (A) flow in opposite directions, so that the resultant current is the difference between them. The voltage across A is proportional to the turns ratio.

2-10 Resonant Circuits

Principle of resonance — It has been shown (§ 2-8) that the inductive reactance of a coil and the capacitive reactance of a condenser are oppositely affected by frequency. In any series combination of inductance and capacitance, therefore, there is one particular frequency for which the inductive and capacitive reactances are equal. Since these two reactances cancel each other, the net reactance in the circuit becomes zero, leaving only the resistance to impede the flow of current. The frequency at which this occurs is known as the *resonant frequency* of the circuit and the circuit is said to be *in resonance* at that frequency, or *tuned* to that frequency.

Series circuits — The frequency at which a series circuit is resonant is that for which $X_L = X_C$. Substituting the formulas for inductive and capacitive reactance (§ 2-8) gives

$$2\pi fL = \frac{1}{2\pi fC}$$

Solving this equation for frequency gives

$$f = \frac{1}{2\pi\sqrt{LC}}$$

This equation is in the fundamental units — cycles per second, henrys and farads — and so, if fractional or multiple units are used, the appropriate factors must be inserted to change them to the fundamental units. A formula in units commonly used in radio circuits is

$$f = \frac{1}{2\pi\sqrt{LC}} \times 10^6$$

where f is the frequency in kilocycles per second, 2π is 6.28, L is the inductance in microhenrys ($\mu\text{h.}$), and C is the capacitance in microfarads ($\mu\text{mfd.}$).

The resistance that may be present does not enter into the formula for resonant frequency.

When a constant a.c. voltage of variable frequency is applied, as shown in Fig. 237-A, the current flowing through such a circuit will be maximum at the resonant frequency. The magnitude of the current at resonance will be determined by the resistance in the circuit. The

curves of Fig. 237 illustrate this, curve a being for low resistance and curves b and c being for increasingly greater resistances.

In the circuits used at radio frequencies the reactance of either the coil or condenser at resonance is usually several times as large as the resistance of the circuit, although the *net* reactance is zero. As the applied frequency departs from resonance, say on the low-frequency side, the reactance of the condenser increases and that of the inductance decreases, so that the net reactance (which is the difference between the two) increases rather rapidly. When it becomes several times as high as the resistance, it becomes the chief factor in determining the amount of current flowing. Hence, for circuits having the same values of inductance and capacity but varying amounts of resistance, the resonance curves tend to coincide at frequencies somewhat removed from resonance. The three curves in the figure show this tendency.

Parallel circuits — The parallel-resonant circuit is illustrated in Fig. 237-B. This circuit also contains inductance, capacitance and resistance in series, but the voltage is applied in parallel with the combination instead of in series with it as in A. As explained in connection with parallel inductance and capacity (§ 2-8), the total current through such a combination is less than the current flowing in the branch having the smaller reactance. If the currents through the inductive and capacitive branches are equal in amplitude and exactly 180 degrees out of phase, the total current, called the *line* current, will be zero no matter how large the individual branch currents may be. The impedance ($Z = E/I$) of such a circuit, viewed from its parallel terminals, would be infinite. In practice the two currents will not be exactly 180 degrees out of phase, because there is always some resistance in one or both branches. This resistance makes the phase relationship between current and voltage less than 90 degrees in the branch containing it, hence the phase difference between the currents in the two branches is less than 180 degrees and the two currents will not cancel completely. However, the line current may be very small if the resistance is small compared to the reactance, and thus the parallel impedance at resonance may be very high.

As the applied frequency is increased or decreased from the resonant frequency, the reactance of one branch decreases and that of the other branch increases. The branch with the smaller reactance takes a larger current, if the applied voltage is constant, and that with the larger reactance takes a smaller current. As a result, the difference between the two currents becomes larger as the frequency is moved farther from resonance. Since the line current is the difference between the two currents, the current increases when the frequency moves away from resonance; in other words, the parallel impedance of the circuit decreases.

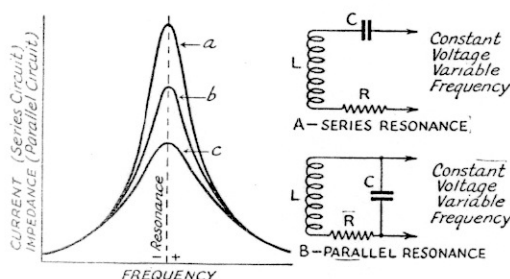


Fig. 237 — Characteristics of series-resonant and parallel-resonant circuits with variations in resistance, R .

The variation of parallel impedance of a parallel-resonant circuit with frequency is illustrated by the same curves of Fig. 237 that show the variation in current with frequency for the series-resonant circuit. The parallel impedance at resonance increases as the series resistance is made smaller.

In the case of parallel circuits, resonance may be defined in three ways: the condition which gives maximum impedance, that which gives a power factor of 1 (impedance purely resistive), or (as in series circuits) when the inductive and capacitive reactances are equal. If the resistance is low, the resonant frequencies obtained on the three bases are practically identical. This condition usually is satisfied in radio work, so that the resonant frequency of a parallel circuit is generally computed by the series-resonance formula given above.

Resistance at high frequencies — At radio frequencies the resistance of a conductor may be considerably higher than its resistance to direct current or low-frequency a.c. This is because the magnetic field set up inside the wire tends to force the current to flow in the outer part of the wire, an effect which increases with frequency. At high radio frequencies this *skin effect* is so pronounced that practically all the current flows very near the surface of the conductor, thereby in effect reducing the cross-sectional area and hence increasing the resistance. For this reason low resistance can be achieved only by using conductors with large surface area, but, since the inner part of the conductor does not carry current, thin-walled tubing will serve just as well as solid wire of the same diameter.

A further effect occurs in coils at radio frequencies. The magnetic fields cause a concentration of current in certain parts of the conductors, again causing an effective decrease in the conductor size and raising the resistance. These effects, plus the effects of stray currents caused by distributed capacity (§ 2-8), raise the effective resistance of a coil at radio frequencies to many times the d.c. resistance of the wire.

Magnetic materials at high frequencies — At frequencies above the audio range (upper limit in the vicinity of 15,000 cycles) ordinary iron and steel cores are not useful for increasing the inductance of coils, although they are highly effective for this purpose at low frequencies. This is principally because losses from currents induced in the iron (eddy currents) increase to a prohibitive extent at high frequencies, since the induced current is proportional to frequency. Coils for radio-frequency purposes either are constructed without magnetic material (*air-core*) or have special types of iron cores particularly designed to reduce losses. Cores for radio-frequency use are made from finely divided iron of selected grades, held together with an insulating binding material in such a way that each iron particle is effectively insulated from the others. This

prevents, or greatly reduces, the loss from eddy currents. The permeability of such a "powdered-iron" core is high enough, and the core losses are low enough, so that it is possible to construct an iron-core coil having lower effective resistance than an air-core coil of the same inductance. Although coils of this type now are used chiefly at the lower radio frequencies (below about 2 Mc.), practicable iron-core coils have been constructed for frequencies approaching the very-high-frequency range.

Sharpness of resonance — As the internal series resistance is increased the resonance curves become "flatter" for frequencies near the resonance frequency, as shown in Fig. 237. The relative sharpness of the resonance curve near resonance frequency is a measure of the *sharpness of tuning* or *selectivity* (ability to discriminate between voltages of different frequencies) in such circuits. This is an important consideration in tuned circuits for radio work.

Flywheel effect; Q — A resonant circuit may be compared to a flywheel in its behavior. Just as such a wheel will continue to revolve after it is no longer driven, so also will oscillations of electrical energy continue in a resonant circuit after the source of power is removed. The flywheel continues to revolve because of its stored mechanical energy; current flow continues in a resonant circuit by virtue of the energy stored in the magnetic field of the coil and the electric field of the condenser. When the applied power is shut off the energy surges back and forth between the coil and condenser, being first stored in the field of one, then released in the form of current flow, and then re-stored in the field of the other. Since there is always resistance present some of the energy is lost as heat in the resistance during each of these *oscillations* of energy, and eventually all the energy is so dissipated. The length of time the oscillations will continue is proportional to the ratio of the energy stored to that dissipated in each cycle of the oscillation. This ratio is called the Q (quality factor) of the circuit.

Since energy is stored by either the inductance or capacity and may be dissipated in either the inductive or capacitive branch of the circuit, a Q can be established for either the inductance or capacity alone as well as for the entire circuit. It can be shown that the energy stored is proportional to the reactance and that the energy dissipated is proportional to the resistance, so that, for either inductance or capacity associated with resistance,

$$Q = \frac{X}{R}$$

This relationship is useful in circuit problems.

In resonant circuits at frequencies below about 28 Mc. the internal resistance is practically wholly in the coil; condenser resistance may be neglected. Consequently, the Q of the circuit as a whole is determined by the Q of the coil, or its ratio of reactance to resistance. Coils

for frequencies below the very-high-frequency region may have Q s ranging from 100 to several hundred, depending upon their size and construction.

The sharpness of resonance of a tuned circuit is directly proportional to the Q of the circuit. As an indication of the effect of Q , the current in a series circuit drops to a little less than half its resonance value when the applied frequency is changed by an amount equal to $1/Q$ times the resonant frequency. The parallel impedance of a parallel circuit similarly decreases with change in frequency. For example, in a circuit having a Q of 100, changing the applied frequency by $1/100$ th of the resonant frequency will decrease the parallel impedance to less than half its value at resonance.

Damping, decrement — The rate at which current dies down in amplitude in a resonant circuit after the source of power has been removed is called the *decrement* or *damping* of the circuit. A circuit with high decrement (low Q) is said to be highly damped; one with low decrement (high Q) is lightly damped.

Voltage rise — When a voltage of the resonant frequency is inserted in series in a resonant circuit, the voltage which appears across either the coil or condenser is considerably higher than the applied voltage. This is because the current in the circuit is limited only by the resistance, and hence may have a relatively high value; however, the same current flows through the high reactances of the coil and condenser, and consequently causes large voltage drops (§ 2-8). As explained above, the reactances are of opposite types and hence the voltages are opposite in phase, so that the net voltage around the circuit is only that which is applied. The ratio of the reactive voltage to the applied voltage is proportional to the ratio of reactance to resistance, which is the Q of the circuit. Hence, the voltage across either the coil or condenser is equal to Q times the voltage inserted in series with the circuit.

Parallel-resonant circuit impedance — The parallel-resonant circuit offers pure resistance (its *resonant impedance*) between its terminals because the line current is practically in phase with the applied voltage. At frequencies off resonance the current increases through the branch having the lower reactance (and

vice versa) so that the circuit becomes reactive, and the resistive component of the impedance decreases as shown in Fig. 238.

If the circuit Q is 10 or more, the parallel impedance at resonance is given by the formula

$$Z_r = X^2/R = XQ$$

where X is the reactance of either the coil or the condenser and R is the internal resistance.

Q of loaded circuits — In many applications, particularly in receiving, the only power dissipated is that lost in the resistance of the resonant circuit itself. Hence the coil should be designed to have as high Q as possible. Since, within limits, increasing the number of turns raises the reactance faster than it raises the resistance, coils for such purposes are made with relatively large inductance for the frequency under consideration.

On the other hand, when the circuit delivers energy to a load, as in the case of the resonant circuits used in transmitters, the energy consumed in the circuit itself is usually negligible compared with that consumed by the load. The equivalent of such a circuit can be represented as shown in Fig. 239-A, where the parallel resistor represents the load to which power is delivered. If the power dissipated in the load is greater by 10 times or more than the power lost in the coil and condenser, the parallel impedance of the resonant circuit alone will be so high compared to the resistance of the load that the latter may be considered to determine the impedance of the combined circuit. (The parallel impedance of the tuned circuit alone is resistive at resonance, so that the impedance of the combined circuit may be calculated from the formula for resistances in parallel. If one of two resistances in parallel has 10 times the resistance of the other, the resultant resistance is practically equal to the smaller resistance.) The error will be small, therefore, if the losses in the tuned circuit alone are neglected. Then, since $Z = XQ$, the Q of a circuit loaded with a resistive impedance, Z , is

$$Q = \frac{Z}{X}$$

where Z is the load resistance connected across the circuit and X is the reactance of either the coil or condenser. Hence, for a given parallel impedance, the effective Q of the circuit including the load is inversely proportional to the reactance of either the coil or the condenser. A circuit loaded with a relatively low resistance (a few thousand ohms) must therefore have a large capacity and relatively small inductance to have reasonably high Q .

From the above it is evident that connecting a resistance in parallel with a resonant circuit decreases the impedance of the circuit. However, the reactances in the circuit are unchanged, hence the reduction in impedance is equivalent to a reduction in the Q of the circuit. The same reduction in impedance also could be brought about by increasing the *series*

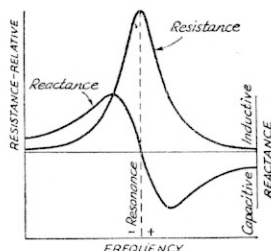


Fig. 238 — The impedance of a parallel-resonant resistance circuit is shown here separated into its reactance and resistance components. The parallel resistance of the circuit is equal to the parallel impedance at resonance.

resistance of the circuit. The *equivalent series resistance* introduced in a resonant circuit by an actual resistance connected in parallel is that value of resistance which, if added in

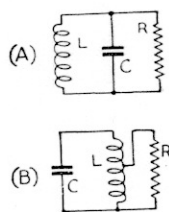


Fig. 239 — The equivalent circuit of a resonant circuit delivering power to a load. The resistor R represents the load resistance. At (B) the load is tapped across part of L , which by transformer action is equivalent to using a higher load resistance across the whole circuit.

series with the coil and condenser, would decrease the circuit Q to the same value it has when the parallel resistance is connected. When the resistance of the resonant circuit alone can be neglected, the equivalent resistance is

$$R = \frac{Z^2}{Z}$$

the symbols having the same meaning as in the formula above.

The effect of a load of given resistance on the Q of the circuit can be changed by connecting the load across only part of the circuit. The most common method of accomplishing this is by tapping the load across part of the coil, as shown in Fig. 239-B. The smaller the portion of the coil across which the load is tapped, the less the loading on the circuit; in other words, tapping the load "down" is equivalent to connecting a higher value of load resistance across the whole circuit. This is similar in principle to impedance transformation with an iron-core transformer (§ 2-9). However, in the high-frequency resonant circuit the impedance ratio does not vary exactly as the square of the turn ratio, because all the magnetic flux lines do not cut every turn of the coil. A desired reflected impedance usually must be obtained by experimental adjustment.

L/C ratio — The formula for resonant frequency of a circuit shows that the same frequency always will be obtained so long as the product of L and C is constant. Within this limitation, it is evident that L can be large and C small, L small and C large, etc. The relation between the two for a fixed frequency is called the L/C ratio. A *high- C* circuit is one which has more capacity than "normal" for the frequency; a *low- C* circuit one which has less than normal capacity. These terms depend to a considerable extent upon the particular application considered, and have no exact numerical meaning.

Piezoelectricity — Properly ground plates or bars of quartz and certain other crystalline materials show a mechanical strain when sub-

jected to an electric charge and, conversely, will show a difference in potential between two faces when subjected to mechanical stress. This characteristic is called the *piezoelectric effect*. A piezoelectric crystal is a mechanical vibrator electrically equivalent to a series-resonant circuit of very high Q , and can be used for many of the purposes for which ordinary resonant circuits are used.

2-11 Coupled Circuits

Energy transfer; loading — Two circuits are said to be *coupled* when energy can be transferred from one to the other. The circuit delivering energy is called the primary circuit; that receiving energy is called the secondary circuit. The energy may be practically all dissipated in the secondary circuit itself, as in receiver circuits, or the secondary may simply act as a medium through which the energy is transferred to a load resistance where it does work. In the latter case, the coupled circuits may act as a radio-frequency impedance-matching device (§ 2-9) where the matching can be accomplished by adjusting the loading on the secondary (§ 2-10) and by varying the coupling between the primary and secondary.

Coupling by a common circuit element — One method of coupling between two resonant circuits is to have some type of circuit element common to both circuits. The three variations of this type of coupling (often called *direct coupling*) shown at A, B and C of Fig. 240, utilize a common inductance, capacity and resistance, respectively. Current circulating in one LC branch flows through the common element (L_c , C_c , or R_c) and the voltage developed across this element causes current to flow in the other LC branch. The degree of coupling between the two circuits becomes greater as the reactance (or resistance) of the common element is increased in comparison to the remaining reactances in the two branches.

If both circuits are resonant to the same frequency, as is usually the case, the common impedance — reactance or resistance — required for maximum energy transfer is generally quite small compared to the other reactances in the circuits.

Capacity coupling — The circuit at D shows electrostatic coupling between two resonant circuits. The coupling increases as the capacity of C_c is made greater (reactance of C_c is decreased). When two resonant circuits are coupled by this means, the capacity required for maximum energy transfer is quite small if the Q of the secondary circuit is at all high. For example, if the parallel impedance of the secondary circuit is 100,000 ohms, the reactance of the coupling condenser need not be lower than 10,000 ohms or so for ample coupling. The corresponding capacity required is only a few micromicrofarads at high frequencies.

Inductive coupling — Fig. 240-E illustrates inductive coupling, or coupling by means of the magnetic field. A circuit of this type re-

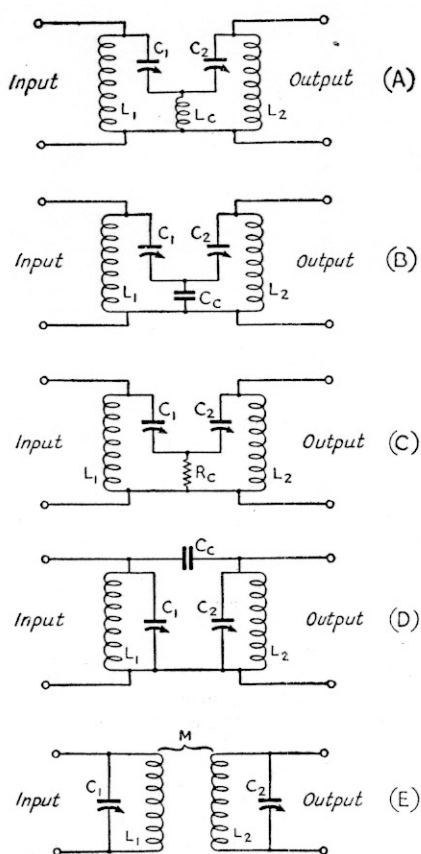


Fig. 240 — Basic methods of circuit coupling.

sembles the iron-core transformer (§ 2-9) but, because only a small percentage of the flux lines set up by one coil cut the turns of the other coil, the simple relationships between turns ratio, voltage ratio and impedance ratio in the iron-core transformer do not hold. To determine the operation of such circuits, it is necessary to take account of the mutual inductance (§ 2-5) between the coils.

Link coupling — A variation of inductive coupling, called *link coupling*, is shown in Fig. 241. This gives the effect of inductive coupling between two coils which may be so separated that they have no mutual inductance; the link may be considered simply as a means of providing the mutual inductance. Because mutual inductance between coil and link is involved at each end of the link, the total mutual inductance between two link-coupled circuits cannot be made as great as when normal inductive coupling is used. In practice, however, this ordinarily is not disadvantageous. Link coupling frequently is convenient in the design of equipment where inductive coupling would be impracticable because of constructional considerations.

The link coils generally have few turns compared to the resonant-circuit coils, since the coefficient of coupling is relatively independent of the number of turns on either coil.

Coefficient of coupling — The degree of coupling between two coils is a function of their mutual inductance and self-inductances:

$$k = \frac{M}{\sqrt{L_1 L_2}}$$

where k is called the *coefficient of coupling*. It is often expressed as a percentage. The coefficient of coupling cannot be greater than 1, and generally is much smaller in resonant circuits.

Inductively coupled circuits — Three types of circuits with inductive coupling are in general use. As shown in Fig. 242, one type has a tuned-secondary circuit with an untuned-primary coil, the second a tuned-primary circuit and untuned-secondary coil, and the third uses tuned circuits in both the primary and secondary. The circuit at A is frequently used in receivers for coupling between amplifier tubes when the tuning of the circuit must be varied to respond to signals of different frequencies. Circuit B is used principally in transmitters, for coupling a radio-frequency amplifier to a resistive load. Circuit C is used for fixed-frequency amplification in receivers. The same circuit also is used in transmitters for transferring power to a load which has both reactance and resistance.

If the coupling between the primary and secondary is "tight" (coefficient of coupling large), the effect of inductive coupling in circuits A and B, Fig. 242, is much the same as though the circuit having the untuned coil were tapped on the tuned circuit (§ 2-10). Thus any resistance in the circuit to which the untuned coil is connected is coupled into the tuned circuit in proportion to the mutual inductance. This is equivalent to an increase in the series resistance of the tuned circuit, and its Q and selectivity are reduced (§ 2-10). The higher the coefficient of coupling, the lower the Q for a given value of resistance in the coupled circuit. These circuits may be used for impedance matching by adjustment of the coupling and of the number of turns in the untuned coil.

If the circuit to which the untuned coil is connected has reactance, a certain amount of reactance will be "coupled in" to the tuned circuit depending upon the amount of reactance present and the degree of coupling. The chief effect of this coupled reactance is to require readjustment of the tuning when the coupling is increased, if the tuned circuit has first been adjusted to resonance under conditions of very loose coupling.

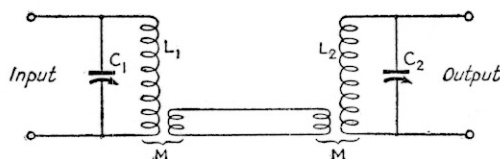


Fig. 241 — Link coupling. The mutual inductances at both ends of the link are equivalent to mutual inductance between the tuned circuits, and serve the same purpose.

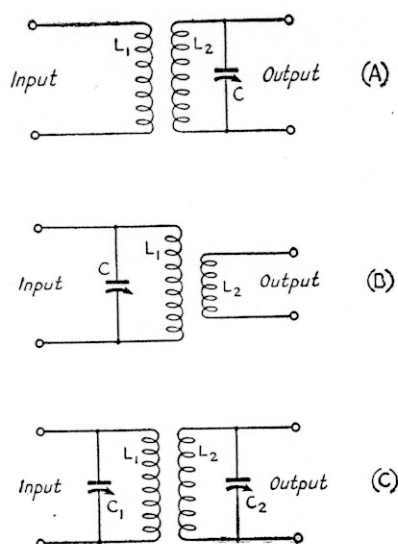


Fig. 242 — Types of inductively coupled circuits. In A and B, one circuit is tuned, the other untuned. C shows the method of coupling between two tuned circuits.

Coupled resonant circuits — The effect of a tuned-secondary circuit on a tuned primary is somewhat more complicated than in the simpler circuits just described. When the secondary is tuned to resonance with the applied frequency, its impedance is resistive only. If the primary also is tuned to resonance, the current flowing in the secondary circuit (caused by the induced voltage) will, in turn, induce a voltage in the primary which is opposite in phase to the voltage acting in series in the primary circuit. This opposing voltage reduces the effective primary voltage, and thus causes a reduction in primary current. Since the actual voltage applied in the primary circuit has not changed, the reduction in current can be looked upon as being caused by an increase in the resistance of the primary circuit. That is, the effect of coupling a resonant secondary to the primary is to increase the primary resistance. The resistance under consideration is the *series* resistance of the primary circuit, not the parallel impedance or resistance. The parallel resistance decreases, since the increase in series resistance reduces the Q of the primary circuit.

If the secondary circuit is not tuned to resonance, the voltage induced back in the primary by the secondary current will not be exactly out of phase with the voltage acting in the primary; in effect, reactance is coupled into the primary circuit. If the applied frequency is fixed and the secondary circuit tuning is being varied, this means that the primary circuit will have to be retuned to resonance each time the secondary tuning is changed.

If the two circuits are initially tuned to resonance at a given frequency and then the applied frequency is varied, both circuits become reactive at all frequencies off resonance. Under these conditions, the reactance coupled into the

primary by the secondary retunes the primary circuit to a new resonant frequency. Thus, at some frequency off resonance, the primary current will be maximum, while at the actual resonant frequency the current will be smaller because of the resistance coupled in from the secondary at resonance. There is a point of maximum primary current both above and below the true resonant frequency.

These effects are almost negligible with very "loose" coupling (coefficient of coupling very small), but increase rapidly as the coupling increases. Because of them, the selectivity of a pair of coupled resonant circuits can be varied over a considerable range simply by changing the coupling between them. Typical curves showing the variation of selectivity are shown in Fig. 243, lettered in order of increasing coefficient of coupling. At loose coupling, A, the voltage across the secondary circuit (induced voltage multiplied by the Q of the secondary circuit) is less than the maximum possible because the induced voltage is small with loose coupling. As the coupling increases the secondary voltage also increases, until critical coupling, B, is reached. At still closer coupling the effect of the primary current "humps" causes the secondary voltage to show somewhat similar humps, while when the coupling is further increased the frequency separation of the humps becomes greater. Resonance curves such as those at C and D are called "flat-topped," because the output voltage is substantially constant over an appreciable frequency range. Such a characteristic is desirable in many receiver applications.

Critical coupling — It will be observed that maximum secondary voltage is obtained in the curve at B in Fig. 243. With tighter coupling the resonance curve tends to be double-peaked, but in no case is such a peak higher than that shown for curve B. The coupling at which the secondary voltage is maximum is known as *critical coupling*. With this coupling the resistance coupled into the primary circuit is equal to the resistance of the primary itself, corresponding to the condition of matched impedances. Hence, the energy transfer is maximum at critical coupling. The over-all selectivity of the coupled circuits at critical coupling

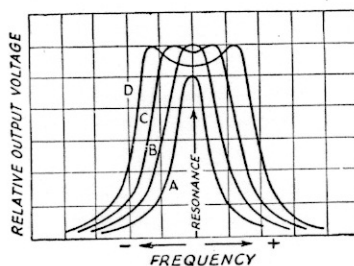


Fig. 243 — Showing the effect on the output voltage from the secondary circuit of changing the coefficient of coupling between two resonant circuits independently tuned to the same frequency. The input voltage is held constant in amplitude while the frequency is varied.

is intermediate between that obtainable with loose coupling and tight coupling. At very loose coupling, the selectivity of the system is very nearly equal to the product of the selectivities of the two circuits taken separately; that is, the effective Q of the circuit is equal to the product of the Q s of the primary and secondary.

Effect of circuit Q —Critical coupling is a function of the Q s of the two circuits taken independently. A higher coefficient of coupling is required to reach critical coupling when the Q s are low; if the Q s are high, as in receiving applications, a coupling coefficient of a few per cent may give critical coupling.

With loaded circuits it is not impossible for the Q to reach such low values that critical coupling cannot be obtained even with the highest practicable coefficient of coupling (coils as close physically as possible). In such case the only way to secure sufficient coupling is to increase the Q of one or both of the coupled circuits. This can be done either by decreasing the L/C ratio or by tapping the load down on the secondary coil (§ 2-10). One or the other of these methods often must be used with link coupling, because the maximum coefficient of coupling between two coils seldom runs higher than 50 or 60 per cent and the net coefficient is approximately equal to the products of the coefficients at each end of the link. If the load resistance is known beforehand, the circuits may be designed for a Q in the vicinity of 10 or so with assurance that sufficient coupling will be available; if unknown, the proper Q s can be determined by experiment.

Shielding—Frequently it is necessary to prevent coupling between two circuits which,

for constructional reasons, must be physically near each other. Capacitive coupling may readily be prevented by enclosing one or both of the circuits in grounded low-resistance metallic containers, called *shields*. The electrostatic field from the circuit components does not penetrate the shield, because the lines of force are short-circuited (§ 2-3). A metallic plate called a *baffle shield*, inserted between two components, may suffice to prevent electrostatic coupling between them, since very little of the field tends to bend around such a shield if it is large enough to make the components electrostatically invisible to each other.

Similar metallic shielding is used at radio frequencies to prevent magnetic coupling. In this case the magnetic field induces a current (*eddy current*) in the shield, which in turn sets up its own magnetic field opposing the original field (§ 2-5). The induced current is proportional to the frequency and also to the conductivity of the shield, hence the shielding effect increases with frequency and with the conductivity and thickness of the shielding material. A closed shield is required for good magnetic shielding; in some cases separate shields, one about each coil, may be required. The baffle shield is rather ineffective for magnetic shielding, although it will give partial shielding if placed at right angles to the axes of, as well as between, the two coils to be shielded from each other.

Cancellation of part of the field of the coil reduces its inductance, and, since some energy is dissipated in the shield, the effective resistance of the coil is raised as well. Hence the Q of the coil is reduced. The effect of shielding on coil Q and inductance becomes less as the distance between the coil and shield is increased. The losses also decrease with an increase in the conductivity of the shield material. Copper and aluminum are satisfactory materials. The Q and inductance will not be greatly reduced if the spacing between the sides of the coil and the shield is at least half the coil diameter, and is not less than the coil diameter at the ends of the coil.

At audio frequencies the shielding container is made of magnetic material, preferably of high permeability (§ 2-5), to short-circuit the external flux about the coil to be shielded. A nonmagnetic shield is quite ineffective at these low frequencies because the induced current is small.

Filters—By suitable choice of circuit elements a coupling system may be designed to pass, without undue attenuation, all frequencies below and reject all frequencies above a certain value, called the *cut-off frequency*. Such a coupling system is called a *filter*, and in the above case is known as a *low-pass filter*.

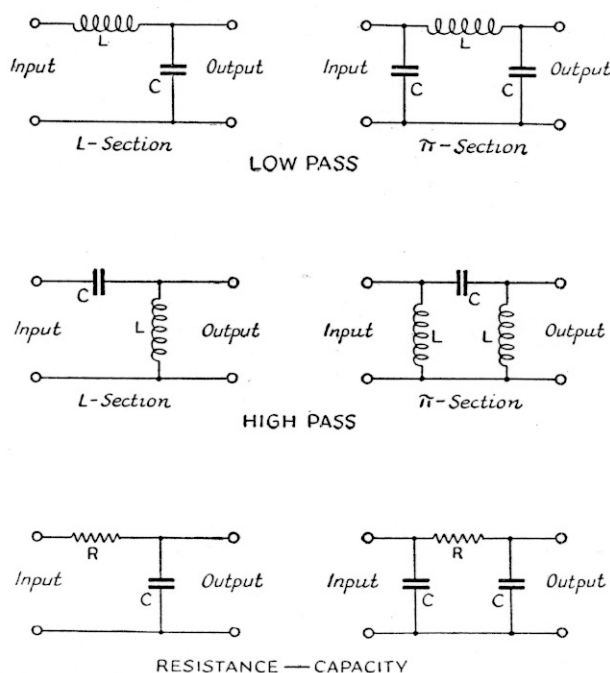


Fig. 244—Examples of the various types of simple filter circuits.

If frequencies above the cut-off frequency are passed and those below attenuated, the filter is a *high-pass filter*. Simple filter circuits of both types are shown in Fig. 244. The fundamental circuit, from which more complex filters are constructed, is the *L-section*. Fig. 244 also shows π -section filters, constructed from the basic L-section, which are frequently encountered both in low-frequency and r.f. circuits. The proportions of L and C for proper operation of the filters depend upon the load resistance connected across the output terminals, L being larger and C smaller as the load resistance is increased.

A *band-pass filter* is one designed to pass without attenuation all frequencies between two selected cut-off frequencies, and to attenuate all frequencies outside these limits. The group of frequencies passed through the filter is called the *pass-band*. Two resonant circuits with greater than critical coupling represent a common form of band-pass filter.

The *resistance-capacity filter*, shown in Fig. 244, is used where both d.c. and a.c. are flowing through the circuit and it is desired to provide greater attenuation for the alternating current than the direct current. It is usually employed where the direct current has a low value so that the d.c. voltage drop is not excessive, or when a d.e. voltage drop actually is required. The time constant (§ 2-6) must be large compared to the time of one cycle of the lowest frequency to be attenuated. In determining the time constant, the resistance of the load must be included as well as that in the filter itself.

Bridge circuits — A *bridge circuit* is a device primarily used in making measurements of resistance, reactance or impedance (§ 2-8), although it has other applications in radio circuits. The fundamental form is shown in Fig. 245-A. It consists of four resistances (called *arms*) connected in series-parallel to a source of voltage, E , with a sensitive galvanometer, M , connected between the junctions of the series-connected pairs. When the equation

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

is satisfied there is no potential difference between points A and B , since the drop across R_2 equals that across R_4 and the drop across R_1 equals that across R_3 . Under these conditions the bridge is said to be *balanced*, and no current flows through M . If R_3 is an unknown resistance and R_4 is a variable known resistance, R_3 can be found from the following equation after R_4 has been adjusted to balance the bridge (*null* indication on M):

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

R_1 and R_2 are known as the *ratio arms* of the bridge; the ratio of their resistances is usually adjustable (frequently in steps of 1, 10, 100, etc.), so that a single variable resistor, R_4 , can serve as a standard for measuring widely different values of unknown resistance.

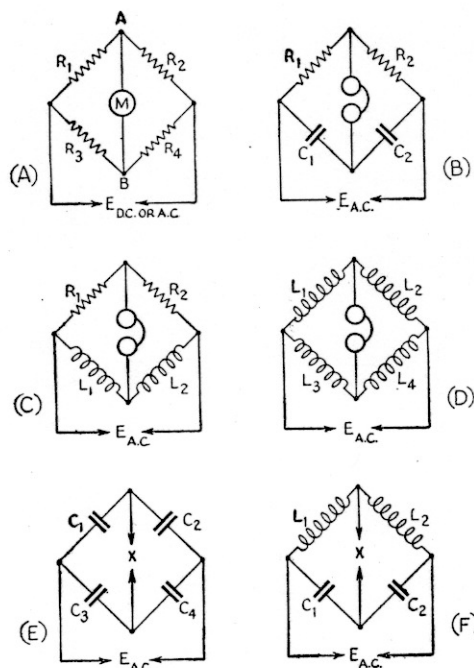


Fig. 245 — Bridge circuits utilizing resistance, inductance and capacity arms, both alone and in combination.

Bridges similarly can be formed with condensers, inductances and combinations of resistance with either. Typical simple arrangements are shown in Fig. 245. For measurements with alternating currents the bridge must not introduce phase shifts which would destroy the balance, hence similar impedances should be used in each branch, as shown in Fig. 245, and the Q s of the coils and condensers should be the same. When bridges are used at audio frequencies, a telephone headset is a good null indicator. The bridges at E and F are commonly used in r.f. neutralizing circuits (§ 4-7); the voltage from the source, E_{ac} , is balanced out at X .

2-12 Linear Circuits

Standing waves — If an electrical impulse is started along a wire, it will travel at approximately the speed of light until it reaches the end. If the end of the wire is open circuited, the impulse will be *reflected* at this point and will travel back again. When a high-frequency alternating voltage is applied to the wire a current will flow toward the open end, and reflection will occur continuously. If the wire is long enough so that time comparable to a half cycle or more is required for current to travel to the open end, the phase relations between the reflected current and outgoing current will vary along the wire, and at one point the two currents will be 180 degrees out of phase and at another in phase, with intermediate values between. Assuming negligible losses, this means that the resultant current will vary in amplitude from zero to a maximum value along the wire. Such a variation is called a *standing*

wave. The voltage along the wire also goes through standing waves, but reaches its maximum values where the current is minimum and vice versa.

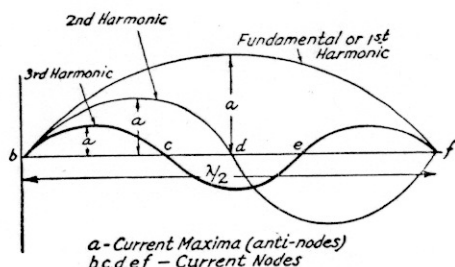


Fig. 246 — Standing-wave current distribution on a wire operating as an oscillatory circuit, at the fundamental, second harmonic and third harmonic frequencies.

Frequency and wavelength — It is possible to describe the constants of such line circuits in terms of inductance and capacitance, or inductance and capacitance per unit length, but it is more convenient to give them simply in terms of fundamental resonant frequency or of length. Since the velocity at which the current travels is 300,000 kilometers (186,000 miles) per second, the *wavelength*, or distance through which the current will travel in the time of one cycle, is

$$\lambda = \frac{300,000}{f_{kc.}}$$

where λ is the wavelength in meters and $f_{kc.}$ is the frequency in kilocycles. The lowest frequency at which the wire or line will be resonant is known as its *fundamental* frequency or wavelength. It is common to describe lines (or antennas, which have similar current and voltage distribution) as *half-wave*, *quarter-wave*, etc., for a certain frequency ("half-wave 7000-kc. antenna," for instance).

Wavelength is also used interchangeably with frequency in describing not only antennas but also tuned circuits, complete transmitters, receivers, etc. Thus, the terms "high-frequency receiver" and "short-wave receiver," or "75-meter fundamental antenna" and "4000-kilocycle fundamental antenna," are synonymous.

Harmonic resonance — Although a coil-condenser combination having lumped constants (capacitance and inductance) resonates only at one frequency, circuits such as antennas which contain distributed constants resonate readily at frequencies which are very nearly integral multiples of the fundamental frequency. These frequencies are, therefore, in *harmonic* relationship to the fundamental frequency, and hence are referred to as *harmonics* (§ 2-7). In radio practice the fundamental itself is called the *first harmonic*, the frequency twice the fundamental is called the *second harmonic*, and so on.

Fig. 246 illustrates the distribution of current on a wire for fundamental, second and

third harmonic excitation. There is one point of maximum current with fundamental operation, two when operation is at the second harmonic, and three at the third harmonic; the number of current maxima corresponds to the order of the harmonic and the number of standing waves on the wire. As noted in the figure, the points of maximum current are called *anti-nodes* (also known as "loops") and the points of zero current are called *nodes*.

Radiation resistance — Since a line circuit has distributed inductance and capacity, current flow causes storage of energy in magnetic and electrostatic fields (§ 2-3, 2-5). At low frequencies practically all the energy so stored is returned to the wire during another part of the cycle (§ 2-8), but above 15,000 cycles or so (radio frequency) some escapes — is *radiated* — in the form of electromagnetic waves. Since energy radiated by a line or antenna is energy dissipated, insofar as the line is concerned, the energy loss can be considered to take place in an *equivalent resistance*. This equivalent resistance is known as *radiation resistance*.

Resonant-line circuits — The effective resistance of a resonant straight wire, such as an antenna, is considerable, because of the power radiated. The resonance curve of such a straight-line circuit is quite broad; in other words, its Q is relatively low. However, by folding the line, as suggested by Fig. 247, the fields about the adjacent sections largely cancel each other and very little radiation takes place. The radiation resistance is greatly reduced, and the line-type circuit can be made to have a very sharp resonance curve, or high Q .

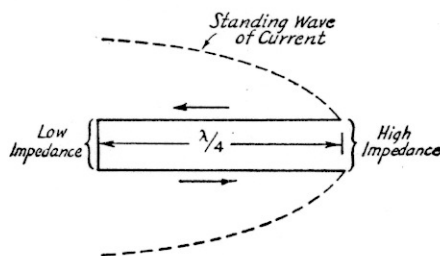


Fig. 247 — Standing wave and instantaneous current (arrows) conditions of a folded resonant-line circuit.

A circuit of this type will have a standing wave on it, as shown by the dashed-line of Fig. 247, with the instantaneous current flow in each wire opposite in direction to the flow in the other, as indicated by the arrows on the diagram. This opposite current flow accounts for the cancellation of radiation, since the fields about the two wires oppose each other. Furthermore, the impedance across the open ends of the line will be very high (thousands of ohms) while the impedance across the line near the closed end will be very low. This is because the current is low and the voltage is high at the open end of the line, but the current is high and the voltage low at the closed end.

A folded line may be made in the form of two concentric conductors, as shown in Fig. 248. The *concentric line* has even lower radiation resistance than the folded-wire line, since the

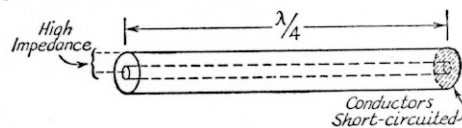


Fig. 248 — A concentric-line resonant circuit.

outer conductor acts as a shield. Standing waves exist but are confined to the outside of the inner conductor and the inside of the outer conductor, since skin effect prevents the currents from penetrating to the other sides. Thus such a line will have no radio-frequency potentials on its exposed surfaces. Because of the low radiation resistance and the relatively large conducting surfaces, such lines can be made to have much higher *Q*s than are attainable with coils and condensers. They are most applicable at very high frequencies (very short wavelengths) (§ 2-7), where the dimensions are small.

2-13 Circuits with Superimposed Currents

Combined a.c. and d.c. — There are many practical instances of simultaneous flow of alternating and direct currents in a circuit. When this occurs there is a *pulsating* current, and it is said that an alternating current is *superimposed* on a direct current. As shown in Fig. 249, the maximum value is equal to the d.c. value plus the a.c. maximum, while the minimum value (on the negative a.c. peak) is the difference between the d.c. and the maximum a.c. values. The average value (§ 2-7) of the current is simply equal to the direct-current component alone. The effective value (§ 2-7) of the combination is equal to the square root of the sum of the effective a.c. squared and the d.c. squared:

$$I = \sqrt{I_{ac}^2 + I_{dc}^2}$$

where I_{ac} is the effective value of the a.c. component, I is the effective value of the combination, and I_{dc} is the average (d.c.) value of the combination.

Beats — If two or more alternating currents of different frequencies are present in a normal circuit they have no particular effect upon one another, and for this reason can be separated again at any time by the proper selective circuits. However, if two (or more) alternating currents of different frequencies are present in an element having unilateral or one-way current flow properties, not only will the two original frequencies be present in the output but also currents having frequencies equal to the sum, and difference, of the original frequencies. These sum and difference frequencies are called the *beat* frequencies. For example, if frequencies of 2000 and 3000 kc. are present in

a normal circuit only those two frequencies exist, but if they are passed through a unilateral-element (such as a properly adjusted vacuum tube) there will be present in the output not only the two original frequencies of 2000 and 3000 kc. but also currents of 1000 (3000 - 2000) and 5000 (3000 + 2000) kc. Suitable circuits can be used to select the desired beat frequency.

By-passing — In combined circuits, it is frequently necessary to provide a low-impedance path for a.c. around, for instance, a source of d.c. voltage. This can be done by using a *by-pass condenser*, which will not pass direct current but will readily permit the flow of alternating current. The capacity of the condenser should be of such value that its reactance is low (of the order of 1/10th or less) compared to the a.c. impedance of the device being by-passed. The lower the reactance, the more effectively will the a.c. be confined to the desired path.

Similarly, alternating current can be prevented from flowing through a direct-current circuit to which it may be connected by inserting an inductance of high reactance (called a *choke coil*) between the two circuits. This will permit the d.c. to flow without hindrance, since the resistance of the choke coil may be made quite low, but will effectively prevent the a.c. from flowing where it is not wanted.

If both r.f. and low-frequency (audio or power) currents are present in a circuit, they may be confined to desired paths by similar means, since an inductance of high reactance for radio frequencies will have negligible reactance at low frequencies, while a condenser of low reactance at radio frequencies will have high reactance at low frequencies.

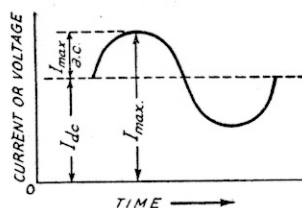


Fig. 249 — Pulsating current, composed of an alternating current superimposed on a direct current.

Grounds — The term “ground” is frequently met with in discussions of circuits. Normally it means the voltage reference point in the circuit. There may or may not be an actual connection to earth, but it is understood that a point in the circuit said to be at *ground potential* could be connected to earth without disturbing the operation of the circuit in any way. In direct-current circuits, the negative side generally is grounded. The ground symbol in circuit diagrams is used for convenience in indicating common connections between various parts of the circuit, as through a metal chassis, and, with respect to actual ground, usually has the meaning indicated above.